**MASTER THESIS**

# Improving Methanol Powered Solid Oxide Fuel Cell – Gas Turbine Power Units for Naval Support Vessels through Fuel and Heat Recovery

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# Hybrid Power Units in Naval Support Vessels

Thesis to obtain a Masters of Science Degree

by


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*This thesis is public*

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# Preface

Lectori salutem,

From an early age I have been interested in the ships of the Royal Netherlands Navy. It was therefore a great honour to be part of a group of engineers who are busy developing these ships every day. The Defensie Materieel Organisatie, part of the Ministry of Defence, has given me the opportunity to research hybrid power units for the auxiliary vessels. I would like to thank Mr. Isaac Barendregt very much for this opportunity. I have tried to produce valuable knowledge that can help solve today's challenges.

The development and research of a hybrid power unit consisting of a Solid Oxide Fuel Cell and Gas Turbine is complex and requires multidisciplinary collaboration. To tackle this properly, a methodical approach has been chosen, which is Systems Engineering in the department of Energy Technology. The Systems Engineering Knowledge Centre Twente (SEKCT) is a network organization of the University of Twente for the further development of Systems Engineering. So, this graduation assignment was therefore used as a pilot in the context of a collaboration between the department of Energy Technology and the Systems Engineering Knowledge Centre Twente.

I would like to thank my family and friends for their support during my education and graduation. My family has always supported me in the choices I have made and that is why I have always been able to do what I like. I just want to thank my friends from high school, college, the student association and my board year for being who they are and for being a part of my life.
Also, many thanks to dr.ir. Hajimolana for the very valuable guidance during the research. The answers to my questions, the feedback on my work and the conversations we had always provided me with new insights that I could use to improve my research. I would also like to thank dr.ir. de Graaf for sharing his knowledge in the field of Systems Engineering. Without his expertise I would not have been able to apply Systems Engineering to this research.
The guidance and expertise of ir. Barendregt and ir. de Jong during the graduation period was also very valuable. Because of their critical view at my work, I was able to take the research to a higher level and to align it even better with the wishes of the Defensie Materieel Organisatie. The same applies to ir. Stroeve's expertise and feedback from the 'Replacement Support Vessels' project team.

Should the reader feel in any way passed over when I forgot to thank you even though you did contribute during my education and graduation, please know that I am grateful to you anyway.

Arjen Kruize

Enschede, July 23, 2021

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# Abstract


The Ministry of Defence (MoD) has to be able to fulfil its constitutional duties, and therefore has to be as agile and reliable as possible. The dependency on fossil fuels, of which the availability and affordability is expected to come under pressure in the coming years, is a threat to the execution of these tasks. Furthermore, the use of fossil fuels is harmful to the environment.
The technology of methanol fuelled Solid Oxide Fuel Cell (SOFC) is a promising tool to efficiently power naval vessels with alternative fuels and without producing pollutants. However, a standalone SOFC power unit lacks the ability to provide either adequate efficiency or load-following capabilities. Therefore, the configuration of the SOFC system needed to be enhanced to make this power unit suitable for naval applicability.
Due to the complexity of the research and the design of a power unit, the systematic approach of Systems Engineering (SE) has been chosen. By using the tools offered by this method, it was possible to design the system in close cooperation with the relevant stakeholders. The early SE-based decision to use a Gas Turbine (GT) has been confirmed by the literature, which concluded that the GT has the most potential and therefore the enhanced system became a SOFC-GT power unit.

In an iterative process, the functions, requirements, and components of the system are determined, on which concept configurations have been designed. The concepts were assessed and given a score which allowed a choice table to determine which concept is best suited for naval applicability. The scores, weighting factors and assessment parameters have been determined in cooperation with stakeholders. After the chosen concept was known, it was investigated whether benefits from the other concepts could be used and whether the design offered integration possibilities with the naval vessel. As a result, the preliminary design was slightly modified after which it could be simulated.
By means of the Simulink® model it was possible to simulate the behaviour of the power unit and characteristics could be observed on which adjustments could be made. The results show that it is possible to meet the requirements of the Royal Netherlands Navy (RNLN). The system, operating at a pressure of 2 MPa, is able to take a power step with the GT in 15 seconds and to operate with a high efficiency, up to 81%. Furthermore, the temperature in the system does not exceed the maximum temperature and the temperature gradient inside the SOFC is within the safety margin of 10 K/cm. The final configuration of the power unit, consisting of among other things a multi-stage GT, PHE and mixing chambers, has a mass of 43 tons and a volume of 81 $m^3$.

In the validation process the relevant stakeholders mention that they are satisfied with the design of the power unit. However, there are also some concerns about the feasibility of the system, since the SOFC is a new development that has not yet been extensively tested and developed for naval applicability. This creates uncertainties when it comes to the reliability and complexity of the system. In any case, this research contributes to the maturing of the technology that may enable naval applicability in the future.

The first conclusion of this research is that the system can meet the requirements of the RNLN and therefore is suitable for naval applicability. Despite some concerns, which could be resolved through follow-up research, the stakeholders are satisfied with the design and the performance of the system.
It was also concluded that the size of the GT system depends on the power step that the system must be able to deliver quickly. The bigger the power step, the bigger the GT system will have to be. The results have also shown that the processes in the system are strongly linked and have a lot of influence on each other, this is also the reason to apply the bypasses for the Plate Heat Exchangers (PHE) in the system. Finally, it can be concluded, based on a comparison with the literature, that a higher operation pressure can increase the efficiency of the power unit.

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# Nomenclature

| | |
|---|---|
| $CH_3OH$ | Methanol. |
| $CH_4$ | Methane. |
| $CO_2$ | Carbon Dioxide. |
| CO | Carbon Monoxide. |
| $H_2O$ | Water. |
| $H_2$ | Hydrogen. |
| $N_2$ | Nitrogen. |
| $NH_3$ | Ammonia. |
| $NO_x$ | Nitrous Oxides. |
| $O_2$ | Oxygen. |
| $O^{2-}$ | Oxide. |
| $SCO_2$ | Supercritical $CO_2$. |
| $SO_x$ | Sulphuric Oxides. |
| $TCO_2$ | Transcritical $CO_2$. |
| $e^-$ | Electron. |
| AC | Alternating Current. |
| AOG | Anode Off Gas. |
| AOGRC | Anode Off Gas Re-Cycling. |
| APU | Auxiliary Power Unit. |
| CCHP | Combined Cooling, Heating and Power system. |
| CLC | Chemical-Looping Combustion. |
| CZSK | Commando Zeestrijdkrachten. |
| DC | Direct Current. |
| DEOS | Defensie Energie en Omgeving Strategie. |
| DMI | Directie Materiële Instandhouding. |
| DMO | Defensie Materieel Organisatie. |
| ER | External Reforming. |
| FC | Fuel Cell. |
| FFBD | Functional Flow Block Diagram. |
| G/M | Generator/Motor. |
| GE | General Electric. |
| GHG | Green House Gases. |
| GMM | Green Maritime Methanol. |
| GT | Gas Turbine. |
| HAT | Humid Air Turbine. |
| HE | Heat Exchanger. |
| HOV | Hydrografische Opnemingsvaartuigen. |

| | |
|---|---|
| HPC | High-Pressure Compressor. |
| HPT | High-Pressure Turbine. |
| ICE | Internal Combustion Engine. |
| IEC | Israel Electric Company. |
| ILS | Integrated Logistic Support. |
| IMCS | Integrated Monitoring Control System. |
| IMO | International Maritime Organization. |
| IR | Internal Reforming. |
| LCF | Luchtverdedigings- en Commando Fregat. |
| LNG | Liquefied Natural Gas. |
| LPC | Low-Pressure Compressor. |
| LPG | Liquid Pressed Gas. |
| LPT | Low-Pressure Turbine. |
| MCDO | Methanation of Carbon Di-Oxide. |
| MCMO | Methanation of Carbon Mono-Oxide. |
| MDR | Methanol Decomposition Reaction. |
| MLU | Mid Life Upgrade. |
| MoD | Ministry of Defence. |
| MSR | Methanol Steam Reforming. |
| NSC | Naval Ship Code. |
| ORC | Organic Rankine Cycle. |
| PEM | Polymer Electrolyte Membrane. |
| PEN | Positive electrode-Electrolyte-Negative electrode. |
| PHE | Plate Heat Exchanger. |
| PM | Particulate Matter. |
| PtL | Power to Liquid. |
| RAS | Requirements Allocation Sheet. |
| RHIB | Rigid Hull Inflatable Boat. |
| RNLA | Royal Netherlands Army. |
| RNLN | Royal Netherlands Navy. |
| S/C | Steam-to-Carbon. |
| SBD | Schematic Block Diagram. |
| SC | Supercapacitors. |
| SE | Systems Engineering. |
| SOFC | Solid Oxide Fuel Cell. |
| SSHS | SOFC-$SCO_2$ Brayton cycle Hybrid System. |
| ST | Steam Turbine. |
| VARS | Vapour Absorption Refrigeration System. |
| VOC | Volatile Organic Compounds. |
| WGS | Water Gas Shift. |

## Roman symbols

| | | |
|---|---|---|
| $A$ | Area | [m$^2$] |
| $b$ | Conductor plate width | [m] |
| $C$ | Heat capacity rate | [W/K] |
| $C_e$ | Capacitance | [F] |
| $c$ | Heat capacity | [kJ/(kg K)] or [kJ/(kmol K)] |
| $c_p$ | Constant pressure specific heat | [kJ/(kg K)] or [kJ/(kmol K)] |
| $c_v$ | Constant volume specific heat | [kJ/(kg K)] or [kJ/(kmol K)] |
| $d$ | Distance | [m] |
| $g$ | Gravitational acceleration | [m s$^{-2}$] |
| $H$ | Manometric head | [m] |
| $h$ | Specific enthalpy | [kJ/kg] or [kJ/kmol] |
| $\bar{h}_C$ | Enthalpy of combustion | [kJ/kmol fuel] |
| $\bar{h}_f$ | Enthalpy of formation | [kJ/kmol] |
| $\bar{h}_r$ | Enthalpy of reaction | [kJ/kmol] |
| $I$ | Electrical Current Density | [A/m$^2$] |
| $I_0$ | Initial current | [A] |
| $i$ | Electric current | [A] |
| $k$ | Specific heat ratio | [$c_p/c_v$] |
| $k_b$ | Boltzmann constant | [J/K] |
| $L$ | Conductor plate length | [m] |
| $M$ | Molar mass | [kg/kmol] |
| $m$ | Mass | [kg] |
| $\dot{m}$ | Mass flow rate | [kg/s] |
| $N$ | Number of moles | [kmol] |
| $N_A$ | Avogadro's number, number of molecules in one mol | [mol$^{-1}$] |
| $n$ | number of conductor plates | [-] |
| $n_p$ | Number of a product | [-] |
| $n_r$ | Number of a reactant | [-] |
| $P$ | Electrical Power | [kW] |
| $p$ | Pressure | [Pa] |
| $\dot{Q}$ | Heat transfer rate | [kW] |
| $Q_B$ | Battery capacity | [Ah] |
| $Q_C$ | Capacitor charge | [C] |
| $R$ | Gas constant | [kJ/(kg K)] |
| $R_e$ | Resistance | [$\Omega$] |
| $R_u$ | Universal gas constant | [kJ/(kmol K)] |
| $r_p$ | Pressure ratio | [-] |
| $s$ | Specific entropy | [kJ/(kg K)] |
| $T$ | Temperature | [K] or [°C] |
| $t$ | Time | [s] |
| $U$ | Potential Energy | [J] or [kWh] |
| $V$ | Volume | [m$^3$] |
| $V_e$ | Potential Difference | [V] |
| $w$ | Work per unit mass | [kJ/kg] |
| $\dot{W}$ | Power | [kW] |
| $Z$ | Compressibility factor | [-] |

## Greek symbols

| | | |
|---|---|---|
| $\alpha$ | Convective heat transfer coefficient | [W/(m$^2$ K)] |
| $\varepsilon_0$ | Electric constant | [F/m] |
| $\varepsilon_u$ | Utilization factor | [-] |
| $\eta$ | Efficiency | [-] |
| $\lambda$ | Thermal conductivity | [J/(m s K)] |
| $v$ | Specific volume | [m$^3$/kg] |
| $\rho$ | Density | [kg/m$^3$] |
| $\tau$ | Thickness | [m] |

## Subscripts

| | |
|---|---|
| $a$ | Actual |
| $C$ | Compressor |
| $c$ | Cold |
| $ch$ | Central heating |
| $cr$ | Critical |
| $G$ | Generator |
| $g$ | gas |
| $h$ | Hot |
| $i$ | Substance index |
| $in$ | At the inlet |
| $l$ | liquid |
| $M$ | Melting |
| $net$ | Net |
| $out$ | At the outlet |
| $P$ | Pump |
| $r$ | Reduced |
| $s$ | Isentropic |
| $T$ | Turbine |
| $Th$ | Thermal |
| $w$ | Wall |
| $wws$ | Warm water system |
| 0 | Dead state |
| 1 | Initial or inlet state |
| 2 | Final or exit state |

## Superscripts

| | |
|---|---|
| $\circ$ | Standard reference state |
| - | Quantity per unit mole |
| $\cdot$ | Quantity per unit time |
| $\sim$ | Average value |

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# 1 | Introduction

The research, described in this document, is the thesis to obtain the degree Master of Science. In this report will be discussed whether it is possible to adequately power naval vessels with a hybrid power unit consisting of a methanol fuelled Solid Oxide Fuel Cell (SOFC) and a Gas Turbine (GT). This question is important since the shift away from fossil fuelled engines is a priority in all transport sectors. This is because fossil fuels are running out and the use of fossil fuels is harmful to the environment.

Where the car industry is now making the step towards electric and Hydrogen ($H_2$) driven engines, at sea fuel oil is still most used. Shipping is therefore subject to a lot of criticism because of the emissions of soot, carbon dioxide and sulphur. For this reason, and the regulations for air pollution and emissions from ships of the International Maritime Organization (IMO) and local politics [7, 8], the maritime sector has to reduce the emission of net Green House Gases (GHG) and other harmful substances.
Also, the Ministry of Defence (MoD) has to be able to fulfil its constitutional duties, and therefore has to be as agile and reliable as possible. The dependency on fossil fuels, of which the availability and affordability is expected to come under pressure in the coming years, is a threat to the execution of these tasks.

These are the main two reasons why it is important to reduce the use fossil fuels and increase the use of alternative fuels. The Royal Netherlands Navy (RNLN) is committed to this assignment and therefore provides the opportunity to implement new power units and alternative fuels. In this quest, the usability of its ships and the safety of personnel has to be assured, which underlines the importance of the question posed above.[8]
The motivation of this research will be described more extensive in this chapter as well as the problem identification, the objective and process of the investigation and the structure of the report.

## 1.1 | Motivation

The motivation for the investigation of these power units has multiple facets. In the first place the climate goals that are set and have to be achieved by the Netherlands government and the MoD. Secondly, the plans of the MoD to reduce energy dependence, to increase the effectiveness and efficiency of the armed forces, will also influence the development of naval vessels and their power units. Furthermore, the opportunity exists for implementing new technologies in naval vessels since some vessels will be replaced or upgraded. Lastly, a recently finished master thesis of a student from the TU Delft, considering an alternative power unit, provides the promising opportunity to build on its results and recommendations.
The changes and improvements that have to be executed are serious challenges for the RNLN and the Defensie Materieel Organisatie (DMO). The combination of these challenges with the recently finished research emphasize the importance of this research.

### 1.1.1 | Climate Goals

Climate change has major consequences for people, nature, and the environment and is mostly caused by the emission of net GHG. Two examples of these consequences are natural disasters and conflicts, which require the deployment of armed forces which in turn influence climate change with their emissions. For these reasons the MoD should make an effort to limit its own contribution to climate change. The RNLN, part of the MoD, is committed to eliminating net GHG and other harmful emissions.

Since the MoD has the ambition that by 2050 the dependence on fossil fuels will be reduced by at least 70% compared to 2010 [9], the search for alternative fuels is in full swing.
The project Green Maritime Methanol (GMM) is initiated with other stakeholders to investigate the possibilities into a renewable methanol infrastructure for the maritime sector. They concluded that methanol would be a suitable fuel for a potentially significant part of the maritime short sea market.[10, 11]

The use of methanol ($CH_3OH$) as fuel is not completely free of carbon emission but the emission will be lower due to new technologies. One of these technologies for eliminating net carbon emission is Power to Liquid (PtL) conversion. Using green electricity, liquid synthetic fuels, such as methanol, can be made of Carbon Dioxide ($CO_2$) and Hydrogen ($H_2$) [1]. This production of alternative fuels may be the key to carbon neutral sailing but is outside of the scope of this investigation.

Other harmful emissions are Sulphuric Oxides ($SO_x$), Nitrous Oxides ($NO_x$), Volatile Organic Compounds (VOC) and Particulate Matter (PM). Eliminating these emissions virtually can be done with Fuel Cells (FC) since they do not have moving parts, can operate without sub optimal combustion, and lack extremely high temperatures. The last is important since $NO_x$ formation takes place above 1300 °C. Through these characteristics, the fuel cell prevents the forming of PM, VOC, and Nitrous Oxides, respectively. Eliminating Sulphuric Oxides can be done by using fuels without Sulphur, for example methanol or methane ($CH_4$).[5]

### 1.1.2 | Energy Independence

Energy supply is essential for any military operation. The energy supply of current military operations is almost completely dependent on fossil fuels [12]. As briefly stated in section 1.1.1 the MoD has the ambition to be more independent of fossil fuels, which will increase the effectiveness and efficiency of the armed forces. In this section the negative effects of energy dependency will be explained more extensive [12].

Firstly, energy independence will influence the operational effectiveness. The ability to continue an operation and the speed of maneuver and autonomy of the deployed military units is depending on the availability of energy carriers.
Moreover, the logistic load to get fuel to the consumer in the deployment area increases when the size of an operation increases. An increasing logistic loads means an increasing demands on human, material and financial resources.
Lastly, the logistics supply and storage of energy is vulnerable to disruption from enemy attacks or natural events, such as bad weather or natural disasters. Securing fuel transports requires military capacity that may be withdrawn from the military operation.

In short, energy independence has a positive influence on the effectiveness and efficiency since personnel, time, materials, and financial resources are used more efficiently. Furthermore, because vulnerability is removed and agility is improved. The implementation of new technologies will contribute to this energy independence since systems will be more efficient and use less energy. Also, new technologies that produce alternative fuels and allow power units to run on these fuels make a contribution.

### 1.1.3 | Performance and Safety

As already mentioned in the introduction of this chapter the usability of the vessels and the safety of personnel are paramount for the RNLN, due to their military role, sometimes in a higher spectrum of violence. This implies that energy independence and the use of new technologies should never be at the expense of, e.g., range, reaction speed, Naval Ship Code (NSC) requirements or the use of weapon and security systems. Adjustments in these areas, as well as in other areas, have to make at least an equivalent, if not greater, contribution to performance and safety.

For example, the RNLN wants to use methanol as fuel, rather then Hydrogen, since the energy density is much higher. Therefore, also the usability is better when methanol is used, since less fuel has to be taken on board. Furthermore, the RNLN does not want to use gaseous fuels, as Hydrogen, on the combatants in connection with safety.[1]

### 1.1.4 | Opportunity

In the coming years the RNLN will execute numerous upgrades and replacements among other things the ten support vessels, see figure 1.1. The current fleet of support vessel consist of all different types of vessel with their own specific purpose and design. Appendix A.1 provides more information about the support vessels and the replacement project [13]. DMO and Commando Zeestrijdkrachten (CZSK) are currently examining whether the replacement of the capacity could be based on 2 'families' of ships: seagoing support vessels and diving support vessels. The basic principle for this bases is that family formation is more efficient than design per current ship class.[2]

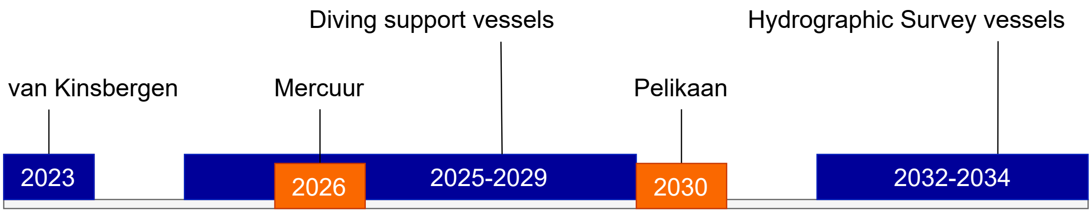


Figure 1.1: Timeline of planned replacements for the support vessels.[1]

Since the tasks of these vessels are so diverse DMO wants to provide the ships with a working deck, for both containers and a heavy crane, and for the use of modular and autonomous systems. This modular design makes it possible for the ships in this new family to have a similar hull, bridge and power unit without interfering with the tasks of each individual vessel by adding specific functionalities. This can be seen clearly in figure 1.2.[2]

Given their smaller operational-critical profile for CZSK these naval vessels are excellent candidates to take a step towards concrete implementation of the Defensie Energie en Omgeving Strategie (DEOS). This implies that they might be suitable for alternative fuels, such as methanol (see section 1.1.1) or even fully electric propulsion.[2]

Taking all the information of this section together, it can be concluded that the opportunity exists to implement a new type of power unit in multiple support vessels.

Figure 1.2: Artist impression of the modular design of the support vessels.[2]

### 1.1.5 | Relevance

In October 2020, a student at the Delft University of Technology graduated on the research into the dynamic behaviour of little-researched, methanol fuelled SOFC in the higher temperature range. The research concluded that the methanol fuelled SOFC system, consisting of a pre-reformer, SOFC, Anode Off Gas Re-Cycling (AOGRC), and heat exchanger (HE), can provide sufficient power for a naval vessel, similar to the Hydrografische Opnemingsvaartuigen (HOV), but lacks the ability to provide either adequate efficiency or load-following capabilities. However, in the recommendations of the research the author stated that the system could be enhanced with a different configuration and improved components.[5]

Since the technology of SOFC is still a promising tool to efficiently power naval vessels, without producing pollutants, and the research is finished just a few months ago, the investigation to improve the methanol fuelled SOFC system is still practically relevant. The scientific relevance is evident from the knowledge gap identified in section 2.2.

## 1.2 | Problem Statement

As briefly mentioned in section 1.1.5 the efficiency and performance in dynamically loaded conditions of the methanol fuelled SOFC system is insufficient to power a naval vessel. This is of great concern considering the development of energy use onboard of naval ships. The reduction of crew size and the expected new weapons systems will shift the ratio between constant electrical service load and high electrical loads [8].

In the current situation it is already the case that, depending on ship operations such as manoeuvring, entering a port, or sailing in harsh weathers, the dynamic load changes of a ship can be large and sudden [14]. These load changes will be amplified by the aforementioned development and therefore require fast deliverable high electrical power.

From the previous research the following problems could be defined [5].

- Unsatisfactory use is made of waste heat and the fuel in Anode Off Gas (AOG), which means that there is much room for improvement of the efficiency.
- A system consisting of SOFC, Plate Heat Exchanger (PHE), and pre-reformer exclusively, lacks the ability to produce adequate transient behaviour for naval applicability. This is because thermal inertia is the main limiting factor for the load-following capabilities of SOFC-based power units.

From the identified problems can be concluded that the configuration of the SOFC system needs to be enhanced to make this power unit suitable for naval applicability. The literature study, conducted in chapter 2, also identifies the knowledge gap about methanol fuelled SOFC power systems for naval applicability. During the improvement process also subjects, like compactness, durability, usability, emissions, maintenance, and reliability, need to be considered. The last two, for example, are important because of the reduction of crew size.

The following knowledge gaps from literature are outside the scope of the investigation but are important for the performance of the SOFC-GT and therefore mentioned in this paragraph. Little is known about the reliability of SOFC-GT power units and the safe handling of the Hydrogen, anode gas flow mixture and AOG. Furthermore, the possibility to use a combination of Hydrogen and methanol in a GT and improvements for the response time of the (PHE) are unknown. Lastly, the optimal operation of the methanol fuelled SOFC hast to be investigated because of the durability, maintenance, and reliability. In chapter 10 the importance of follow-up research for these knowledge gaps and related recommendations will be provided.

## 1.3 | Objective

What exactly this enhanced configuration of the methanol fuelled SOFC-based power system should look like to achieve naval applicability is the objective of this study. The early SE-based decision to use a GT has been confirmed by the literature, which concluded that the GT has the most potential. Therefore, the SOFC-based power system will be a hybrid system consisting of a SOFC and a GT. The research questions considering the objective are mentioned in this section.

### Main Research Question

What are the design characteristics of a methanol fuelled Solid Oxide Fuel Cell - Gas Turbine hybrid power unit that meets the technical criteria for naval applicability on the support vessels of the Royal Netherlands Navy?

### Sub-questions

To adequately answer the main research question, the system and its performance are studied more in depth by answering the following sub-questions.

- What are the mission and technical criteria, established by the RNLN and the literature, of the hybrid power unit?
- What are possible hybrid energy system configurations that meet technical performance criteria with the focus on dynamic behaviour and efficiency?
- Which concept hybrid energy system configuration is expected to best meet the technical criteria and has to be modelled for optimizing the dynamic behaviour and performance, verification, and validation?
- To what extent can the SOFC-GT hybrid power unit meet the technical criteria and fulfill the mission imposed by the RNLN?

## 1.4 | Report Structure

In chapter 2 "Literature study" of this report the important information from the literature about the system characteristics and identified knowledge gaps will be presented. Chapter 3 "Report Baseline" provides information about the Systems Engineering (SE) method that will be used to execute this investigation, the stakeholders, and the technical criteria for the power unit. Chapter 4 "Concept designs" provides the starting configuration and the concepts configurations. Chapter 5 "Simulation Model" will provide the equations, assumptions and other required information for the simulation as well as the verification. The results of the simulation are presented and explained in chapter 6 "Simulation Results". The verification and validation of the design of the power unit are discussed in chapter 7 "System Design Completion". Furthermore, the final design of the power unit is presented in this chapter, which also answers the main research question. Chapter 8 "Discussion" will elaborate further on the results of the investigation and will discuss the validity and quality. In chapter 9 "Conclusion" the results of this investigation will be discussed and conclusions will be drawn about these results. Chapter 10 "Recommendations" will provide input for follow-up research.

Appendix A "Background Information" provides background information about the the current, to be replaced, support vessels of the RNLN and the assignment of the replacement of the support vessels. Furthermore, this appendix discusses information about the SOFC system, existing configurations, other identified knowledge gaps, and the SE method. Appendix B "Functional Diagrams" shows the functions of the power unit in the Functional Flow Block Diagram (FFBD). Appendix C "Allocation Sheet" links the functions from the FFBD to the required components in the Requirements Allocation Sheet (RAS). Appendix D "Argumentation" will provide the argumentation behind the grades given to the concepts for every parameter. Appendix E "Schematic Diagram" provides information of the components and the interfaces in the Schematic Block Diagram (SBD). Additional simulation results are discussed in appendix F "Additional Simulation Results". Appendix G "Decision database" contains the reporting of all decisions made during this investigation. Lastly, appendix H "SE Process Evaluation" evaluates the pilot of applying the SE method during this investigation.

# 2 | Literature Study

This chapter provides the results of the literature study, one of the first steps in the SE process, about SOFC-GT hybrid power units. It should be noted that the literature study mostly provides information about SOFC-GT hybrid power units that are not methanol fuelled, but for example, methane fuelled. The few papers that are published about methanol fuelled SOFC-GT hybrid power units are not in line with this investigation as will be explained in section 2.1.2. With this literature review, the aim has been to provide all the information necessary to understand the characteristics of the methanol fuelled SOFC-GT hybrid power unit and to identify the knowledge gaps. This is important to be able to model the power unit correctly and accurately create new information. Additional background literature about the SOFC system and already existing configurations is provided in appendices A.2 and A.3, respectively.

## 2.1 | Characteristics

In this section of the report the characteristics of SOFC-GT power units are discussed. This considers the operational aspects like dynamic behaviour and usability as well as other characteristics like durability, reliability, maintenance, compactness, emissions, and fuel consumption.

### 2.1.1 | Dynamic Behaviour

Several investigations state that the dynamic response of SOFC systems are limited by the dynamic behaviour of the HE [5,14–16], as already mentioned in section 1.2. To enhance the dynamic behaviour of the SOFC system literature was consulted whether it is possible to use a GT, which resulted in several papers about this subject. Although in the reviewed papers, methane fuelled GT were used this is not a problem since section 2.1.4 will elaborate on the methanol fuelled GT. In this section only the possibility to enhance the dynamic behaviour is subject.

The investigations show that the dynamic behaviour of the hybrid power system can be significantly improved using a GT or ICE. In the hybrid power unit, the response of both the GT and ICE to sudden and large load changes is of the order of magnitude of 15 seconds [14, 15]. The change in power of GT during that time is typically in the range of 100-200 kW/second [17]. This is significantly faster than the response time of the SOFC system described in [5, 14, 15], which is in the order of hundreds of seconds. The HE aside, 15 seconds is also faster than the response time of the SOFC itself, which starts from 25 seconds for small load steps [5].
Another research states that the SOFC-GT power unit can provide the required power for moving a freight train along a specific, demanding rail line. In that research also the decision-making behaviour of a locomotive engineer about the motion of the train is modelled so not only the power system's operation alone is considered.[3]
The SOFC-GT system of a third study is intended to be used as an Auxiliary Power Unit (APU) for military ground vehicles. In this research is stated that this power unit could provide sufficient power to support surveillance and other missions with reduced aural detectability during engine-off operations. The results show that the dynamic behaviour of the hybrid system can be improved by allowing the turbine to take on greater loads, thus mitigating the slow dynamic response of the SOFC, and taking full advantage of the dual operating G/M as a generator during normal operation or a motor for the compressor in case there is not enough power for air delivery.[18]
Besides using a GT, the configuration also influences the dynamic behaviour of the power unit. In an, so called, open loop system, the variation of rotational speed of the GT influences the air mass flow through the system. This influences the behaviour of the SOFC since the cell temperature, heat flux,

and temperature gradient change, resulting in a different output voltage and current [19], which are called coupling effects. A fluctuating mass flow through the SOFC improves the response time a little [19], but it is still significantly slower than the response time of the GT [5, 14, 15].

Other research showed that the dynamic behaviour can be improved even further using a module of SC installed in parallel with the GT. The SC can compensate the relative low dynamics of the GT[20]. Furthermore, the SC can be used for peak-shaving, leveling the electricity demand and thus the load on the generation system [21]. By only using these options, a lot of waste heat and residual fuel is still lost, so that the efficiency will not be improved much. Hence, a better option is to use these components in a supporting role further improving the dynamic behaviour.
The implementation intentions for the SOFC-GT power units and results of these studies are very promising for the implementation of a SOFC-GT power unit on naval vessels, also confirmed by [21].

### 2.1.2 | Compactness

The research about the performance of a SOFC-GT driven locomotive also investigated, based on conservative estimations, the compactness of such a power unit [3]. A conceptual drawing of how the SOFC-GT power unit, including sulphur removal bed, can be placed inside the locomotive's frame is presented in figure 2.1. The sulphur removal bed is not considered in this section since methanol ($CH_3OH$) does not contain sulphur, see also section 1.1.1. The results of the size specifications, power output and mass in comparison with standard diesel locomotive engines are displayed in tables 2.1 and 2.2. Table 2.2 shows the generalized results from table 2.1. In addition, a comparison with the SOFC-ICE power unit is made based on the results of [14].

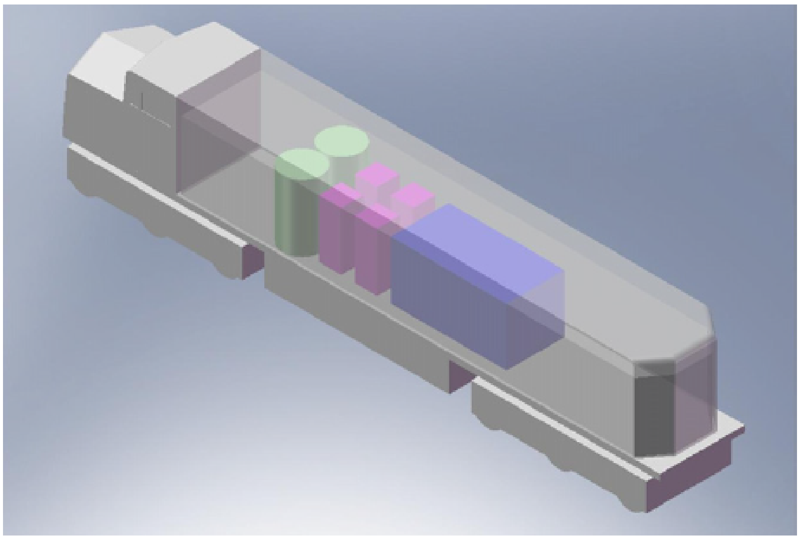

Figure 2.1: Conceptual layout for a SOFC-GT onboard of a locomotive. The green units represent the external reformer and sulphur removal bed. The four maroon objects represent SOFC stacks, and the blue object represents the GT.[3]

| Power unit | Footprint [m$^2$] | Volume [m$^3$] | Power [kW] | Mass [kg] |
|---|---|---|---|---|
| ICE | - | 29.67 | 1000 | 14,285 |
| GT | 9.02 | 21.74 | 1000 | 9,525 |
| SOFC | 2.70 | 13.55 | 2900 | 14,260 |
| ER | 1.58 | 3.78 | - | ∼ 250 |
| Total Diesel-Electric system | ∼ 11 | ∼ 53 | 3355 | 19,736 |
| Total SOFC-GT system | 13.3 | 39.07 | 3900[1] | 24,035 |
| Total SOFC-ICE system | - | 43.22 | 3900 | 28,545 |

Table 2.1: The calculated size specifications, power outputs and masses of standard diesel locomotive engines and potential SOFC-GT and SOFC-ICE power units.[3]

Table 2.1 shows that the Diesel-Electric system has a slightly smaller footprint than the SOFC-GT power unit, but the volume is significantly larger. In addition, the research states that the footprint might be reduced when the power unit is carefully engineered [3]. Furthermore, the table shows that most of the footprint and volume is taken by the GT, so when power supply shifts from GT to the SOFC the size of the system can even be further reduced. Except for the footprint, the same conclusions can be drawn in the comparison of the SOFC-ICE power unit with the Diesel-Electric system. The table also shows that the ICE is larger than the GT, which argues for the choice of a GT.

Table 2.1 also compares the weight of the Diesel-Electric system with the SOFC-ICE and SOFC-GT power units. It shows that the mass of the train with the SOFC-GT power unit increases with approximately 4.3 tons (22%). For the SOFC-ICE power unit the increase of mass will be 8.8 tons (45%). From that can be concluded that the mass of the SOFC-GT power units in all probability will be smaller than the mass of the SOFC-ICE power units, which also argues for the choice of a GT.

| Power unit | Surface density [$kW \cdot m^{-2}$] | Volumetric density [$kW \cdot m^{-3}$] | Gravimetric density [$kW \cdot kg^{-1}$] |
|---|---|---|---|
| ICE [14] | - | 33.7 | 0.070 |
| GT | 111 | 46.0 | 0.105 |
| SOFC | 1074 | 218.0 | 0.203 |
| Total Diesel-Electric system | 305 | 63.3 | 0.170 |
| Total SOFC-GT system | 293 | 99.8 | 0.162 |
| Total SOFC-ICE system | - | 90.2 | 0.137 |

Table 2.2: The calculated power output per area, volume and mass unit of standard diesel locomotive engines and potential SOFC-GT and SOFC-ICE power units.

Reviewing the generalized results shown in table 2.2, it appears that the same conclusions can be drawn as in the paragraphs before. The size of the SOFC-GT power unit will be smaller than the size of the SOFC-ICE and Diesel-Electric system. Furthermore, the mass of the hybrid power systems will be larger than the mass of the Diesel-Electric system, with the mass of the SOFC-ICE system larger than the mass of the SOFC-GT system.

Although the research shows that the hybrid power units increase the mass of the locomotive, it also states that the development of higher power per kilogram ratios is promising [3]. So, the mass of the power unit can be reduced in the future, confirmed by [22] which states that in the future SOFC can reach volumetric densities in the range of 3-10 $MW \cdot m^{-3}$ and gravimetric densities in the range of 2-4 $kW \cdot kg^{-1}$. Since size and mass constraints are also present onboard of naval vessels this is very promising for the implementation of SOFC-based hybrid power units. The paper also states that GT can reach larger gravimetric and volumetric power densities then ICE, which argues for the choice of a GT.

It has to be noted that the configurations of the hybrid systems described in section A.3 are more complicated and consist of more components than the simple SOFC-GT power unit considered in this section. Therefore, it can be concluded that the footprint, volume and mass of the to be designed system will be larger. This will result in a lower surface, volumetric, and gravimetric power density than shown in table 2.2.
Especially the currently existing methanol fuelled power units and CCHP, considering the large number of HE and other components, will most certainly be excessively large and heavy for maritime applications.

### 2.1.3 | Durability

The investigations discussed in this section show that the lifespan of the SOFC significantly increases in constant voltage operation, from which can be concluded constant temperature operation. This is not strange when one considers that, because the cells in the stack are thin and short, temperature differences cause large thermal gradients and therefore thermal stresses which are harmful for the cell.

[1] The attentive reader will notice that the total power of the hybrid system is larger than the power of the Diesel-Electric system. This is because the authors chose a larger turbine for integration into the hybrid system. The actual power supply on which the results of the paper are based is 3411 kW with a power split of 85% SOFC and 15% GT.[3]

The first study investigated the effect of standalone cases, a SOFC system without a GT, and SOFC-GT hybrid cases on the lifespan of the cell. In the standalone cases the SOFC had to react to the load changes of the system. This required changes in the voltage and therefore the temperature, which caused a significantly larger degradation of the SOFC. In the SOFC-GT hybrid cases the turbine responded to the load changes and the cell operated at constant voltage mode which caused much slower degradation. The results show that in those standalone cases the lifespan of the cell was approximately 20 weeks, while in the hybrid cases the lifespan is increased to 351 weeks.[23]
A second research also concluded that maintaining the SOFC at a constant value improves the lifespan. This study then also advised to use a module of SC in the hybrid power unit to ensure fast response to power demand variations. Next to using a GT this is a way of avoiding SOFC power variations and thus increasing the lifespan of the cell.[20].

The SOFC manufacturers target stack lifetime between 40,000-80,000 hours with longer lifetimes for the system itself [24]. This is also based on stationary application of continuous, uninterrupted power supply. Although these system lifetimes are still a challenge to most SOFC developers the target lifetime is long compared to the lifetime of other fuel cell technologies. For example, stack lifetimes of Polymer Electrolyte Membrane (PEM) fuel cell stacks are usually limited to 20,000 to 30,000 hours.[21]

### 2.1.4 | Usability

In this section the usability of the SOFC-GT hybrid power unit is discussed. This considers signatures and safety of the power unit and its components during operation as well as the safety of the fuels used in the system. Additionally, the practicality of the components and the fuels used within the hybrid system are reviewed.

#### Signatures

In SOFC-GT power units fewer moving parts are present than in diesel engines, which may allow it to produce less noise and vibrations and therefore be less aural detectable [3, 18, 21]. As a result, these hybrid power units most likely will meet the noise requirements set by the RNLN and provide save operation. Furthermore, the SOFC reduces infrared signatures which makes the system less visually detectable [21].

#### Safety

In section 1.1.1 is mentioned that the project GMM concluded that methanol is a suitable fuel for the maritime short sea market. Besides methanol is also a safer liquid fuel for storage than gasoline, Diesel and Liquid Pressed Gas (LPG) since the risk range, in case of a fire, is smaller [25]. Despite that the fuel storage and fuel cell installation should be separated from each other [26].
However, some modifications are suggested to guarantee safe operation. For personnel handling methanol additional protective gear will likely be required since methanol is toxic for humans. Furthermore, methanol burns with an invisible flame and therefore special flame detection equipment, for example infrared video cameras, is required to assist with methanol flame detection.[27]
To ensure safe operation of the hybrid system in general, adequate fire suppression, monitoring and control systems have to be installed. Furthermore, vapour detectors, forced ventilation, double walled pilings and safety valves have to be considered as large quantities of vapour can cause ignition and possible flashback.[26–28]

These modifications are also mentioned in the regulations for vessels that use gases, other low-flashpoint fuels or FC systems to guarantee safety, see [29–31]. These regulations will also state which modifications have to be made to work safely with Hydrogen since using Hydrogen onboard of naval vessels also could be a safety risk. It has to be noted that [29] and [30] focus on using methane and methanol, respectively, and therefore may be not strict enough for using Hydrogen.[32]

During operation of the SOFC it is important to consider the safety of the power unit, despite the trade-off with the performance of the system [33]. The SOFC should be operated between 873 K and 1123 K to ensure safety [34]. The section 2.1.3 and 2.1.7 mention that a large temperature gradient has a negative influence on the durability and reliability but also for safety reasons the temperature gradient should not be greater than 10 K/cm.

Furthermore, when the Steam-to-Carbon (S/C) ratio in the pre-reformer is insufficient, too little water is presents for the thermodynamic equilibrium conditions. This results in the risk that the potentially dangerous problems, like carbon deposition, overheating, and catalyst deactivation, arise in the pre-reformer and at the anode of the SOFC.[5, 34, 35]

The other components of the SOFC-GT system also need to be considered when it comes to safety. The temperature of the turbine inlet gases must be lower than the maximum permissible temperature of the turbine materials, so research states that the turbine inlet temperature should not exceed 1773 K [36, 37]. When no speed control is implemented for the GT, the rotational speeds can also be a safety issue since excessive rotational speeds can damage the turbine [19].
Besides, the surge margin of the compressor has to be greater than 12% to prevent surge during off design operation and the chocked flow should be lower 0.20 kg/s. Surge has to be prevented since it can cause damage to other components in the system and occurs along with loud noises.[35]

### Practicality

In operation of the SOFC system the start-up and shutdown time are delayed due to the high temperatures of the cell [21, 38]. However, this does not detract from the practicality of the SOFC system but is something to be considered when using the system. During the start-up time energy from a battery can be used and during shutdown time the battery can then be charged [21]. The limiting part of the system, the dynamic behaviour, can be solved using a GT as discussed in section 2.1.1. On the other hand, SOFC efficiencies are size independent [22] and the modularity of the SOFC allows a more flexible integration in vessel design [21].

Most SOFC-GT hybrid power units are fuelled with methane, as already mentioned in the introduction of this chapter, therefore it is important to obtain knowledge about using methanol as a fuel for GT. Experimental research provides this knowledge since it shows that it is not only possible but also improves the performance of the GT because of the higher mass flow and lower combustion temperature. Furthermore, the experiments concluded that the ability of starting, stopping, accelerating, decelerating, performing automatic synchronization, and responding to control signals is equal to operations on either natural gas or distillate fuel [39, 40].
Practical examples of methanol fuelled GT can be found in drag racing and tractor pulling [32]. A practical example that provides more information is the successful conversion of a GT power unit in Eilat from Diesel fuelled to 100% methanol fuelled by DOR and the Israel Electric Company (IEC). The results of this conversion show a reduction of 75% $NO_x$, 100% $SO_x$, and 80% PM, with no degradation of performance. Moreover, the methanol fuelled GT provides safe operation for the entire load range.[25]

Since the outflow products of the SOFC is Hydrogen gas ($H_2$), it is also important to know if GT are able to run on this fuel. General Electric (GE) and Siemens Energy has combustion technologies for GT that are capable of operating on a wide range of Hydrogen volume concentrations up to 100% [41, 42]. However, in most available GT a blend of fuels is required due to the chemical properties of Hydrogen.

From the previous paragraphs of this section can be concluded that the use of a methanol fuelled GT does not only contribute to an improved dynamic behaviour of the hybrid power unit but it also contributes to the climate goals, described in section 1.1.1, and safe operation when methanol fuelled. Furthermore, they conclude that it is possible to use the exhaust gases from the SOFC in the GT, possibly mixed with methanol. Therefore, also this section argues for the use of a GT in the power unit.

## 2.1.5 | Emissions and Fuel Consumption

The paper about the SOFC-GT driven locomotive estimated that, in the specific case described in that research, the fuel and $CO_2$ savings could be approximately 18% [3]. The power split in that specific situation is 85% SOFC and 15% GT.
Other investigations confirm that with a SOFC-based hybrid power unit emissions of GHG and other harmful substances can be reduced as well as the fuel consumption. The results of the investigations to emission reduction by the hybrid systems, compared to a Diesel engine [43] and a conventional marine natural gas engine [14], are shown in table 2.3.

| Power unit | Power split | $NO_x$ [%] | $CO_2$ [%] |
|---|---|---|---|
| Diesel-powered SOFC-GT | 85-15 | 97.7 | 30.3 |
| Natural gas-powered SOFC-GT | 85-15 | 97.7 | 53.8 |
| SOFC-ICE | 67-33 | 60 | 20.74 |
| SOFC-ICE | 33-67 | 30 | 12 |

Table 2.3: The determined emission reduction of the SOFC-GT and SOFC-ICE power units.

The investigations conclude that the amount of emissions of GHG and other harmful substances mainly depends on the power split, which is also visible in table 2.3. The more power delivered by the SOFC, the more reduction of emissions. Besides, the type of fuel used is also of influence on the amount of emissions reduced. As the table shows, using natural gas as fuel ensures a greater reduction in emissions of $CO_2$ than using Diesel as fuel.

The study investigating the locomotive also compared the fuel consumption of the Caterpillar 3516 BTA Diesel engine (1678 bkW) and the SOFC-GT power unit. Onboard of Zr.Ms. Pelikaan, one of the support vessels of the RNLN, the same Diesel engine is used in the same power range (1491 kW)[44]. The results show that the fuel consumption of the Diesel engine is 0.242 L/bkWh while the fuel consumption of the SOFC-GT power unit is 0.182 L/bkWh [3]. This concludes that for a vessel like Zr.Ms. Pelikaan the use of a SOFC-GT hybrid system could save 24.7% fuel.

### 2.1.6 | Maintenance

In general, the maintenance of fuel cell power units involves maintenance to the rotating parts in the system and the regular inspection and calibration of gas detection systems. However, since SOFC power systems have a reduced number of rotating parts the maintenance requirements, compared to conventional engines, may be reduced. Other maintenance tasks are occasional replacement of the stack [45], filters, and sorbents [46]. A stack lifetime of 40,000 hours, as mentioned in section 2.1.3, implies that the stack has to be replaced every 6 to 10 years in most commercial vessels, which is comparable to current engine overhaul intervals.[21]

Since the SOFC is modular it is possible to replace and repair only those components of the fuel cell system that are no longer functioning properly, which makes maintenance easier [3, 21]. Moreover, due to this modularity of fuel cell systems it is possible to do maintenance onboard without compromising the functionality of the ship. Most of the maintenance tasks can be carried out by a properly educated crew. For more intensive maintenance and maintenance that does not occur very often, such as stack replacement, a specialized maintenance team is required.[47]

More information has been found about the maintenance of the GT since these are widely used for several decades. For legibility reasons the maintenance of GT is not discussed in detail in this section. For more details, see [48, 49]. Since a methanol fuelled GT is part of the subject of this study and these are not widely used, literature information about maintenance of specifically these GT is given below.

The clean combustion of methanol is expected to lead to a cleaner turbine, compared to combustion of distillate fuel, and lower maintenance [39, 40]. After an experimental test of 500 hours, visual and metallurgical inspections were performed on selected hot gas path components showing less soot deposits on the fuel nozzles and turbine. Furthermore, detail inspections of the fuel nozzles, combustion chambers and turbine showed no detrimental effects after using methanol. From those inspections is estimated that the hot section life of a methanol fired turbine will be improved compared to distillate fuel operation and equivalent to natural gas operation. However, 500 hours of operation was insufficient to provide enough data to reach a definite conclusion.[40]

The lower combustion temperature of methanol also lowers the maintenance since the probability of fracture of components GT is smaller. Higher temperatures reduce the stiffness and strength of materials and increase the risk of fracture. Furthermore, materials creep over time when exposed to elevated temperatures under applied load, resulting in plastic deformation and reduction of the lifespan of the component.

Lastly, methanol has poor lubricating properties and requires changes in the main fuel pump and use of a pressure flow divider or optional addition of a lubricity agent [39]. However, the experimental test showed that components had no signs of wear after methanol fuelled operation, reducing the concerns about the low lubricity of methanol [40].

### 2.1.7 | Reliability

GT technology has proven reliability advantages compared to a reciprocating engine [3], so for that reason the GT would be a better power source than the ICE. However, SOFC technology is still in development [38] and literature research provides little information about reliability. A few investigations have been found that provide some information about the failure modes.

In general, studies state that due to few moving parts in the SOFC, making it less prone to failure, it is capable of achieving high levels of reliability [21, 46]. Also, when the SOFC-based power unit is designed with sub-modules for the stacks, the reliability is improved since failure in one cell or stack does not compromise the entire power system [21].

The environment in which the SOFC is placed influences the reliability since temperature differences between the cold edges and warm centre of the SOFC stacks lead to a higher risk of internal tensions. These internal tensions can cause fracture of the weakest cell, which reduce the performance of the cell and can ultimately destroy it, lowering the performance of the entire stack.[50]

The risk of fracture of a cell also holds for temperature gradients inside the cell caused by the reactions within the cell or the temperature differences between inflow gases. For example, in case of a SOFC with internal reforming these temperature gradients would be caused by the endothermic reforming reactions, see section A.2.1. The required energy for reforming will be extracted from the environment, which means that the surroundings will be cooled. When this process would take place inside the SOFC, at the anode at high temperatures, this will create large temperature gradients inside the cell and stack.[5, 51]

At third study confirms the risk of fracturing the cell due to thermal cycling and variation of the electrical load. In these situations, the risk of anode and cathode fracture changes due to losses of contact pressure caused by irreversible deformation.[52]

Fracture is a relative unpredictable failure mode and because of the risk of sudden performance reduction a major concern for reliability. Note that in all these investigations the temperature variations are the cause of the failure modes, which corresponds to what has been said in section 2.1.3. So, from a reliability point of view it is also important to operate the SOFC at constant temperature avoiding fracture. However, uncertainty is still present about other aspects of the SOFC-GT power unit's reliability, also confirmed by [21].

## 2.2 | Knowledge Gap

Literature research has shown that little information is available in some areas of the methanol fuelled SOFC-GT power units. As already mentioned in section 1.2 the configuration of the SOFC-based power unit needs to be enhanced to improve efficiency, load-following capabilities and performance. The results of the literature study argue for the use of a GT. However, from section 2.1.2 and appendix A.3 can also be concluded that there are few SOFC-GT configurations that are as compact as the simplest case. Especially, a methanol fuelled SOFC-GT power unit configuration for maritime application considering compactness is missing. In general the literature study has shown that little information is available about methanol fuelled SOFC-GT power systems for naval applicability.

Some other knowledge gaps have also been identified during the literature study, which however fall outside the scope of this study. However, for completeness, these knowledge gaps have been added in appendix A.4 of this report and are recommended for further research in chapter 10.

# 3 | Research Baseline

This chapter will provide more information about the method of this research, the stakeholders of the project and their importance and influence. Furthermore, the mission of the power unit, the first step in the V-model of figure A.11, is also established. The requirements for the power unit, determined in cooperation with the stakeholders, supplemented with the other requirements, will also be discussed in this chapter. In short, the sub-question that will be answered in this chapter is:

- What are the mission and technical criteria, established by the RNLN and the literature, of the hybrid power unit?

## 3.1 | Systems Engineering Method

In order to make a design for the SOFC-GT hybrid power unit the Systems Engineering (SE) method is used during this investigation. The SE process is an accepted approach for designing large systems in which the system is designed from coarse to fine in combination with feedback loops. The first steps in this investigation is the literature study, as performed in chapter 2, and determining the requirements. However, in the SE process there are multiple tools that will be used during this investigation. In this section these tools will be discussed and explained in more detail. In appendices A.5 and A.6 more information about the SE method is presented.

### 3.1.1 | System Architecting

The system architecting process consist of multiple tools, such as the Functional Flow Block Diagram (FFBD), the Requirements Allocation Sheet (RAS) and the Schematic Block Diagram (SBD). With the help of these documents the functions and components of the system can be determined.

#### Functional Flow Block Diagram

The purpose of FFBD is to describe system requirements in functional terms from which designs can be synthesized. It has to be noted that the FFBD is functionally oriented and not solution orientated. Decomposition, as mentioned in section A.6, is present in the process of defining lower-level functions and sequencing relationships. This allows traceability of functions from the system and subsystems vertically through the levels of the decomposition.[53]

#### Requirements Allocation Sheet

The RAS documents the connection between the determined functions, requirements, performance, and the physical system. Each function is assigned a number in the FFBD, which corresponds to the function numbers in the RAS. This allows traceability between the determined functions, the requirements and the choice of components.[53]

#### Schematic Block Diagram

The SBD displays the hardware and software components of the system and their interfaces as well as the interfaces between other systems or subsystems. The diagrams show a solution to the functional and performance requirements established in the FFBD and it is a valuable tool to enhance configuration control. Furthermore, the SBD provides traceability between components and their functional origin via the RAS and FFBD.[53]

### 3.1.2 | Reviewing

After the system architecting process is completed the concept configurations for the SOFC-GT power unit will be designed. In order to choose the best concept, reviews sessions have to be organized to discuss the different concepts and to determine to what extent they meet the requirements. The two tools used in this stage of the investigation will be explained in this section.

#### Weighting Factors

It will be clear that it is not always immediately obvious which concept is the best. That is why a considered choice can be made between the different concepts by means of weighting factors. In this process the requirements will be given a specific weighting factor, after which it will be graded to what extent the concept meets the requirement. The sum of the multiplication of grades by the weighting factors gives a total score for the concept. The concept with the highest score is the best concept. However, it is always possible that a combination of concepts will be chosen.

#### Decision Database

To provide traceability of all the decisions made in the investigations they will be noted in the decision database, see appendix G. In this database also the argumentation behind the decisions and the consequences will be noted. In this way it is possible to easily determine the consequences of changing a particular decision or making a new one, so that a considered choice can be made.

### 3.1.3 | Simulation Model

Optimizing the dynamic behaviour and performance of the hybrid SOFC-GT system as well as the verification and validation will be done using the simulation model from study [5] as basis. This model simulated the behaviour of a methanol fuelled SOFC system via a set of integrated subsystems. The model will be adjusted according to the decisions made in this investigation and will be extended with the subsystems and components of the chosen concept. The computer program that will be used to model and simulate the SOFC-GT power unit is Simulink®, owned by the company MathWorks®.

## 3.2 | Stakeholders

Before the requirements can be determined it is important to determine the stakeholders, persons and organizations that affect or are affected by the system, of the project. The hybrid power system will become more usable, and it will create support for the project when the various stakeholders and their demands are taken into account as much as possible. Furthermore, the already available knowledge of the stakeholders can be used by actively involving them in the project. In this section of the report some more information about the stakeholders of the project is provided.[54]

The project is one of the MoD and has therefore only three stakeholders according to their mapping [32]. These stakeholders are the Defensie Materieel Organisatie, the ship crew and Directie Materiële Instandhouding (DMI). The last of these three is the supplier of spare-parts and maintenance support. These three stakeholders possess all the knowledge and expertise required for the design and use of naval vessels. For example, there is knowledge about performance, maintenance, safety, mechanical and electrical engineering. Thanks to this knowledge and expertise the stakeholders, despite their small number, will be able to provide sufficient input for the requirements, verification and validation.

Since there are only three stakeholders, it is decided to not categorize them and therefore not making a distinction between their importance. Via this way all stakeholders are considered equally important key players, the most important stakeholders, since they have a large stake and a lot of power [54].

## 3.3 | Technical Criteria

In consultation with the stakeholders, their demands, and contribution to the project, the requirements and mission of the power unit are determined. Additional requirements are determined from the literature and other readily available knowledge, for example the operation of the SOFC determined by

[5]. As SE tools the functional architecture and feedback loops with section 3.4 are used to determine the functions the system and subsystems have to perform. From this FFBD in appendix B some of the requirements could be determined and linked to the functions. In this section these requirements will be discussed, with a distinction made between the system requirements and subsystem requirements.

It has to be noted that this study is executed during an early stage of development of the support vessels and therefore in all probability the requirements will change during or after this study. This is, for example, visible in the difference between the principal design characteristics in table A.6 and the established requirements in this section. For the same reason, some of the requirements for the power unit are also not completely clear for which an initial estimate or a comparison with the HOV, using [55], has been made.

The established mission of the methanol fuelled SOFC-GT power unit, and with that also the first requirement, is[1]:

1. Provide the support vessel with all the electrical power required to perform all its tasks, responding as quickly as possible to change in power demand.

The operational profile of the seagoing support vessels, which is shown in table 3.1, is used as a guideline for the required power. From this table can be concluded that more than half the time the power percentage is 52% and that the average power percentage is 59%.

| Type of operation | Power | Time | Speed [knots] | Power [MW] |
|---|---|---|---|---|
| Low speed and station keeping | 33% | 15% | 4 | 0.66 |
| Operations | 52% | 40% | 6-10 | 1.04 |
| Economic transit | 52% | 15% | 9 | 1.04 |
| High speed transit | 82% | 25% | 12 | 1.64 |
| Maximum speed | 99% | 5% | 15 | 1.98 |

Table 3.1: The operational profile of the seagoing support vessels of the RNLN [6].

### 3.3.1 | System Requirements

1.1 The residual fuel in the AOG and air from the cathode shall be combusted and the waste heat shall be used elsewhere in the naval vessel to increase the efficiency of the power unit.[1, 5]

1.2 The dynamic behaviour of the power unit in load-following conditions shall be enhanced, so the response time to load steps will be shorter than 30 seconds.[1, 5]

1.3 The power unit shall provide power up to 2000 kW, with the operational profile of table 3.1.[5,11,56]

1.4 The naval vessel shall be able to operate autonomously for 21 days. Onboard of the support vessels 435 $m^3$ is available for fuel storage capacity[2], for methanol this results in 6,270 GJ energy and 345 tons mass storage [11]. With an average power percentage of 59% of 2 MW this results in a minimum power unit efficiency of 34%.[32]

1.5 The power unit shall contain supportive components for peak-shaving and dynamic support.[57]

1.6 The system shall be operated at a pressure of 2 MPa.[5]

1.7 The available electrical power supply will be 440 V, 60 Hz, and 3 phase. This results in an available power supply of 76 kW for the pumps.[55]

### 3.3.2 | SOFC System Requirements

1.8 The pre-reformer shall operate at a temperature of 520 K, by using a fraction of the AOG, to prevent methanation.[5]

[1] From here on, the term 'power unit' refers to the entire system that fulfils this mission.
[2] Another option is applying dual-fuel, resulting in 20% reservation for diesel, leaving 357 $m^3$ fuel capacity for methanol.

1.9 The air supplied to the cathode and anode of the SOFC shall be pre-heated so the temperature gradient between the inlet and outlet of the SOFC is lower than 10 K/cm, resulting in a maximum temperature difference of 400 K.[5, 34]

1.10 Steam and methanol shall be pre-heated and vaporized before entering the pre-reformer to reduce the amount of AOGRC used to control the temperature of the pre-reformer.[5]

1.11 The SOFC should be operated between 873-1123 K and as constant as possible to ensure a longer lifetime.[34]

### 3.3.3 | Gas Turbine System Requirements

1.12 The temperature of the inflow gases for the GT shall be lower than 1773 K to prevent the GT from over-heating.[36, 37]

1.13 The GT shall be able to combust Hydrogen and methanol.

1.14 The GT system shall have a separate air and fuel supply to respond adequately to load steps.

1.15 The gases shall leave the GT before the saturated vapour pressure and temperature are reached to prevent water droplets to be formed.

1.16 Methanol needs to be vaporized before combustion to provide proper mixing of the fuel and the air and therefore a clean and efficient combustion.

1.17 The air and fuel inflow will be pre-heated, using waste heat, before entering the combustion chamber to reduce the fuel consumption and increase efficiency.[37]

## 3.4 | Component Selection

Using the Requirements Allocation Sheet (RAS), see appendix C, and feedback loops with section 3.3 the link between the determined functions, requirements, performance, and the physical system is made. From this RAS there could be selected what components are required to fulfil the stated mission according to the requirements. These results are displayed in the list below and are the input for chapter 4.

The power unit shall contain:

1. a GT for improvement of the dynamic behaviour.
2. a SOFC for reduction of GHG and other harmful substances.
3. heat exchangers, external heating or mixers for pre-heating the flows in the system.
4. pumps and a compressor to pressurize the fuel, water, and air required in the system.
5. high-temperature blowers or ejectors to make transport of gases and reuse of waste heat possible.
6. a pre-reformer to produce Hydrogen from methanol which can be used in the SOFC.
7. a generator to translate the rotational speed to electrical power.
8. a battery pack and (super)capacitors for peak-shaving, dynamic assistance and energy storage.
9. a combustion chamber to combust the additional fuel and residual fuel leaving the SOFC.
10. an electronic control system to combine the power from the generator and the SOFC.

The influence of the high-temperature blowers or ejectors and the electronic control system are outside the scope of this investigation. Therefore, they are not considered in the simulation and concept configuration design of the SOFC-GT power unit but are mentioned in this section of the report for completeness.

The precise simulation of the battery pack and (super)capacitors is also outside the scope of this investigation. However, the influence of the power supplied by these components is important for the performance of the power unit. Therefore, these components will be simulated using a simplified model.

# 4 | Concept Configurations

In this chapter the configuration, which serves as a starting point is discussed as well as some of the decisions for components made in study [5]. Furthermore, the different concept configurations, designed according to the requirements and components of sections 3.3 and 3.4 respectively, will be discussed and the best configuration will be chosen, using weighting factors and grading. The configurations of SOFC-GT systems presented in section A.3 are used as inspiration for the possible SOFC-GT configurations discussed in this chapter, since they show what is already investigated and what is possibly relevant for naval applicability. Lastly, a preliminary design will be presented which will serve as starting point for the simulation. By means of these points, this chapter will answer the following sub-questions:

- What are possible hybrid energy system configurations that meet technical performance criteria with the focus on dynamic behaviour and efficiency?
- Which concept hybrid energy system configuration is expected to best meet the technical criteria and has to be modelled for optimizing the dynamic behaviour and performance, verification, and validation?

## 4.1 | Initial Position

In this section of the report the starting point, see figure 4.1, for this investigation is discussed which is based on the results of study [5]. The components of the starting configuration will be explained in more detail to provide a clear overview. During this phase of the investigation the starting configuration will be extended, with among other things the components of section 3.4, in order to meet the requirements.

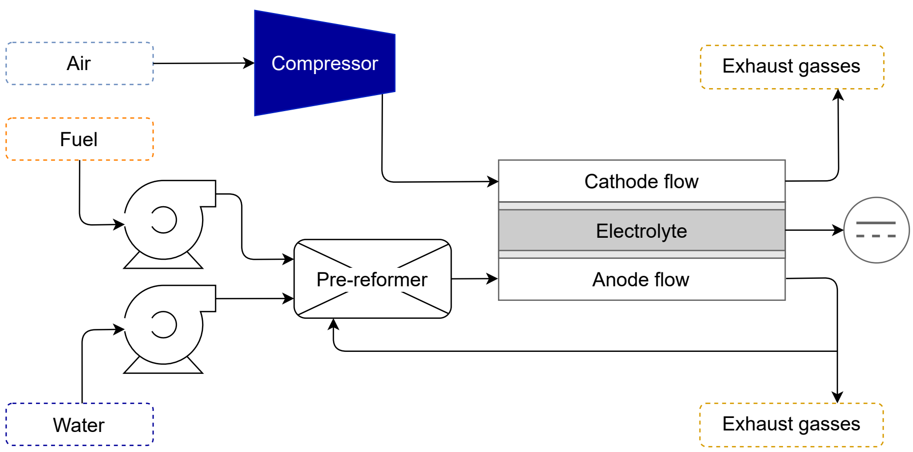


Figure 4.1: The starting point from which the configuration of the hybrid power unit is designed.

In this starting configuration the pumps will pressurize the methanol and water required in the pre-reformer. The compressor will pressurize the air required in the cathode flow of the SOFC. The pre-refromer will reform the methanol into Hydrogen and Carbon Dioxide and the SOFC produces electricity via a series of chemical reactions using the Hydrogen from the pre-reformers. More details about the process of the pre-reformer and SOFC can be found in sections A.2.1 and A.2.2, respectively. After

leaving the SOFC some of the AOG is reused in the pre-reformer to keep it at the right temperature while the remaining gases, also from the cathode, will be released.
The use of an external reformer was chosen, because of the high temperature of the SOFC and the endothermic nature of methanol reforming, see section A.2.1. Using a pre-reformer, temperature gradients within the SOFC caused by reforming are prevented. As already discussed in the sections 2.1.3 and 2.1.7, these temperature gradients could severely limit the lifespan of the SOFC or even crack it [5, 51, 52].

From the results of the literature study, it appears that not only the design variables, such as the size of the GT system or the component selection, are important for the performance of a hybrid system but also the good matching of the system components [58]. There are trade-offs between, for example, efficiencies, operation, safety, size, and power outputs of the components in the system [59, 60], see also section 2.1 of the literature study. During extending the starting configuration to concept configurations of the power unit, with the components of section 3.4, these trade-offs are considered as far as possible in this stage of the investigation. In the paragraphs below these considerations are described.

The literature shows that batteries and SC can be used for peak-shaving and energy storage of excessive power during load step-down transients and shutdown. Moreover, the SC can be used for even faster response time and the battery can be used during start-up of the system or during smaller long lasting load step-up transients. For those reasons, explained in more detail in sections 2.1.1 and 2.1.4, batteries and SC will be used in all concepts.

Furthermore, in the design of the concepts other information from the literature study is considered. In sections 2.1.3 and 2.1.7 is described how stationary operation of the SOFC increases the lifetime and the reliability. It follows that series operation of the SOFC and the GT is not possible considering the dynamic behaviour and stationary operation of the SOFC. In series operation all the air and fuel for the GT has to travel through the SOFC influencing the temperature and operation of the cell making stationary operation impossible. Therefore, in all concept configurations the SOFC and GT operate in parallel, which means that the combustion chamber has its own fuel and air supply.

Section 2.1.2 describes the size of the hybrid SOFC-GT compared to the conventional power unit and concludes that even the simplest hybrid system will be significantly heavier due to the SOFC. Regarding the footprint the conventional power unit has a small advantage and considering volume the simplest hybrid system will have an advantage. However, because of the increase in weight it was tried to keep the concept configurations as small as possible despite the promise that the weight of the SOFC will decrease in the coming years.

Since pre-heating the air before entering the combustion chamber decreases the required fuel [37, 61], and is required before entering the SOFC [5], in all concept configurations this is taken into account. In case of indirect coupling this will increase the size of the SOFC-GT power unit due to addition of HE. Therefore, in some of the configurations there is also chosen for direct coupling.

Pre-heating the methanol and water before entering the pre-reformer will decrease the amount of AOGRC and therefore increase the efficiency. The heat in the exhaust gases from the GT are extremely suitable for this since they still contain a lot of heat. Because of the difference in substances the pre-heating has to be done with indirect coupling, which is taken into account in all concepts.

Lastly, without external heating of the anode inflow gases, the temperature difference between the anode and cathode inflows would almost certainly produce unallowable thermal stresses on the PEN structure of the cell [5]. Therefore, in all concepts configurations this external heating is considered via direct coupling or indirect coupling, see figure A.9. Also, in this case the heat in the exhaust gases from the GT are extremely suitable.

## 4.2 | Concept 'Regeneration'

In this concept configuration, see figure 4.2, the regeneration of the exhaust gases from the GT is central. In this section this concept configuration will be discussed in more detail considering the differences

with the other concept configurations. In general, this concept can be considered as a regular Brayton cycle in parallel operation with the SOFC and regeneration of the exhaust gases.
The gas leaving the SOFC at the anode and cathode still contain Hydrogen and Oxygen, respectively, which are transported to the combustion chamber where it will be combusted with additional methanol and air. A small amount of the AOG will be used in the AOGRC. After the fuel is combusted the heated gases will expand in the GT where this expansion is converted into rotational speed or rotational acceleration to drive the compressor and to produce electrical power in the generator.

When the gases are expanded the exhaust gases still contain a lot of heat, which will be used for all pre-heating of the methanol, water, and air and the external heating of the gases leaving the pre-reformer. When as much heat as possible is regenerated, the exhaust gases are released to the surroundings.

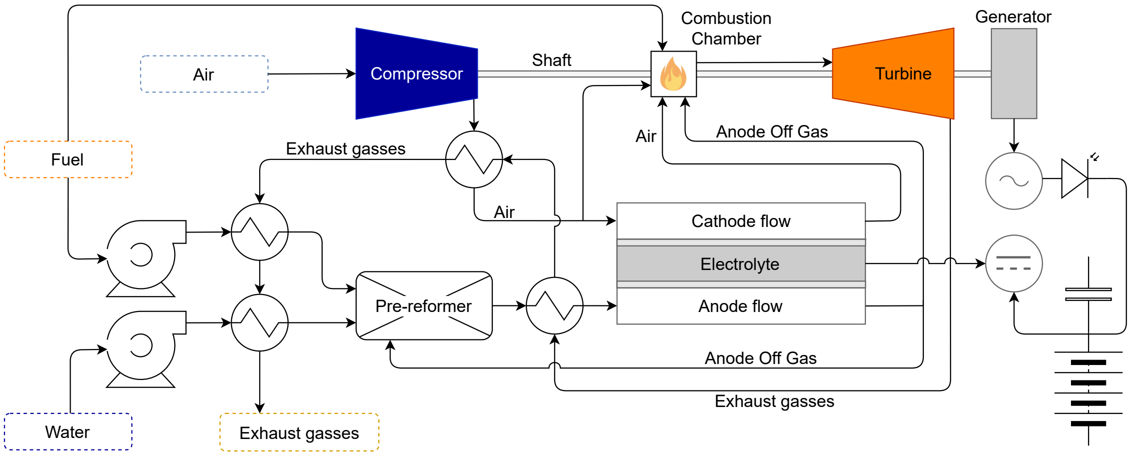


Figure 4.2: The configuration of the concept hybrid power unit using regeneration.

## 4.3 Concept 'Multistage'

In this concept configuration, see figure 4.3, the intercooling of the compressed air and reheating of the exhaust gases from the HPT is central. In this section this concept configuration will be discussed in more detail considering the differences with the other concept configurations. In general, this concept can be considered as a Brayton cycle with intercooling and reheating in parallel operation with the SOFC.

This concept configuration uses multistage compression with intercooling to reduce the work required to compress the air to the required pressure [61]. In this case the air will be compressed in two stages, where after the first stage the air is cooled in a HE. After leaving the HPC the air will be separated into one flow for the first combustion chamber and one flow for the cathode of the SOFC. The air flows are pre-heated in the mixers where the flows will be combined with the gases leaving the SOFC at the cathode.

The gases leaving the SOFC at the anode will be used in the AOGRC for keeping the pre-reformer at the right temperature and as external heating, in a third mixer, for the gases leaving the pre-reformer. The remaining portion of AOG, which still contains Hydrogen, will be combusted, in combination with additional methanol, in the first combustion chamber.

This concept configuration also uses multistage expansion with reheating to increase the work output of the GT operating between two pressure levels. The advantage is that this can be accomplished without raising the maximum temperature in the cycle.[61]
After the fuel is combusted in the first combustion chamber the heated gases will expand in the HPT where this expansion is converted into rotational speed or rotational acceleration to drive the compressors. When the gases are expanded, the exhaust gases are still pressurized and still contain a lot of Oxygen. Therefore, in the second combustion chamber again methanol is added for combustion depending on the amount of electrical power required.

After the fuel is combusted in the second combustion chamber, the heated gases will expand in the LPT where this expansion is converted into rotational speed or rotational acceleration to produce electrical power in the generator.

When the gases are expanded, the exhaust gases leave the GT at a higher temperature than in single-stage expansion, so they still contain a lot of heat, which will be used for pre-heating the methanol and water. When as much heat as possible is regenerated, the exhaust gases are released to the surroundings.

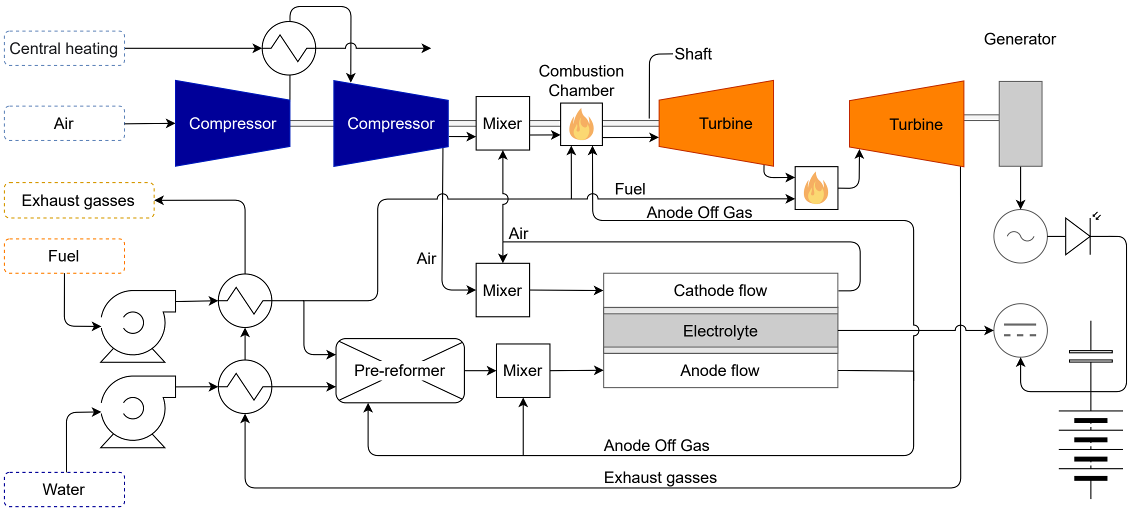


Figure 4.3: The configuration of concept 'Multistage' using intercooling and reheating.

## 4.4 | Concept 'Rankine'

In this concept configuration, see figure 4.4, the regeneration of the exhaust gases from the GT in an ORC is central. In this section this concept configuration will be discussed in more detail considering the differences with the other concept configurations. Also in this concept configuration the general principle, is a regular Brayton cycle in parallel operation with the SOFC.

In this concept configuration the air leaving the compressor is pre-heated in the mixer where it will be combined with the gases leaving the SOFC at the cathode. The gases leaving the mixer will be distributed and used in the combustion chamber and at the cathode of the SOFC.

The gases leaving the SOFC at the anode will be used in the AOGRC for keeping the pre-reformer at the right temperature and as external heating, in a second mixer, for the gases leaving the pre-reformer. The remaining portion of AOG will be combusted, in combination with additional methanol, in the combustion chamber since it still contains Hydrogen.

After the fuel is combusted in the combustion chamber, the heated gases will expand in the GT where this expansion is converted into rotational speed or rotational acceleration to drive the compressor and to produce electrical power in the generator. When the gases are expanded the exhaust gases leaving the GT still contain a lot of heat which will be used for the ORC and for pre-heating the methanol and water. When as much heat as possible is regenerated, the exhaust gases are released to the surroundings.

In the ORC the heat from the exhaust gases is used in a HE, which functions as a boiler, to vaporize and superheat the water, pressurized by a pump, in the cycle. The superheated vapour flows through the steam turbine where it will be expanded, and this expansion is converted into rotational speed to produce electrical power in the generator. After the water vapour leaves the steam turbine it will be cooled in the condenser to its liquid phase. Then the whole cycle repeats starting at the pump where the water again is pressurized after which it again flows to the HE.

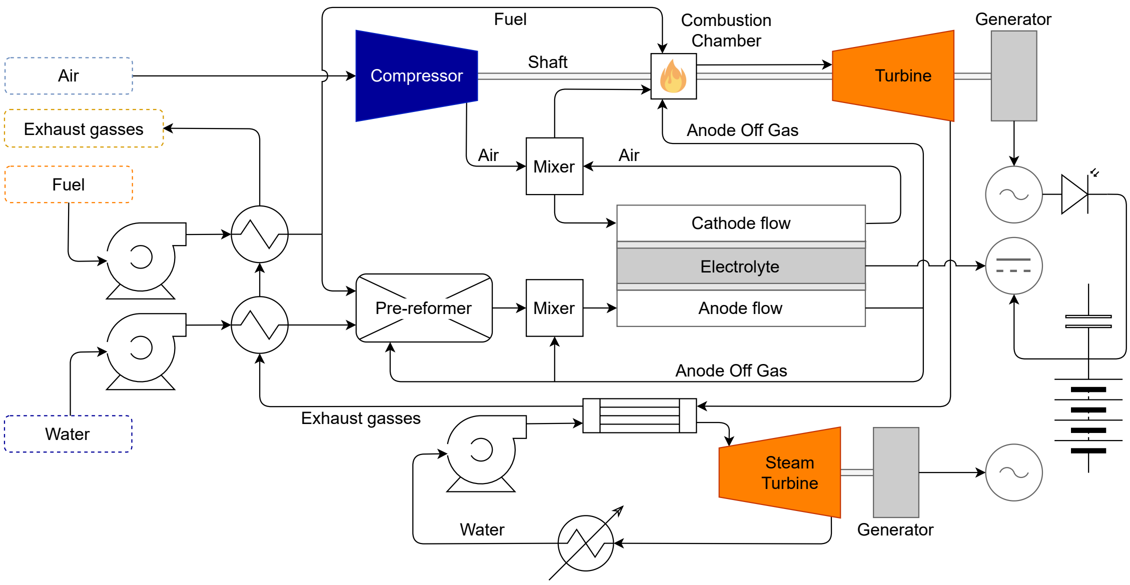


Figure 4.4: The configuration of the concept 'Rankine' using an ORC.

## 4.5 | Concept Selection

In this section of the report there will be determined which concept hybrid energy system configuration best meets the technical criteria and has to be modelled for optimizing the dynamic behaviour and performance, verification, and validation. Using the pros and cons of the concepts and a comparison table, the selection of the concept can be determined and argued, as can be seen in table 4.1. In appendix D more information is provided about the details behind the parameters and the argumentation behind the score of the concepts is discussed in more detail.

### 4.5.1 | Pros and Cons

In this section the pros and cons of the concept configurations are discussed. These pros and cons are the basis for the argumentation for the points given to the concepts in appendix D. In that appendix the pros and cons will also be explained more extensive and in more detail.

'Regeneration' has the advantage that it is the simplest configuration of the three concepts, a regular Brayton cycle connected in parallel to the SOFC, and will therefore be the smallest, lightest, and least complex. Furthermore, this concept will use as much waste heat as possible during pre-heating the flows in the system, which increases the efficiency.
The disadvantage of this concept is that the temperature of the pre-heated flows is dependant on the output temperature of the GT system and the thermal inertia of the PHE. This negatively influences the controllability and starting time of the entire system and durability of the SOFC.

The pros of 'Multistage' are the smaller and lighter compressors and turbines and the controllable temperature of the gases because of the mixers. Furthermore, the multistage principle increases the output power of the turbines and decreases the power input to the compressors [61]. Furthermore, it ensures lower temperature inflow in the first turbine and a larger temperature outflow of the second turbine, positively influencing the maintenance. Lastly, combustion in two combustion chambers also increases the safety since less fuel in combusted in one time.
The disadvantage of this concept is the use of more components such as two turbine and two compressors, which will be more expensive, larger, and heavier than a system with one larger compressor and turbine. Furthermore, this increases the complexity of the flows, the connection between components and the control of the flows to the mixers. The last disadvantage of the concept considers the intercooling, which is applied to decrease the work done by the compressors. However, the heat obtained by compression of the air is required in the SOFC, making intercooling disadvantageous.

The controllable temperature of the gases because of the mixers is also one of the pros of concept 'Rankine'. Another advantage of this concept is that it will use as much waste heat as possible for power production in the Rankine cycle, increasing the efficiency and the power output.
The disadvantage of this concept is that the heat transferred to the ORC cannot be controlled precisely, because it depends on the output temperature of the GT system and the thermal inertia of the PHE. This negatively influences the controllability and starting time of the entire system. Lastly, this concept consists of an entire extra power cycle, including an extra HE, pump, and steam turbine, so it is larger, heavier, more complex, and more expensive. Furthermore, the extra generator contributes to a more complex processing of the electrical power.

### 4.5.2 | Comparison Table

In accordance with stakeholders of DMO, [32, 56], it was decided to use a 1-3 score for the parameters. In this way, the differences between the concepts per parameter will be less, which compensates for the lack of objectivity. This way the focus is not so much on how well the concept scores on that specific parameter but can simply be determined which concept scores best. The concept that scores best will receive 3 points and the least concept will score 1 point. Section 8.2.3 will elaborate more on the validity of this selection procedure since it still might be subjective. For a few parameters two of the concepts will receive the same score since it is found that those two concepts should be rated equally due to minimal differences.

| ***Parameter*** | **Weighting factor** | **'Regeneration'** | | **'Multistage'** | | **'Rankine'** | |
|---|---|---|---|---|---|---|---|
| | | Score | Result | Score | Result | Score | Result |
| *Durability* | 8 | 2 | 16 | 3 | 24 | 3 | 24 |
| *Maintenance* | 6 | 2 | 12 | 3 | 18 | 1 | 6 |
| *Controllability* | 6 | 1 | 6 | 3 | 18 | 1 | 6 |
| *Safety* | 9 | 2 | 18 | 3 | 27 | 2 | 18 |
| *Starting time* | 3 | 2 | 6 | 3 | 9 | 1 | 3 |
| *Overall efficiency* | 8 | 3 | 24 | 2 | 16 | 3 | 24 |
| *Weight/size/cost* | 4 | 3 | 12 | 2 | 8 | 1 | 4 |
| ***Total*** | | | **94** | | **120** | | **85** |

Table 4.1: The comparison table containing the weighting factors and the grades of the concepts.

The rows of the comparison table 4.1 show the parameters on which the concepts will be assessed. The parameters and their importance, expressed in weighting factors, are determined in cooperation with the stakeholders of DMO. The scores of the concepts and the argumentation behind these scores are reviewed in cooperation with all stakeholders. The last row shows which concept configuration appears to be the best option. Despite possible subjectivity, with these results it can be said that concept 'Multistage' is the best concept since it scores significantly better than the other concepts.

## 4.6 | Integration Possibilities

During the analysis of the requirements and the principal design characteristics and designing of the concept configurations also the integration possibilities have been considered. The integration possibilities that have been identified are discussed in this section of the report. The information about certain installations, mentioned in this section, is obtained from [55]. It has to be noted that these integration possibilities are additional options for the power unit to increase the value and do not necessarily have to be implemented. The simulation will show whether the integration options are possible.

### 4.6.1 | Low-Pressure Air System

The support vessels are all equipped with a low-pressure air system which delivers air with a pressure of 1 MPa to the vessel with a capacity of 50 $m^3$ per hour. Since concept 'Multistage' uses multistage compression there is the possibility to integrate the low-pressure air system with the SOFC-GT power unit. The first compression stage compressor can deliver air to both the low-pressure air system and the second compression stage compressor of the power unit, saving weight and space of one compressor and starting time since the air supply to the power unit is continuously. Since the air supply to the air system is not constant, the compressor probably cannot be connect to the GT via a shaft and has to be powered by the electrical system, which has to be confirmed by the simulation model.

### 4.6.2 | Central Heating

The central heating of the support vessel consists of a freshwater circuit in which the water enters at 70 °C and leaves at 90 °C. The waste heat leaving the GT could be used for heating the water of the central heating. This saves the space and energy required for the use of an additional external heater and the emissions produced in case of the fuel-fired central heating boiler of the HOV. Since the required mass flow of the central heating water is not known there will be determined what the mass flow can be when the available waste heat is used.

### 4.6.3 | Drinking and Warm Water

In the naval vessel there are several water installations that transport water to different parts of the vessel. Two of them have the potential to be integrated with the SOFC-GT power unit. The first is the drinking water installation where a pump could be shared with the power unit, saving space of the pump and starting time since the pump for the power unit is permanently running. This pump has to have multiple outlets since the drinking water is pressurized to 5 bar.
The second installation is the warm water installation where water at 10 bar and a temperature of more than 65 °C is distributed throughout the ship at a maximum flow rate of 2.5 $m^3$. This installation can also share the pump with the SOFC-GT power unit and additionally make use of the waste heat from the GT, saving space and energy required for the use of a boiler.

### 4.6.4 | Microgrids

In DEOS is mentioned that the MoD is interested in microgrids, a decentralized group of electricity sources that normally operates connected but can also function autonomously [9]. The power unit may also be able to supply electricity to other users as part of microgrids, for example in the harbour or as a mobile charging station. The advantage is that the power unit has the ability to achieve high efficiency and can be fuelled with PtL produced methanol, eliminating emissions that would otherwise be produced by other power stations. Being a part of microgrids will will affect the lifetime of the system, since it will operate continuously, but also provides the opportunity to avoid starting up and heating up the SOFC.

## 4.7 | Preliminary Design

Section 4.5 has shown that concept of 'Multistage', is rated highest and has to be modelled for optimizing the dynamic behaviour and performance, verification, and validation. However, the other concepts have the advantage that more waste heat is used to pre-heat the flows of the system and that the temperature of the air after compression is higher, which both possibly can also be applied to the chosen concept. Furthermore, the integration possibilities are not yet included in the design of the power unit. In this section of the report the changes to concept 'Multistage', based on the pros and cons of the concepts and the integration possibilities, will be explained and argued.

Firstly, the intercooling between the two stage of compression of the air, to reduce the work done by the compressors, will not be executed since the heat obtained by compression is required for the inflow gases of the SOFC. By retaining this heat, the temperature of the gases will also be higher, which means that the temperature gradient between the input and output of the SOFC will be smaller. Intercooling would significantly decrease the temperature of the inflow gases increasing the temperature gradient which negatively affects the lifetime of the SOFC.

The second change to the concept considers the mixing chambers. Exergy will be destroyed within the mixing chamber and therefore need to be used as little as possible. This can be done by using the heat from the exhaust gases to pre-heat the air before entering the mixer in front of the SOFC, as can be seen in concept 'Regeneration'. This way, the efficiency of the concept will be further improved and the mass flow through the cathode will increase as little as possible.

Lastly, the integration possibilities, mentioned in section 4.6, are also considered in the preliminary design, which is displayed in figure 4.5. It again has to be noted that these integration possibilities are additional options and the simulation has to show whether the integration options are possible.

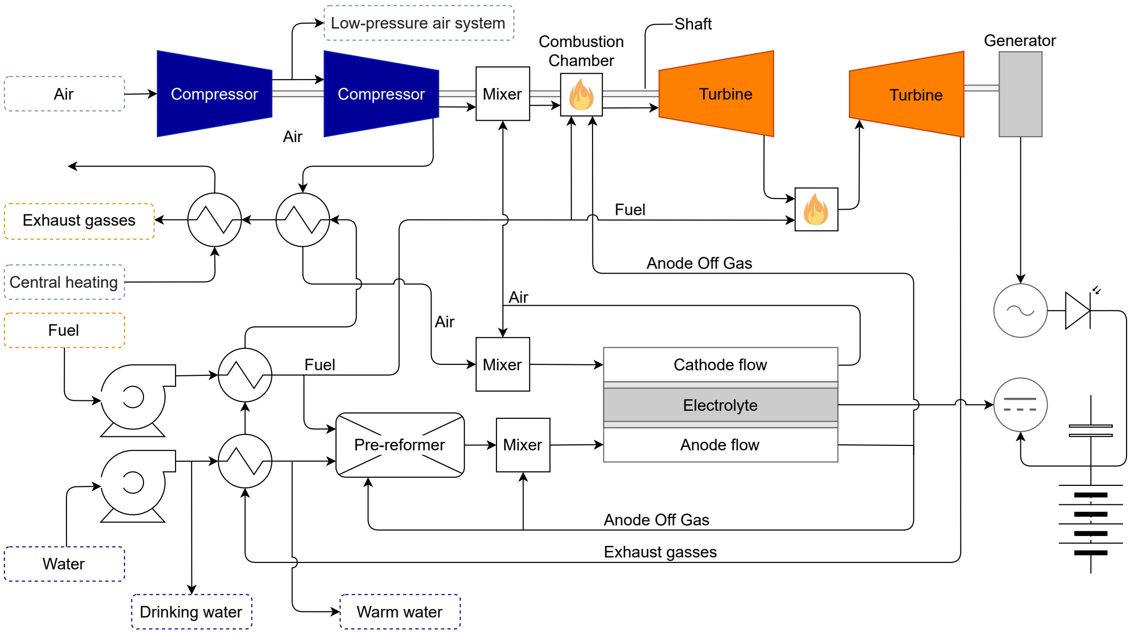


Figure 4.5: The preliminairy design of the SOFC-GT power unit.

### 4.7.1 | Preliminary Power Unit Operation

The preliminary operation of the design of the SOFC-GT power unit will be explained in this section. It is important to note that this operation of the hybrid system needs to be tested using the simulation model, so changes in operation are still possible and this section only provides a first impression.

The SOFC system operates as constant as possible and therefore always provides a minimal amount of power. The operational profile, displayed in table 3.1, shows that most of the time the vessel operates 'Operations/Economic transit'. Therefore, there is chosen to operate the SOFC such that the combination of SOFC system and GT system provides this power in stationary operation, with as much power as possible produced by the SOFC so the efficiency is as high as possible. When the power request decreases to, for example, 'Low speed and station keeping' the battery and SC will be charged with the difference in power supply by the power unit and power request by the naval vessel.

The GT system assists the power unit to reach the power steps from 'Operations/Economic transit' to, for example, 'Maximum speed' within the required time by increasing the power supply. In stationary operation the system combusts the residual fuel from the SOFC and expands the gases in the turbines so it produces power to drive the compressors and increase the efficiency of the hybrid system.

The SC assists the GT system during the first few seconds of the power step, since it takes some time to increase the power from the GT system. To make power available almost immediately, the SC provides the difference in power supply by the power unit and the power request of the naval vessel as long as the GT system is still increasing the power supply. The battery assists the power unit during longer and smaller load steps.
Lastly, the mixers for the anode and cathode are used to control the temperature of the inflow gases for the SOFC by increasing or decreasing the flows leaving the SOFC and flowing into to mixers.

# 5 | Simulation Model

As already mentioned in section 3.1.3, optimizing the dynamic behaviour and performance of the SOFC-GT power unit will be done using the simulation model from study [5] as basis. This Simulink® model simulated the behaviour of a methanol fuelled SOFC system via a set of integrated subsystems. The model is adjusted and extended according to the decisions made in this investigation and is extended with the subsystems and components of the chosen concept. The adjustments and extension of the simulation model will be discussed in this chapter of the report. Furthermore, the used data, thermodynamic relations, and the verification of the simulation model will be shown in this chapter.

## 5.1 | SOFC Model

In this section the Simulink® simulation model used during study [5], which is the basis for the simulation model of this investigation, is briefly explained considering the setup, inputs and outputs. A detailed description of the SOFC and pre-reformer simulation model is provided in the report of the study "*An investigation into the possibilities concerning Solid Oxide Fuel Cells in naval vessels*". The simulation model of that investigation is extend with the components of the preliminary design, of which the equations are provided in section 5.2. More detailed information about the operation and the design characteristics of the SOFC system can be found in appendix A.2 and section 7.3, respectively.

### 5.1.1 | Setup

The model for the simulation of the behaviour of a methanol fuelled SOFC system consists of multiple integrated models of subsystems. These sub-models represent the pre-reformer, including reaction kinetics, the dynamic SOFC stack model which incorporates heat losses normal to the cell orientation, and a PHE including its dynamic behaviour. The simulation model is verified by checking energy- and mass-balances, chemical equilibrium, and comparison with other studies. This ensures that the final model represents an entire verified SOFC system which can be used in the current investigation.[5]
In the model all the temperatures, pressures, and flow compositions in the pre-reformer and SOFC are calculated and controlled automatically. The same holds for the S/C-ratio and AOGRC for the pre-reformer. The model also calculates the output power of the SOFC as well as the efficiency.

### 5.1.2 | Inputs

The relevant input parameters of the simulation model and their value are provided by [5]. For example, the SOFC system is operated at a pressure of 2 MPa and the pre-reformer operates at a temperature of 520 K, to prevent methanation. The stated pressure is a chosen value and not specifically required for the operation of the SOFC.
There are also parameters that can be changed in value to optimize the SOFC system in the hybrid context. The power output of the SOFC can be controlled by changing the current density. The inflow temperature of methanol and steam can be changed, considering the operating temperature of the pre-reformer, to reduce the AOGRC-ratio. Adjusting the temperature also holds for the anode and cathode inflow, so the temperature gradient between the inlet and outlet of the SOFC is below 10 K/cm.

### 5.1.3 | Outputs

The relevant outputs of the simulation model that can be used in this investigation are discussed in this section starting at the temperature of the PEN, which can be used to check whether the SOFC still operates at a safe temperature. The values of the SOFC efficiency, the AOGRC-ratio and utilization ratio can be used to optimize the operation of the fuel cell as far as possible within this research.

The fuel, water and air flow into the SOFC system can be used to determine the required power for the pumps and compressor. The anode and cathode flow composition and temperature can be used to determine the heat added to the mixing chambers and the combustion chamber and to calculate the power produced in the GT.
The power produced by the SOFC can be used to determine whether the hybrid system provides sufficient power and how much power the GT has to provide. The methanol inflow of the SOFC system can be added to the methanol inflow of the combustion chamber to calculate the efficiency of the hybrid power system.

### 5.1.4 | Heat Exchanger

As already mentioned in section 5.1.1 the simulation model of study [5] uses a dynamic model of a PHE. This model will also be used in the extension of the simulation model and therefore this section will provide some more information about the equations used for modelling this PHE.

The flow arrangement in which the fluids can flow through the HE is counter flow, in which the hot and cold fluid enter at the opposite side and move in the opposite direction. The advantage of counter flow is that the outflow temperature of the cold fluid can be higher than the outflow temperature of the hot fluid, so it is more effective. For that reason, a smaller surface area, thus a smaller HE, is required to obtain the same heat transfer rate.[62]

The HE is a device that transfers heat from one flowing fluid to another without mixing the fluids because they are separated by a wall. The heat from the hot fluid is transferred to the wall by convection, through the wall by conduction and from the wall to the cold fluid again by convection. The radiation effects are usually included in the conduction and convection coefficients. The heat transferred from the hot fluid to the cold fluid can be calculated using the equation below [5].

$$\dot{Q}_{PHE} = A \cdot \frac{F}{Z} \cdot \frac{(T_{h,out} - T_{c,in})}{\left(\frac{2}{\alpha} + \frac{\tau}{\lambda}\right)} \cdot \left(1 - e^{-\frac{Z}{F} \cdot L}\right) \tag{5.1.1}$$

The product of the mass flow rate and specific heat can be used to determine the fluid strength [5, 62]. This is shown in the equation below and used in the equation above. These heat capacity rates show the amount of energy that is required to change the temperature of the fluid flow by 1 °C as the fluid is traveling through the HE.

$$F = \left(\frac{1}{C_h} + \frac{1}{C_c}\right)^{-1} = \left(\frac{1}{\dot{m}_h \cdot c_{p,h}} + \frac{1}{\dot{m}_c \cdot c_{p,c}}\right)^{-1} \tag{5.1.2}$$

The heat admittance, also used in equation 5.1.1, is defined as follows [5].

$$Z = \left(\frac{1}{\alpha_h \cdot A} + \frac{\tau}{\lambda_w \cdot A} + \frac{1}{\alpha_c \cdot A}\right)^{-1} \tag{5.1.3}$$

The heat flowing in and out of the HE can be calculated using the following equations [5].

$$\dot{Q}_{in} = \sum (T_{in} \cdot h_x(T_{in})) \quad \text{and} \quad \dot{Q}_{out} = \sum (T_{out} \cdot h_x(T_{out})) \tag{5.1.4}$$

With the transferred heat from the PHE, the heat inflow and the heat outflow the temperature of the outflow gases can be determined. The result is the equation given below [5].

$$T(t) = T(0) + \int_0^t \left(\frac{\dot{Q}_{in} - \dot{Q}_{out} + \dot{Q}_{PHE}}{\sum (N_i(t) \cdot c_{p,i}(T)) + C_{PHE}}\right) dt \tag{5.1.5}$$

In the equation above the following terms are:

$$N_i(t) = N_i(0) + \int_0^t \left(\sum_{in} \dot{N}_i(t) - \sum_{out} \dot{N}_i(t)\right) dt \tag{5.1.6}$$

$$C_{PHE} = \frac{1}{2} \cdot n \cdot A \cdot \tau \cdot \rho_{steel} \cdot c_{steel} \tag{5.1.7}$$

## 5.2 | Model Extension Components

In this section of the report the extension of the simulation model with the components of concept 'Multistage' will be discussed. This concerns the governing equations of the pump, compressor, combustion chamber, GT, mixing chambers, battery and SC. These equations will be used during the modelling and simulation of the SOFC-GT power unit.

### 5.2.1 | Pump

The pump is a power absorbing turbomachine, since power is used to pressurize the water and air that are required in the SOFC, combustion chamber and GT. The equations required for calculation the input power are given and explained in this section.

To determine the specific enthalpy of the water and methanol in the liquid phase at atmospheric pressure the following equation can be used [61]. This specific enthalpy can also be found in property tables as well as the specific enthalpy at other pressures and temperatures.

$$h = c_p \cdot \int_{T_M}^{T} dT \tag{5.2.1}$$

The efficiency of the pump needs to be considered, since there will be some pressure drop in the process and the actual input is greater due to irreversibilities. The deviation of the actual pump from the ideal pump can be accounted for by using the isotropic efficiency [61, 63]:

$$\eta_P = \frac{w_s}{w_a} \cong \frac{h_{out,s} - h_{in}}{h_{out,a} - h_{in}} \tag{5.2.2}$$

The work absorbed by the pump then can be calculated using [61, 63]:

$$\dot{W}_P = \frac{\dot{m} \cdot g \cdot H}{\eta_P} = \frac{\dot{m} \cdot v_{in} \left(p_{out} - p_{in}\right)}{\eta_P} = \frac{\dot{m} \cdot \left(h_{out,s} - h_{in}\right)}{\eta_P} = \dot{m} \cdot \left(h_{out,a} - h_{in}\right) \tag{5.2.3}$$

### 5.2.2 | Compressor

The compressor is also a power absorbing turbomachine, since power is used to pressurize the air that is required in the SOFC, combustion chamber and GT. The equations required for calculating the input power are given and explained in this section.

The output temperature of the compressor, assuming isentropic process and ideal gas, can be determined by the following equation [61, 63].

$$\frac{T_{out}}{T_{in}} = \left(\frac{p_{out}}{p_{in}}\right)^{\frac{k-1}{k}} = r_p^{\frac{k-1}{k}} \quad \text{, with: } k = \frac{c_p}{c_v} \tag{5.2.4}$$

With this temperature the specific enthalpy can be found in property tables or calculated with the following equation in case the gas is an ideal gas, so both thermally and calorically perfect [61, 63–65].

$$h = c_p \cdot T \tag{5.2.5}$$

The efficiency of the compressor needs to be considered, since there will be some pressure drop in the process and the actual input is more due to irreversibilities. The deviation of the actual compressor from the ideal compressor can be accounted for by using the isotropic efficiency [61, 63]:

$$\eta_C = \frac{w_s}{w_a} \cong \frac{h_{out,s} - h_{in}}{h_{out,a} - h_{in}} \tag{5.2.6}$$

The work absorbed by the compressor then can be calculated using [61]:

$$\dot{W}_C = \frac{\dot{m} \cdot \left(h_{out,s} - h_{in}\right)}{\eta_C} = \dot{m} \cdot \left(h_{out,a} - h_{in}\right) \tag{5.2.7}$$

### 5.2.3 | Combustion Chamber

In the combustion chamber the residual fuel and gases from the SOFC is added to the additional fuel and compressed air. Combustion in a GT typically occurs at four times the amount of air required for complete combustion to avoid excessive temperatures [61]. So, for complete combustion the chemical reactions that occur inside the combustion chamber are the following:

$$2\,CH_3OH(g) + 3\,O_2(g) \longrightarrow 2\,CO_2(g) + 4\,H_2O(g)$$

$$2\,H_2(g) + O_2(g) \longrightarrow 2\,H_2O(g)$$

$$CH_4(g) + 2\,O_2(g) \longrightarrow CO_2(g) + 2\,H_2O(g)$$

$$2\,CO(g) + O_2(g) \longrightarrow 2\,CO_2(g)$$

Since the methanation and MDR reactions can largely be prevented by a pre-reformer operating temperature below 520 K and adding sufficient water, respectively, the last two reactions will hardly occur.

The amount of energy per mole that is produced in the combustion chamber can be determined using the following equation [61]:

$$\bar{h}_C = \sum n_p \cdot \bar{h}_{f,p} - \sum n_r \cdot \bar{h}_{f,r} \tag{5.2.8}$$

The value of the enthalpy of formation depends on the temperature at which the combustion takes place and will be calculated in the simulation model when these temperatures are known. The following equation uses the enthalpy of formation at the reference state, 25 °C and 1 atmosphere, and the specific heat at the temperature in the combustion chamber to obtain the enthalpy of formation at this temperature [66].

$$\bar{h}_f = \bar{h}_f^\circ + \int_{298}^{T} c_p \, dT \tag{5.2.9}$$

Since the temperature in the combustion chamber is not yet known in this stage of the investigation, only the enthalpy of formation at reference state can be used to obtain an idea about the enthalpy of combustion of the fuels. It should be noted that the enthalpy of formation at reference state for stable elements, $N_2$, $H_2$ and $O_2$, is zero and therefore not considered in equations 5.2.10 - 5.2.13.[61]

For the combustion of methanol ($CH_3OH$), the first of the reactions given above, this means that the energy produced per mole is the following:

$$\begin{aligned}\bar{h}_C^\circ &= (N\bar{h}_f^\circ)_{CO_2} + (N\bar{h}_f^\circ)_{H_2O} - (N\bar{h}_f^\circ)_{CH_3OH} \\ &= (2)(-393,520) + (4)(-241,820) - (2)(-200,670) = -1,352,980 \text{ kJ/kmol}\end{aligned} \tag{5.2.10}$$

Since in the reaction equation the number of moles methanol is multiplied by two to make the equation correct, the energy calculated in the equation above needs to be divided by two. This results in an enthalpy of combustion for methanol of -676.49 MJ/kmol.

For the combustion of Hydrogen ($H_2$), the second of the reactions given above, this means that the energy produced per mole is the following:

$$\bar{h}_C^\circ = (N\bar{h}_f^\circ)_{H_2O} = (2)(-241,820) = -483,640 \text{ kJ/kmol} \tag{5.2.11}$$

Since in the reaction equation the number of moles Hydrogen is multiplied by two to make the equation correct, the energy calculated in the equation above needs to be divided by two. This results in an enthalpy of combustion for Hydrogen of -241.82 MJ/kmol.

For the combustion of Methane ($CH_4$), the third of the reactions given above, this means that the energy produced per mole is the following:

$$\begin{aligned}\bar{h}_C^\circ &= (N\bar{h}_f^\circ)_{CO_2} + (N\bar{h}_f^\circ)_{H_2O} - (N\bar{h}_f^\circ)_{CH_4} \\ &= (1)(-393,520) + (2)(-241,820) - (1)(-74,850) = -802,310 \text{ kJ/kmol}\end{aligned} \tag{5.2.12}$$

So, the enthalpy of combustion of methane is -802.31 MJ/kmol.

For the combustion of Carbon Monoxide (CO), the fourth of the reactions given above, this means that the energy produced per mole is the following:

$$\begin{aligned}\bar{h}_C^\circ &= (N\bar{h}_f^\circ)_{CO_2} - (N\bar{h}_f^\circ)_{CO} \\ &= (2)(-393,520) - (2)(-110,530) = -565,980 \text{ kJ/kmol}\end{aligned} \quad (5.2.13)$$

Since in the reaction equation the number of moles carbon monoxide is multiplied by two to make the equation correct, the energy calculated in the equation above needs to be divided by two. This results in an enthalpy of combustion for carbon monoxide of -282.99 MJ/kmol.

The negative values of the enthalpy of combustion show that the combustion reactions are exothermic, so release energy to the system. Furthermore, it is clearly visible that during combustion of methanol more energy is released than during combustion of Hydrogen.

In the combustion chamber heat is added to the gases by means of chemical reactions, which results in a temperature increase and a new composition of the gas mixture. The new temperature of the gas mixture can be calculated using the conservation of energy principle and the conservation of mass principle, resulting in the following equation [61].

$$\sum \dot{m}_i \cdot c_{p,i} \cdot T_i + \sum N_{r,i} \cdot \bar{h}_{C,i} = \sum \dot{m}_i \cdot c_{p,i} \cdot T_{out} \quad (5.2.14)$$

### 5.2.4 | Gas Turbine

The GT is a power generating turbomachine, since the hot gaseous mixture leaving the combustion chamber is expanded to deliver useful power. Using an electrical generator this power can be converted into electricity. The equations required for calculation the output power are given and explained in this section.

The output temperature of the GT, assuming isentropic process and perfect gas, can be determined by the following equation [61, 63].

$$\frac{T_{in}}{T_{out}} = \left(\frac{p_{in}}{p_{out}}\right)^{\frac{k-1}{k}} = r_p^{\frac{k-1}{k}} \quad \text{, with: } k = \frac{c_p}{c_v} \quad (5.2.15)$$

With this temperature the specific enthalpy can be found in property tables or calculated with the following equation in case the gas is an ideal gas, so both thermally and calorically perfect [61, 63–65].

$$h = c_p \cdot T \quad (5.2.16)$$

The efficiency of the turbine needs to be considered, since there will be some pressure drop in the process and the actual output is less due to irreversibilities. The deviation of the actual turbine from the ideal turbine can be accounted for by using the isotropic efficiency [61, 63]:

$$\eta_T = \frac{w_a}{w_s} \cong \frac{h_{in} - h_{out,a}}{h_{in} - h_{out,s}} \quad (5.2.17)$$

The work produced by the turbine then can be calculated using [61]:

$$\dot{W}_T = \eta_T \cdot \dot{m} \cdot (h_{in} - h_{out,s}) = \dot{m} \cdot (h_{in} - h_{out,a}) \quad (5.2.18)$$

To produce electrical power a generator is connected to the GT. Considering the efficiency of the generator the electrical power output can be calculated using:

$$P = \eta_G \cdot \dot{W}_T = \eta_G \cdot \eta_T \cdot \dot{m} \cdot (h_{in} - h_{out,s}) = \eta_G \cdot \dot{m} \cdot (h_{in} - h_{out,a}) \quad (5.2.19)$$

### 5.2.5 | Mixing Chambers

The devices where the mixing process of streams of fluids takes place is commonly referred to as a mixing chamber. The shape of the mixing chamber does not necessarily need to be a 'chamber', as shown in the chosen concept 'Multistage' but can also be an ordinary T-elbow or a Y-elbow. The chambers are usually well insulated and usually do not involve any kind of work.

The mixing of the gases inside the mixing chambers can be calculated using the conservation of energy principle and the conservation of mass principle, resulting in the following equation [61].

$$\sum \dot{m}_i \cdot h_i = \sum \dot{m}_i \cdot h_{out} \quad (5.2.20)$$

### 5.2.6 | Supercapacitor

A capacitor is a device that stores electric potential energy and is mostly used because of its ability to store and release energy. The capacitance is a measure of the ability of a capacitor to store energy and is a constant. It depends on the sizes and shapes of the conductors and on the insulating material between them. The greater the capacitance, the greater the magnitude of charge on either conductor for a given potential difference and hence the greater the amount of stored energy. It can be calculated using the equation below.[67]

$$C_e = \frac{Q_C}{V_e} = \varepsilon_0 \frac{A}{d} \tag{5.2.21}$$

The energy stored in a charged capacitor is just equal to the amount of work required to charge it, separating opposite charges and place them on different conductors. When the capacitor is discharged, the stored energy is recovered as work done by electrical forces. The energy storage of the capacitor can be calculated using the equation that follows.[67]

$$U = \frac{Q_C^2}{2 \cdot C_e} = \frac{1}{2} \cdot C_e \cdot V_e^2 = \frac{1}{2} \cdot Q_C \cdot V_e \tag{5.2.22}$$

A special type of capacitor which is the SC, already mentioned in section 2.1.1. This type of capacitor has a high capacitance so it can store more energy than a regular capacitor. It can be used for energy storage undergoing frequent charge and discharge cycles at high current and short duration. Another difference is the potential difference during the charge and discharge of the SC, which changes linearly as is also displayed in figure 5.1. The condition is that the electrical current remains the same during charge and discharge, which can be controlled by DC-DC converters. This means that the power delivered by the SC can be calculated using the following equation.[68]

$$P(t) = V(t) \cdot i(t) \tag{5.2.23}$$

Besides storing energy, capacitors can also be used to smooth out the gaps when converting AC to DC and for peak-shaving, already mentioned in section 2.1.1. The capacitors thus ensure a calm and even power delivery, which is beneficial for the electricity network of the naval vessel. However, this topic is outside the scope of this investigation and is therefore not considered in the simulation.

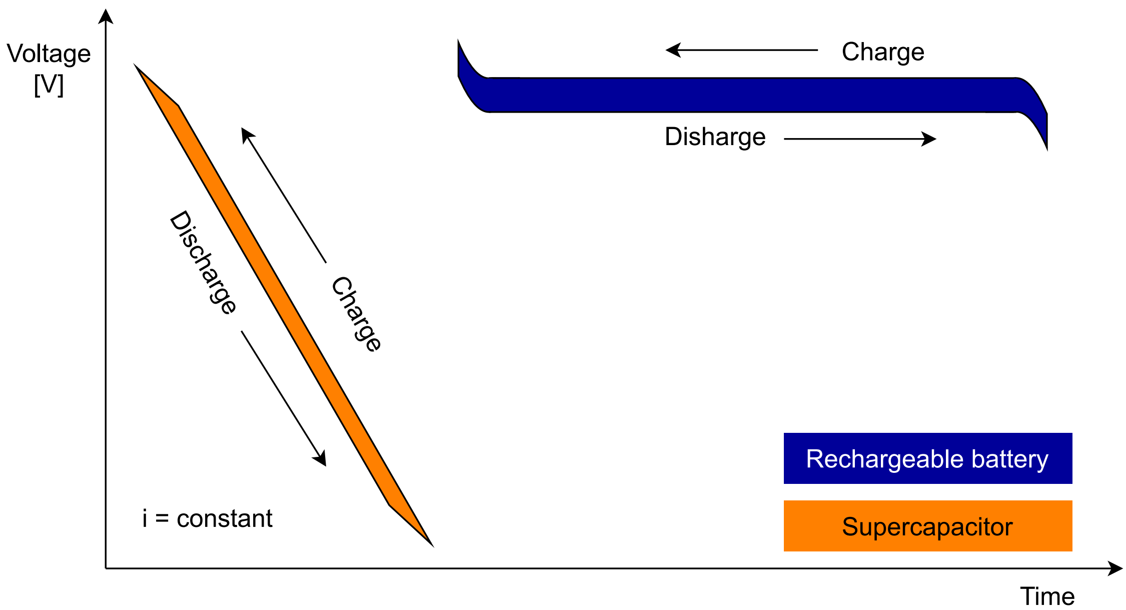


Figure 5.1: A schematic display of the change in potential difference over time considering a SC and rechargeable battery. Adapted from [4]

### 5.2.7 | Battery

Batteries work according to the principle of storing chemical energy inside a battery cell. This chemical energy is transformed into electrical energy which then can be used by the consumer. The capacity is the amount of energy that is stored inside the battery that can be used, often measured in Ampere-hours, which is the current that can be delivered for one hour. The following equation can be used for calculating the capacity during charge of the battery.

$$Q_B = \frac{I_0 \cdot t}{3600} \tag{5.2.24}$$

The voltage is kept nearly constant during charge and discharge of, for example, a lithium-ion battery [69, 70], so the battery energy storage can be calculated using the equation below. The change of potential difference over time, considering the rechargeable battery, is also displayed in figure 5.1.

$$U = V_e \cdot Q_B \cdot 3600 = V_e \cdot I_0 \cdot t \tag{5.2.25}$$

The power that can be delivered by the battery then can be calculated using the following equation and will be nearly constant since the voltage and current can be kept nearly constant during discharge.

$$P = V \cdot I_0 \tag{5.2.26}$$

## 5.3 | Thermodynamics

In this section other information required for modelling and simulating the SOFC-GT power unit is provided. This considers the assumptions and approximations as well as the thermodynamic relations. The section will also give some explanation about the average values of certain quantities of the gas mixtures that are used in the simulation model.

### 5.3.1 | Assumptions and Approximations

In order to simplify the problem and to make it possible to obtain a solution and a working simulation model assumptions and approximations are made. Using these assumptions and approximations makes the simulation model a simplification of the reality which requires reviewing the obtained results, as will be done in chapter 8. The assumptions used in the extension of the simulation model are:

1. The ideal gas law is valid.
2. Isentropic flow in the system.
3. Dynamic pressure effects are negligible.
4. No leaking of any substances from the system.
5. Homogeneous mixture of gases in the system.
6. Constant mass flow rate throughout the cycle.
7. Kinetic and potential energy changes are negligible.
8. Components are well insulated.
9. $c_p$ is constant during a process.

Also, the efficiencies of the components have to be approximated to be able to complete the simulation model. The efficiencies have been determined using [61, 63, 69] and are displayed in the table below.

| Component | Efficiency [%] | Component | Efficiency [%] |
|---|---|---|---|
| Pump | 85 | GT | 87 |
| Compressor | 80 | Generator | 97 |
| Shaft | 99 | Battery | 99.5 |
| Capacitor | 95 | PHE | 98 |

Table 5.1: The approximated efficiencies of the components of the SOFC-GT power unit.

### 5.3.2 | Thermodynamic Relations

Besides the equations described in section 5.2 there are also other equations, thermodynamic relations, and properties that need to be considered for modelling and simulating the SOFC-GT power unit. In this section these are considered where the data and properties are obtained from [61, 65–67, 71]. Furthermore, some of the used constants and data are taken from studies [5, 69].

Table 5.2 provides data from the specific substances that are used in the hybrid system. The dead-state situation data in the table is at atmospheric pressure and 300 K. However, the dead-state temperature can vary between -15 °C and +35 °C [55]. Temperature dependent dead-state data could be obtained from property tables.

| Quantity | $CH_3OH$ | $H_2$ | $H_2O$ | CO | $CO_2$ | $CH_4$ | $O_2$ | $N_2$ |
|---|---|---|---|---|---|---|---|---|
| $M$ | 32.042 | 2.016 | 18.015 | 28.011 | 44.01 | 16.043 | 31.999 | 28.013 |
| $\bar{h}^\circ_C$ | -676,490 | -241,820 | - | -282,990 | - | -802,310 | - | - |
| $v^\circ$ | 0.00127 | - | 0.001003 | - | - | - | - | - |
| $h_0$[1] | 290.5 | 8,522 | 112.5 | 8,723 | 9,431 | 1199.8 | 8,736 | 8,723 |
| $s_0$ | 4.038 | 130.754 | 0.393 | 197.723 | 213.915 | 11.629 | 205.213 | 191.682 |

Table 5.2: The data for the substances used in the SOFC-GT power unit.

Constants used in the simulation model are displayed in table 5.3. These constants are used for the simulation of the PHE and in the equations below to determine, for example, the gas constant of a substance.

| Quantity | Value | Quantity | Value | Quantity | Value |
|---|---|---|---|---|---|
| $g$ | 9.81 [m/s$^2$] | $\alpha_l$ | 1000 [W/(m$^2$K)] | $N_A$ | $6.022 \cdot 10^{23}$ [mol$^{-1}$] |
| $V_{battery}$ | 3.7 [V] | $\alpha_g$ | 20 [W/(m$^2$K)] | $k_b$ | $1.38 \cdot 10^{-23}$ [J/K] |
| $V_{capacitor}$ | 3.3 [V] | $\rho_{steel}$ | 7800 [kg/m$^3$] | $c_{steel}$ | 470 [J/(kg K)] |
| $\tau_{plate}$ | 0.0004 [m] | $\rho_{air}$ | 1.205 [kg/m$^3$] | $M_{air}$ | 28.97 [kg/kmol] |
| $\tau_{channel}$ | 0.0008 [m] | $C_e$ | 10,000 [F] | $U_B$ | 50 [kWh] |
| $L$ | 0.1-0.2 [m] | $\lambda$ | 40 [J/(m s K)] | $R_u$ | 8.31447 [kJ/(kmol K)] |

Table 5.3: The constants used in the simulation model.

A thermally perfect gas is defined by the following equations [65]. Equation 5.3.1 gives the ideal gas law and equation 5.3.2 gives the definition of the universal gas constant.

$$p \cdot V = N \cdot R \cdot T \tag{5.3.1}$$

$$R_u \equiv k_b \cdot N_A \tag{5.3.2}$$

Equation 5.3.2 can be used to determine the gas constant of the various substances [61]. This results in the equation given below.

$$R = \frac{R_u}{M} = \frac{k_b \cdot N_A}{M} \tag{5.3.3}$$

Since the gases used in the system consist of multiple substances, it can be convenient to determine the average value of the gas constant. For example, for determining the specific heat at constant volume, $c_v$. as will be shown in equation 5.3.8. The average gas constant of a mixture can be determined using the following equation.

$$\tilde{R} = \frac{R_u}{M_{average}} \tag{5.3.4}$$

The average molar mass, used in the equation above, can be calculated with the following equation.

$$\tilde{M} = \frac{\sum M_i \cdot \dot{m}_i}{\sum \dot{m}_i} \tag{5.3.5}$$

[1] The specific enthalpy and specific entropy of liquids is given in [kJ/kg] while for gases they er given in [kJ/kmol].

### Specific Heats

The following equation, in combination with the data in table 5.4, can be used to determine the specific heat at constant pressure of various ideal gases as a function of temperature in the range of 273-1800 K[2][61]. Note that in this equation the unit is [kJ/(kmol K)] and therefore has to be divided by the molar mass in order to obtain the unit [kJ/(kg K)].

$$c_p = a + b \cdot T + c \cdot T^2 + d \cdot T^3 \tag{5.3.6}$$

| Substance | Formula | a | b | c | d |
|---|---|---|---|---|---|
| Methanol | $CH_3OH$ | 19.00 | $9.152 \cdot 10^{-2}$ | $-1.22 \cdot 10^{-5}$ | $-8.039 \cdot 10^{-9}$ |
| Hydrogen | $H_2$ | 29.11 | $-0.1916 \cdot 10^{-2}$ | $0.4003 \cdot 10^{-5}$ | $-0.8704 \cdot 10^{-9}$ |
| Water | $H_2O$ | 32.24 | $0.1923 \cdot 10^{-2}$ | $1.055 \cdot 10^{-5}$ | $-3.595 \cdot 10^{-9}$ |
| Carbon Monoxide | $CO$ | 28.16 | $0.1675 \cdot 10^{-2}$ | $0.5372 \cdot 10^{-5}$ | $-2.222 \cdot 10^{-9}$ |
| Carbon Dioxide | $CO_2$ | 22.26 | $5.981 \cdot 10^{-2}$ | $-3.501 \cdot 10^{-5}$ | $7.469 \cdot 10^{-9}$ |
| Methane | $CH_4$ | 19.89 | $5.024 \cdot 10^{-2}$ | $1.269 \cdot 10^{-5}$ | $-11.01 \cdot 10^{-9}$ |
| Oxygen | $O_2$ | 25.48 | $1.520 \cdot 10^{-2}$ | $-0.7155 \cdot 10^{-5}$ | $1.312 \cdot 10^{-9}$ |
| Nitrogen | $N_2$ | 28.90 | $-0.1571 \cdot 10^{-2}$ | $0.8081 \cdot 10^{-5}$ | $-2.873 \cdot 10^{-9}$ |

Table 5.4: The data for the calculation of the specific heat at constant pressure $c_p$.

Similar to equation 5.3.4, it can be convenient to determine the average value of the specific heat a constant pressure since the gases used in the system consist of multiple substances. The average specific heat a constant pressure of a mixture can be determined using the following equation.

$$\tilde{c_p} = \frac{\sum c_{p,i} \cdot \dot{m}_i}{\sum \dot{m}_i} \tag{5.3.7}$$

Using the specific heat at constant pressure and the gas constant of a certain gas or the average values of a gas mixture the specific heat at constant volume be determined. This by using the following equation provided by [65].

$$c_v = c_p - R \quad \text{or} \quad \tilde{c_v} = \tilde{c_p} - \tilde{R} \tag{5.3.8}$$

The specific heat ratio, required for equations 5.2.4 and 5.2.15, can be determined using the equation below [61]. The average value of the specific heat ratio can be determined by using the average values of the specific heats.

$$k = \frac{c_p}{c_v} \quad \text{or} \quad \tilde{k} = \frac{\tilde{c_p}}{\tilde{c_v}} \tag{5.3.9}$$

### Overall Efficiency

In order to gain insight into the fuel consumption of the power unit and the power that is supplied with it, use can be made of the overall efficiency. The overall efficiency is a measure of how efficiently the SOFC-GT power unit converts fuel into work.

The overall efficiency of the GT can be determined with the following equation [61], which describes the ratio of the net work delivered to the chemical energy of the fuel put into the system.

$$\eta_{Th} = \frac{\dot{W}_{net}}{\dot{Q}_{in}} = \frac{P - 2 \cdot \dot{W}_P - 2 \cdot \dot{W}_C}{\sum N \cdot \bar{h}_C} \tag{5.3.10}$$

The utilization factor shows how much of the energy put into the system is usefully used and thus shows the influence of the integration possibilities. In the SOFC-GT system of this study this includes the net work and the regenerated heat for the central heating and warm water system. The following equation can be used to determine the utilization factor.

$$\varepsilon_u = \frac{\dot{W}_{net} + \dot{Q}_{delivered}}{\dot{Q}_{in}} = \frac{P - 2 \cdot \dot{W}_P - 2 \cdot \dot{W}_C + \dot{Q}_{ch} + \dot{Q}_{wws}}{\sum N \cdot \bar{h}_C} \tag{5.3.11}$$

[2] For Methanol and Methane the temperature range is 273-1000 K and 273-1500 K, respectively.

## 5.4 | Simulation Model Verification

In this chapter the verification of the simulation model is discussed and explained. The model will be verified by means of checking the mass balance of the entire system. Once the model is verified it will provide a thrust-worthy model for the entire SOFC-GT hybrid system. The pre-reformer, PHE, and the SOFC already have been verified in the study of [5] and therefore will not be considered in this chapter. The validation of the simulation model and its results are discussed in chapter 8.

### 5.4.1 | Mass balance

In the system the molar quantities change under the influence of chemical reactions in the SOFC, pre-reformer, and combustion chamber. However, the mass flow into the hybrid system must be equal to the mass flow of the exhaust gases out of the system. The same holds for the individual components of the system. The comparison of these mass flows is therefore a useful tool to evaluate whether the model of the SOFC-GT hybrid system is built without faults.

Since the molar quantities change under the influence of chemical reactions the best way to test the mass balance is to count the number of various atoms in the molecules of the molar inflows and the molar outflows. The following molar flows into the system, including the specific atoms in one molecule between brackets, are identified:

- The methanol ($CH_3OH$) flow trough the pump into the pre-reformer and combustion chambers.
- The water ($H_2O$) flow through the pump into the pre-reformer.
- The Nitrogen ($N_2$) flow through the compressor.
- The Oxygen ($O_2$) flow through the compressor.

The following molar flows in the exhaust gases out of the system, including the specific atoms in one molecule between brackets, are identified:

- The carbon dioxide ($CO_2$) flow.
- The water ($H_2O$) flow.
- The Nitrogen ($N_2$) flow.
- The Oxygen ($O_2$) flow.

From these lists of molar flows can be concluded that four type of atoms can be identified: C, H, O, and N. The equation to calculate the error of the balance of these atoms is given below.

$$\frac{\sum \dot{N}_{in} - \sum \dot{N}_{out}}{\sum \dot{N}_{in}} = \text{error} \tag{5.4.1}$$

The results of the model verification of the entire hybrid system are displayed in table 5.5, which shows the maximum deviation peaks between the inflow and outflow of the system. The different scenarios of this table correspond with the scenarios explained in section 6.1.

| Atom | Scenario I | Scenario II | Scenario III |
|---|---|---|---|
| C | 0.74% | 0.36% | 0.12% |
| H | 0.62% | 0.36% | 0.12% |
| O | 0.66% | 0.29% | 0.15% |
| N | 1.3% | 0.73% | 0.25% |

Table 5.5: The error in the mass balance of the simulation model.

The mass balance fluctuations can be both positive and negative and in general appear during power steps and at times where fuel and air supply are manually controlled. Since flow into the mixing chambers differs during the simulation of the different scenarios the outflow of the substances also differs resulting in the mass balance error. The manual controlling of the fuel and air supply effects the mixing ratios and therefore also influence the mass balance errors. So, the reason for the large seems to be the effect of the mixing chambers and the manual controlling of the fuel and air supply.
During steady state operation of the system or during smaller power steps the mass balance error is in the order of 0.03%. There the minor deviations of the mass balance are caused by the multitude of mass transfers that occur in the model and the corresponding inaccuracies.

# 6 | Simulation Results

The Simulink® model was made in order to determine whether the system is able to fulfil the requirements and the stated mission. This chapter provides the results obtained by the simulation model of the SOFC-GT power unit. Using the model various scenarios have been simulated and the results show the behaviour of the power unit, such as power output, temperature output, fuel consumption and available flow rate for the central heating. The values of the constants, parameters and dimensions of the power unit are determined iteratively and can be found in section 7.3.2. The results shown in this chapter are the basis for the verification and validation of the SOFC-GT power unit in chapters 7.1 and 7.2, respectively. Additional results showing the characteristics of the power unit can be found in appendix F.

The input parameters that were varied during operation simulation of the power unit are:

- The molar flow of methanol and air into the GT system.
- The temperature of the cathode and anode flow into the SOFC.
- The current density of the SOFC, to control its power output.
- The molar flows of exhaust gases through the PHE of the anode flow, methanol, and water.

The values of these input parameters during the different scenarios can be found in appendix F.1. The molar flow of methanol and air into the SOFC system is controlled automatically through the current density, see section 5.1.1. In reality the current density can only be adjusted via a series of other controllers, but to simplify the simulation, a direct control of the current density has been chosen.

## 6.1 | Simulation Scenarios

To test the virtual power unit extensively, several scenarios are imitated, in which the power request increases suddenly to a certain level. The power requests of these scenarios are determined from the types of operation displayed in table 3.1. The result is three scenarios, displayed in figure 6.1, in which the power request increases from 'Low speed and station keeping', 'Operations/Economic transit' and 'High speed transit' to 'Maximum speed', respectively scenario I, scenario II, and scenario III. In the first scenario also the use of the low-pressure air system is simulated, which is one of the integration possibilities, where air is drained between the first and second stage compressor.

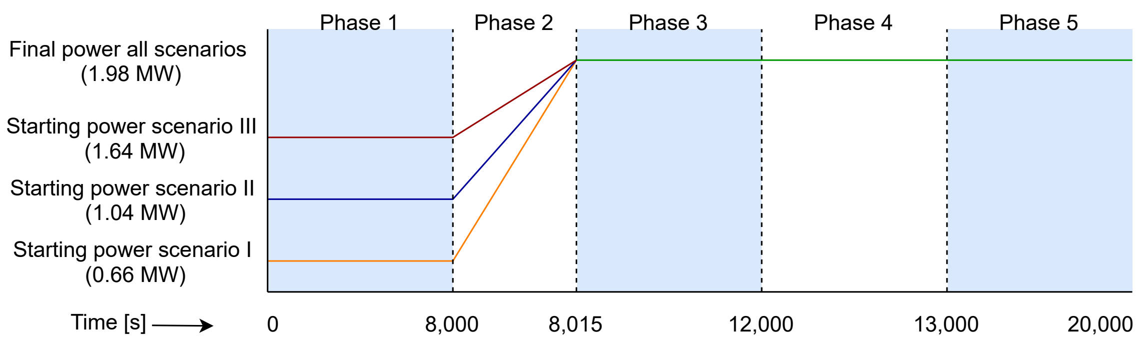


Figure 6.1: A schematic display of the simulation scenarios.

In general, all scenarios have the same course when it comes to the power steps of the GT and SOFC, presented schematically in figure 6.2 and explained in the next paragraph. The duration of phases 1, 3 and 5 have been chosen in such a way that there is more than sufficient time to achieve steady state operation. The duration of phase 4 has been chosen to simulate the slow increase of SOFC power considering durability. The response time of the GT, the duration of phase 2, is set to 15 seconds for all scenarios. This response time of the GT is taken from [14, 15], described in section 2.1.1, and a conservative estimation compared to the power increase of 100 kW/second of [17].

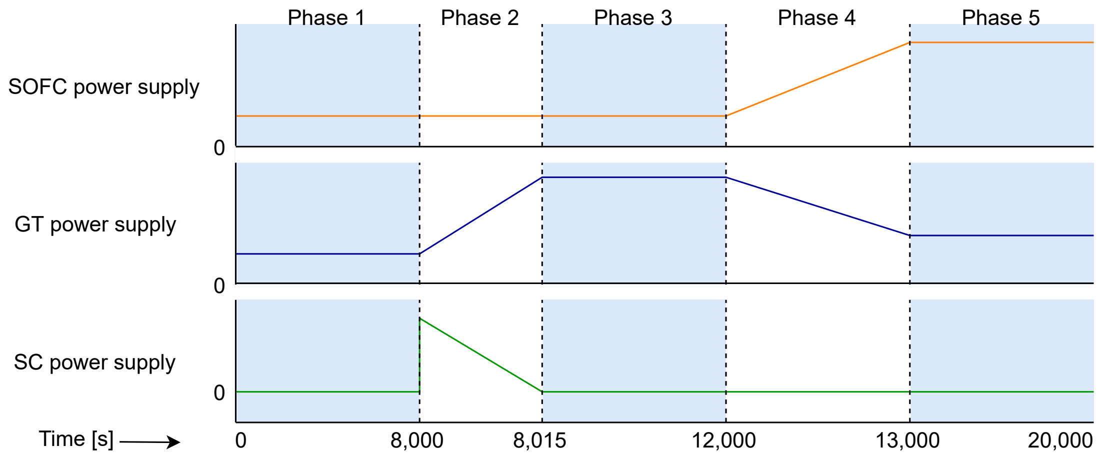


Figure 6.2: A schematic display of the power distribution in the simulation scenarios.

In phase 1 the system operates using mainly the SOFC for power supply. At 8,000 seconds, the start of phase 2, the power request of the naval vessel is increased to the power of operation type 'Maximum speed', which is 1.98 MW. The GT system responds to this power step by increasing the air flow and combustion of fuel in the second combustion chamber. During phase 2 the SC provides power to compensate for the power shortage while the GT is still accelerating making power available almost immediately. In phase 3 the system operates with steady state use of the GT for the power step. After 12,000 seconds the power output of the SOFC increases and the power of the GT system decreases, so the SOFC takes over the power supply, which is phase 4. This phase is simulated so the possibility to switch the power supply from GT to SOFC is investigated and there can be determined whether short term use of the GT during the power step is possible. After 13,000 seconds the SOFC is ready and delivers the required power until the ending of the simulation at 20,000 seconds, which is phase 5.

It has to be noted that the power step down of the SOFC is not considered in the simulation of the hybrid power unit because it is outside the scope of the investigation, because the most suitable way considering durability is not known, and is therefore recommended for follow-up research in section 10.2.1. A check with the simulation model has shown that this is justifiable because only the current density is different at the different power levels of the SOFC. The inflow temperature of the anode and cathode remains the same. This can also be seen in the appendix F.1. In addition, due to the design of the system, as can be seen in section 7.3, the mixers also allow the SOFC to make load steps independently of the GT system.
The same applies to the power step up of the SOFC, but to clearly show the properties of the hybrid system during load steps up, especially because the power step up of the SOFC and the power step down of the GT are at the same time, this has been included in the simulation. To be on the safe side, it has been decided to increase the power of the SOFC over a period of 1000 seconds to the required power.

In addition, during the first scenario a fraction of the air supply is used in the low-pressure air system of the naval vessel between 6,000 and 7,000 seconds. The volume flow to this air system is 50 $m^3$ per hour. Since the air flow during the operation type 'Low speed and station keeping' is the lowest, the fraction of the drained air is the largest and therefore will have the most influence. For that reason, this scenario is chosen to show the effect of this integration possibility. During the time the low-pressure air system is used, the battery provides power to compensate for the power decrease caused by the reduction of mass flow in the GT system, which is schematically shown in figure 6.3.

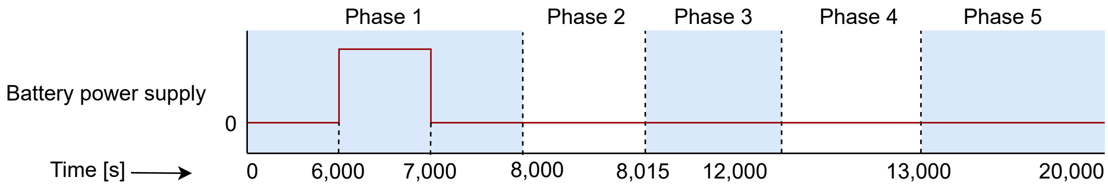


Figure 6.3: A schematic display of the power from the battery in scenario I.

Since the scenarios are so similar the results are also very similar and there is a possibility that many things will be described more than once in this chapter. However, for the investigation it is important that the performance of the hybrid power unit in the operational profile, described in table 3.1, is shown and discussed. For that reason, scenario I is described more extensive than the other scenarios. In scenario II and scenario III the relevant information and differences between the scenarios are addressed.

## 6.2 | Scenario I: Power Step from 'Low Speed and Station Keeping'

In this scenario the power step increases from 0.66 MW to 1.98 MW of 'Maximum speed' operation. In addition to the other scenarios the integration possibility of the low-pressure air system is also simulated in this scenario. The results of this simulation scenario, connected to the verification and validation of the power unit, are shown, and explained in this section of the report. The additional results of this simulation scenario can be found in appendix F.2 and concerns, for example, the behaviour of the PHE, the fuel consumption and the amount of $CO_2$ emissions.

Figure 6.4 shows the power output of the SOFC-GT power unit without the support of the battery or SC. On the left-hand side, the power step from 'Low speed and station Keeping' to 'Maximum speed' is shown. The power overshoot around 13,000 seconds is caused by the manual controlling of the fuel and air supply. On the right-hand side is zoomed in on the region where the low-pressure air system is used and shows that the power output of the system decreases. This is caused by the lower mass flow of air flowing through the GT system since a fraction of air is used in the low-pressure air system.

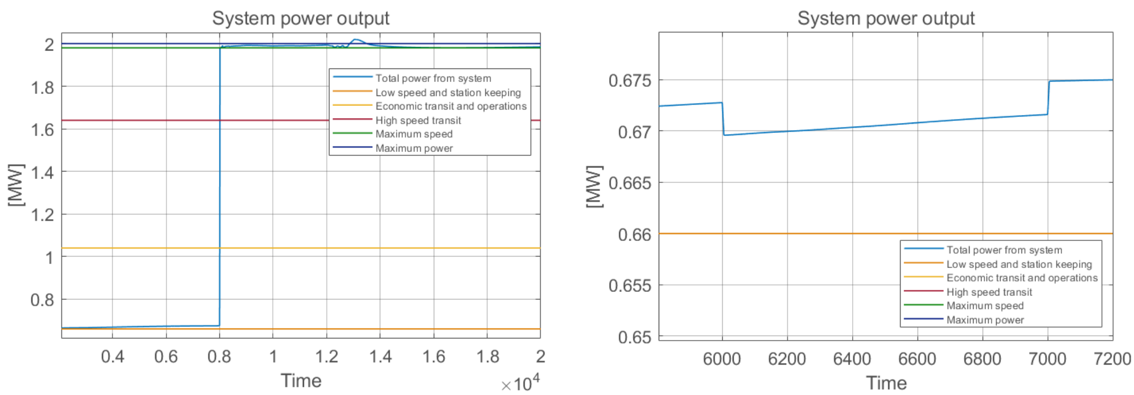


Figure 6.4: The power production of the hybrid system during the simulation

The left-hand side of figure 6.5 shows the support of the battery during the reduction of power caused by the used of the low-pressure air system. There can be seen that the battery is able to provide the difference in power during the time that the power output is reduced. The right-hand side shows the support of the power provided by the SC which is available almost immediately. Furthermore, the right-hand side shows that the GT system is able to provide the power required in 15 seconds.

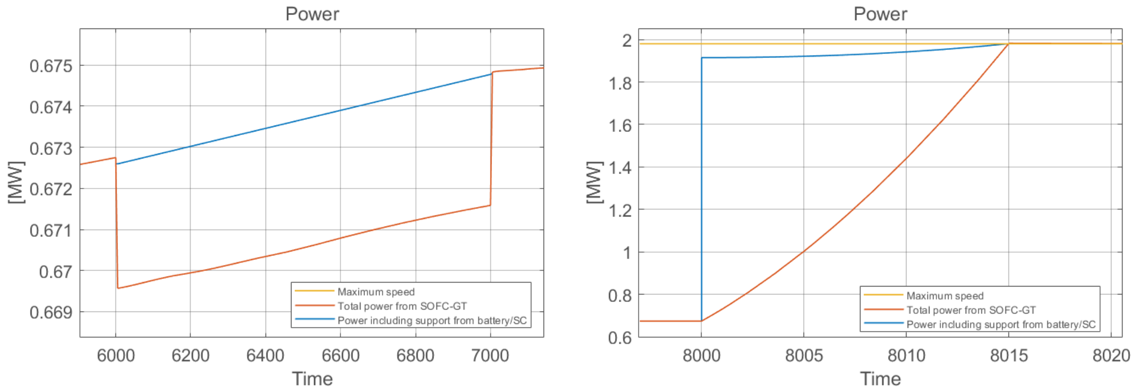


Figure 6.5: The power of the system including supportive components.

The power consumption of the water and methanol pump and the distribution of the power supply of the components are shown in figure 6.6. On the left-hand side, it is clearly visible that the power consumed by the methanol pump increased when the methanol consumption increasing during the power step of the GT. The peak just after 8,000 seconds is caused by the large fuel supply to reach the required power, see also figure F.1. Just after the power step the temperature of the air leaving the PHE is lower than after some time, due to the thermal inertia, resulting in a larger fuel supply just after the power step to reach the required power. After some time, the temperature of the air leaving the PHE increases and a smaller fuel supply is required to provide the power. The power supply is produced by multiple sources, which are the generator couple to the second GT, the SOFC, the battery and the SC. On the right-hand side can clearly be seen when the GT and SOFC make a power step.

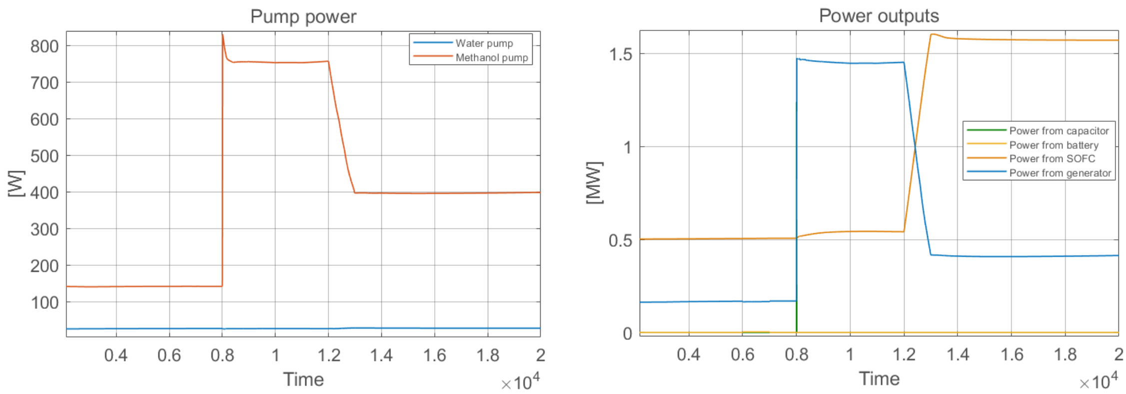


Figure 6.6: The power consumption of the pumps and power distribution of the different components.

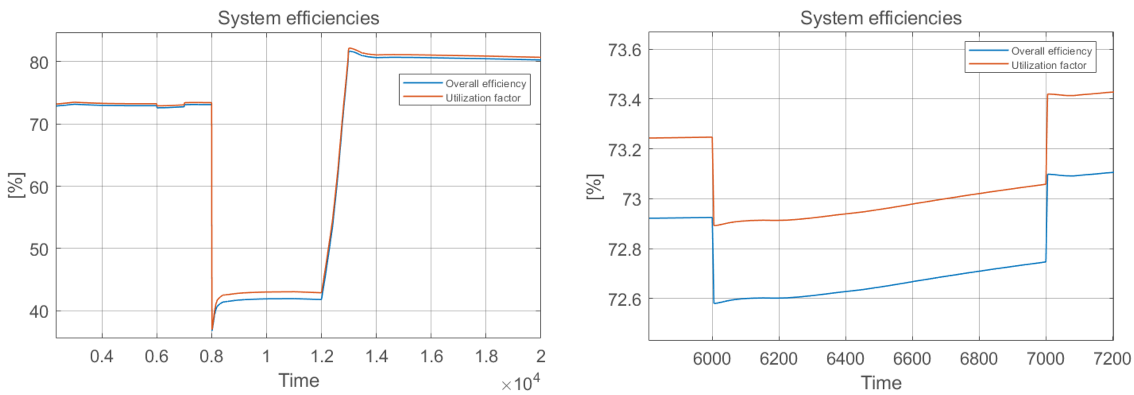


Figure 6.7: The efficiency of the power unit.

The efficiency and utilization factor of the SOFC-GT power unit is shown in figure 6.7. The utilization factor also includes the heat delivered to the central heating and the warm water system. The efficiency decreases during the power step of the GT system which is caused by the increase of fuel consumption to reach the required power, see also figure F.1. After the power step up of the SOFC and the power step down of the GT the efficiency increases again. On the right-hand side is zoomed in on the region where the low-pressure air system is used and the efficiency also decreases which is caused by the lower mass flow of air and the equal fuel consumption during the use of that system.

What stands out is that the efficiency during the 'Low speed and station keeping' is lower than the efficiency during the power supply of the SOFC during 'Maximum speed' operation. This has to do with the temperature of the methanol flowing into the pre-reformer. The pressure of the pre-reformer is controlled with the inflow of methanol, so when the pressure decreases the methanol supply is increased to restore the pressure. When the temperature of the methanol increases the pressure in the pre-reformer decreases resulting in an increase of fuel supply and therefore a decrease in efficiency. The temperature of the methanol during 'Low speed and station keeping' is higher than during 'Maximum speed' operation to prevent the temperature from decreasing to below the saturation temperature of methanol during a rapid increase of fuel supply caused by the power step of the GT. The result is the lower efficiency of the hybrid system during the 'Low speed and station keeping' operation.

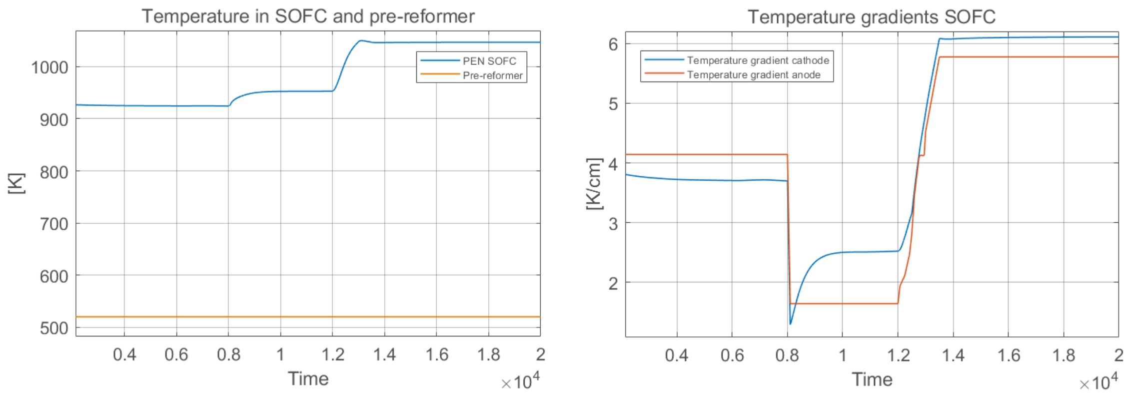


Figure 6.8: The temperature of the SOFC and pre-reformer and temperature gradients in the SOFC.

In figure 6.8 the temperature of the SOFC, pre-reformer and the temperature gradient inside the SOFC is shown. The left-hand side shows that the temperature of the pre-reformers remains constant during the operation and the power step of the power unit. The temperature increase of the SOFC after 8,000 seconds and 12,000 is caused by the increase of inflow temperature of the gases and the increase of the power supply by the SOFC, respectively. The temperature gradients over the length of the anode and cathode, shown on the right-hand side, decreases around 8,000 seconds because of the increase of the inflow temperature via the mixing chambers. The temperature gradient of the cathode increases almost immediately due to the increase of the cathode outflow temperature caused by the PEN temperature of the SOFC. The temperature gradients increase after 12,000 seconds due to a decrease in inflow temperature of the gases and an increase of flow temperatures in the SOFC caused by the PEN temperature.

In the last figure of this scenario, figure 6.9, the temperatures of the gases in the GT system and the air flow to the first combustion chamber are shown. On the left-hand side, the effect of the power step by the GT on the temperature is shown. The small increases during the use of the low-pressure air system are caused by the lower mass flow at equal fuel combustion. The increase of the temperatures during the load step of the GT are caused by the increase of fuel combustion. On the right-hand side, the decrease of air flow into the GT system is shown. Between 6,000 and 7,000 seconds the air flow to the low-pressure air system increases and the air flow to the first combustion chamber decreases. The difference between Nitrogen and Oxygen is because of the composition of air with these molecules.

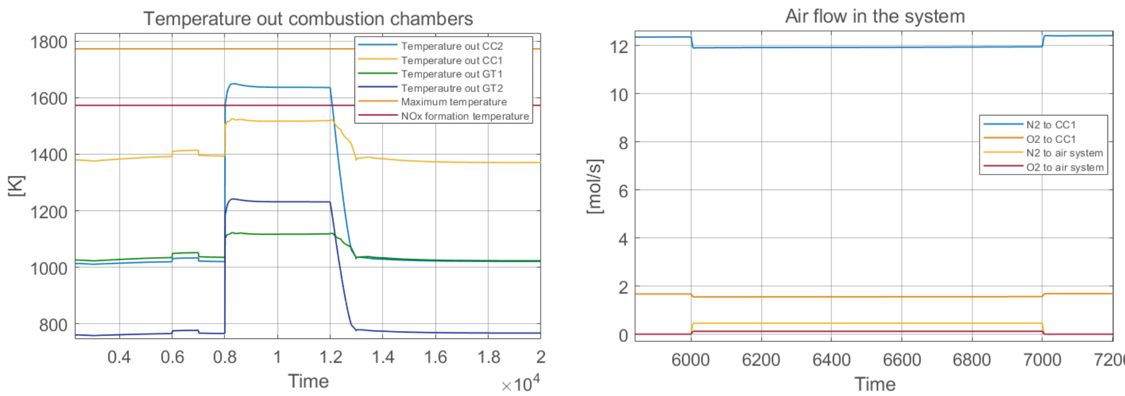


Figure 6.9: The temperature of the gases in the system and the air supply.

What stands out is the difference between the temperature at the outlet of the first GT and at the outlet of the second combustion chamber before the power step and after the power step of the SOFC. Although there is no combustion of fuel in the second combustion chamber during those situations there is a difference in temperature. This is caused by the recalculation of the specific heat at constant pressure for the temperature at which the gases flow into the seconds combustion chamber. This changes the specific heat a little and therefore also the outflow temperature of the gases from the second combustion chamber although there is no combustion. In scenario II and scenario III this difference is also visible and has the same cause, but it is smaller due to smaller temperature differences.

## 6.3 | Scenario II: Power Step from 'Operations/Economic Transit'

In this scenario the power step increases from 1.04 MW to 1.98 MW of 'Maximum speed' operation. The results of this simulation scenario, connected to the verification and validation of the power unit, are shown, and explained in this section of the report. The additional results of this simulation scenario can be found in appendix F.3.

The results for the power supply without supportive components of this scenario is displayed in figure 6.10, which shows that the power unit is able to provide the required power step to reach 1.98 MW. On the right-hand side of the figure there is zoomed in on the region where the power step is made. The fluctuations during the power step and the overshoot around 13,000 seconds are caused by the manual control of fuel and air supply.

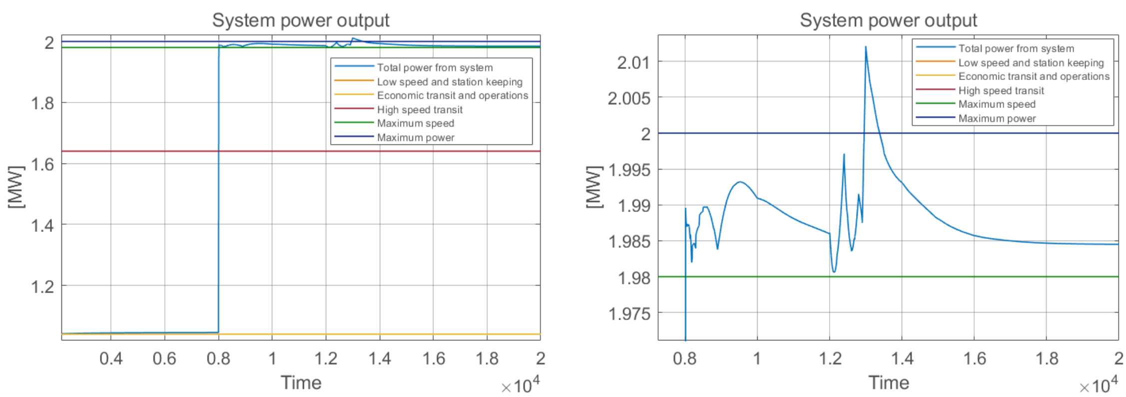


Figure 6.10: The figures showing the power supply of the power unit.

The left-hand side of figure 6.11 shows the support of the power provided by the SC and the ability of the GT system to provide the power required in 15 seconds. The efficiency and utilization factor, which includes the heat delivered to the central heating and the warm water system, of the SOFC-GT power unit is shown on the right-hand side of figure 6.11. The efficiency decreases during the power step and increases after the power step up of the SOFC and the power step down of the GT the efficiency, which is the same as in the other scenarios. However, during the power step in this scenario the efficiency is larger than during scenario I, 50% instead of 42%.

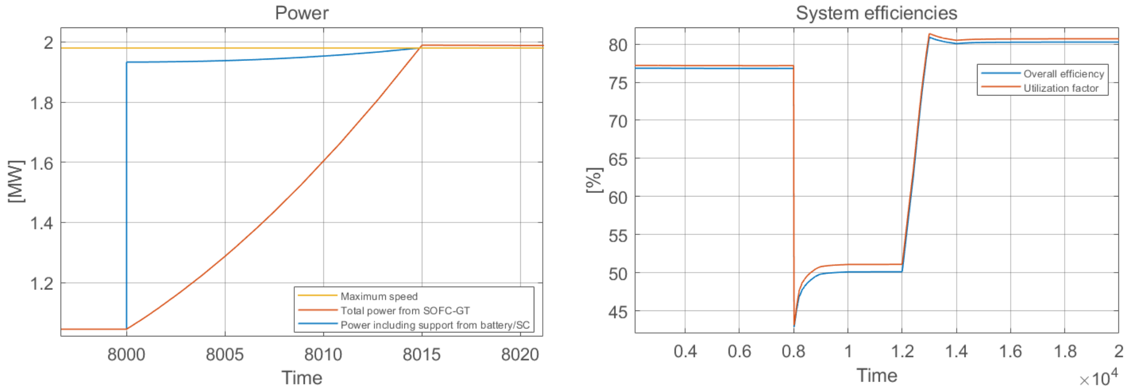


Figure 6.11: The power of the system including supportive components and the efficiency of the system.

The power consumption of the water and methanol pump and the distribution of the power supply of the components is shown in figure 6.12. On the left-hand side, it is clearly visible that the power consumed by the methanol pump shows the same profile as in the other scenarios. However, in this scenario the power step is smaller than in scenario I and larger than in scenario II. Furthermore, the methanol pump requires more power in phase 1 than in the previous scenario, since the starting power supply is larger. On the right-hand side can clearly be seen when the GT and SOFC make a power step. The small increase of the power produced by the SOFC around 9,000 seconds is caused by a higher temperature of the inflow gases.

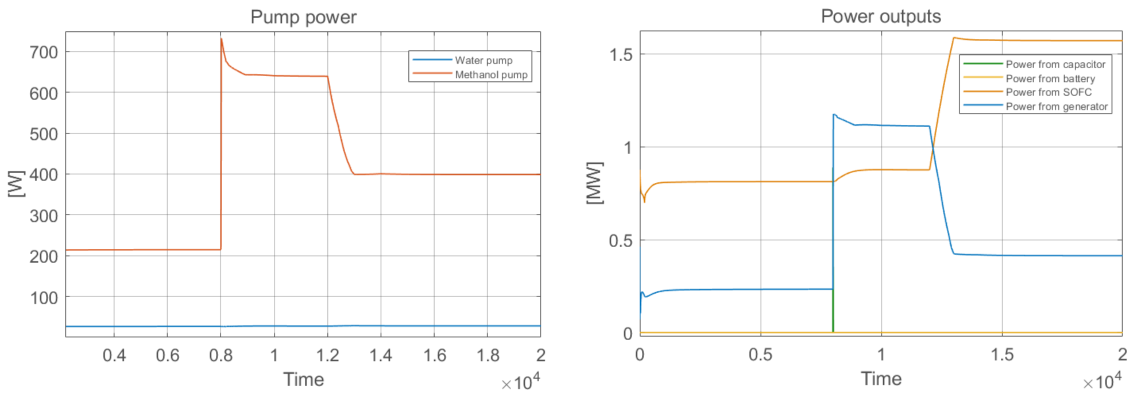


Figure 6.12: The power consumption of the pumps and power distribution of the different components.

In figure 6.13 the temperature of the gases in the system and the temperature gradient inside the SOFC is shown. On the left-hand side, the effect of the power step by the GT on the temperature is shown. Compared to scenario I the temperature is just below the $NO_x$ formation temperature, so probably no $NO_x$ will be formed which is favourable for the emission requirements. The temperature gradients over the length of the anode and cathode, show the same behaviour as in scenario I. However, the temperature gradient is larger during the power step since the PEN temperature of the SOFC, influencing the outflow temperature, was already larger due to a larger power supply.

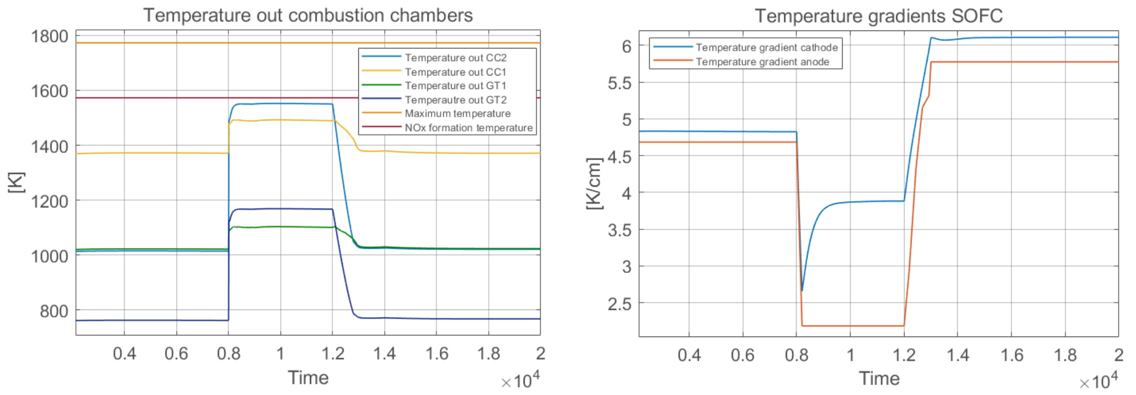


Figure 6.13: The temperature of the gases in the system and the temperature gradients in the SOFC.

## 6.4 | Scenario III: Power Step from 'High Speed Transit'

In this scenario the power step increases from 1.64 MW to 1.98 MW of 'Maximum speed' operation. The results of this simulation scenario, connected to the verification and validation of the power unit, are shown, and explained in this section of the report. The additional results of this simulation scenario can be found in appendix F.4.

The results for the power supply without supportive components of this scenario is displayed in figure 6.14, which shows that the power unit is able to provide the required power. On the right-hand side of the figure there is zoomed in on the region where the power step is made. The fluctuations during the power step and the overshoot around 13,000 seconds are again caused by the manual control of fuel and air supply.

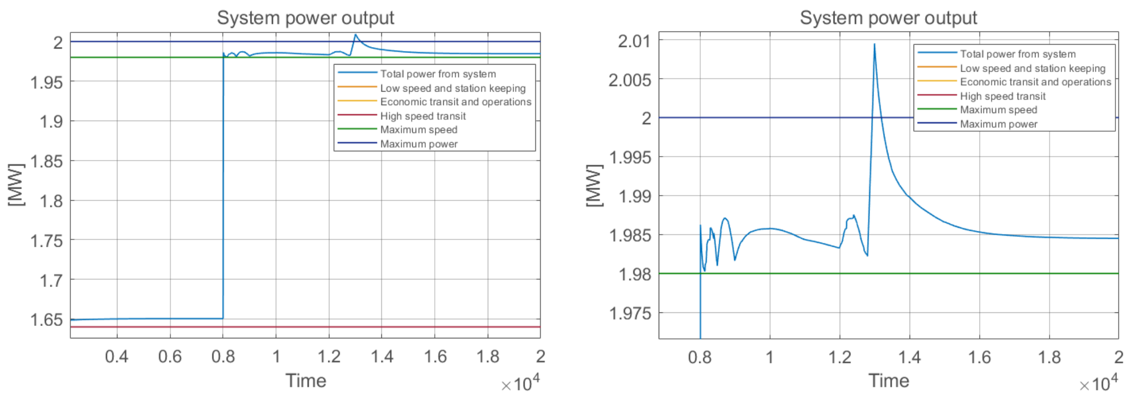


Figure 6.14: The figures showing the power supply of the power unit.

The left-hand side of figure 6.15 shows the support of the power provided by the SC which is available almost immediately. Furthermore it shows that the GT system is also in this scenario able to provide the power required in 15 seconds. The efficiency and utilization factor of the SOFC-GT power unit is shown on the right-hand side of figure 6.15. The efficiency decreases during the power step of the GT system and increases after the SOFC and the power step down of the GT. This is because the SOFC system has a better efficiency and therefore affects the entire systems efficiency positively. Compared to scenario I and scenario II the efficiency during the power step is higher.

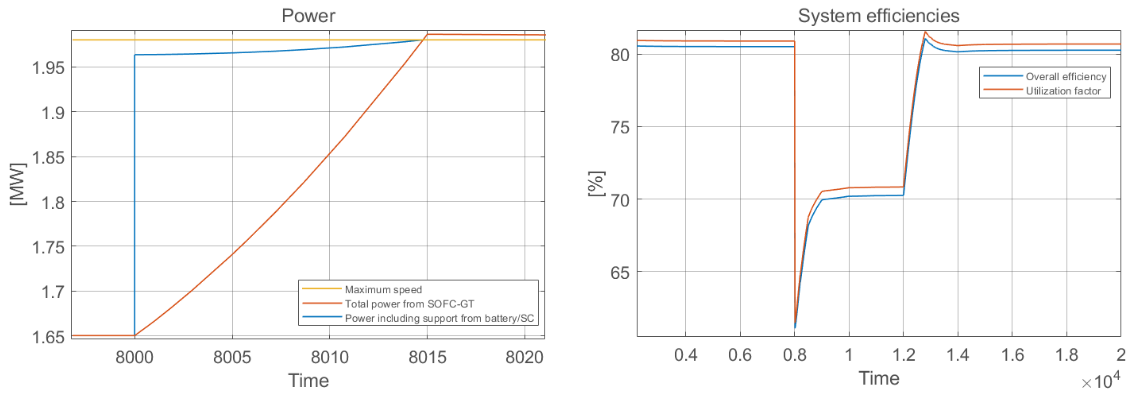


Figure 6.15: The power of the system including supportive components and the efficiency of the system.

The power consumption of the water and methanol pump and the distribution of the power supply of the components is shown in figure 6.16. On the left-hand side, it is clearly visible that the power consumed by the methanol pump shows the same profile as in the other scenarios. The peak just after 8,000 seconds is caused by the large fuel supply to reach the required power, but it is much lower than in scenario I. On the right-hand side can clearly be seen when the GT and SOFC make a power step, as well as the support of the SC, the green peak. The profile of the produced power of these components is similar to that of scenario I and scenario II.

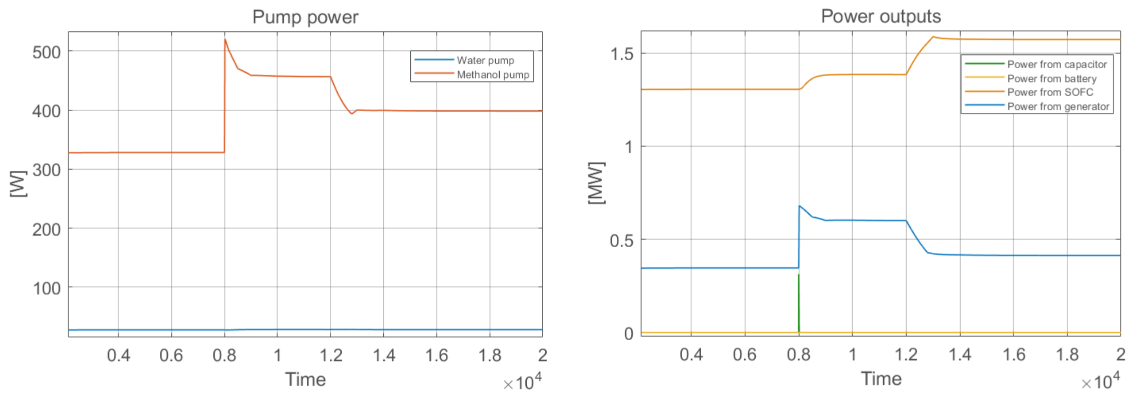


Figure 6.16: The power consumption of the pumps and power distribution of the different components.

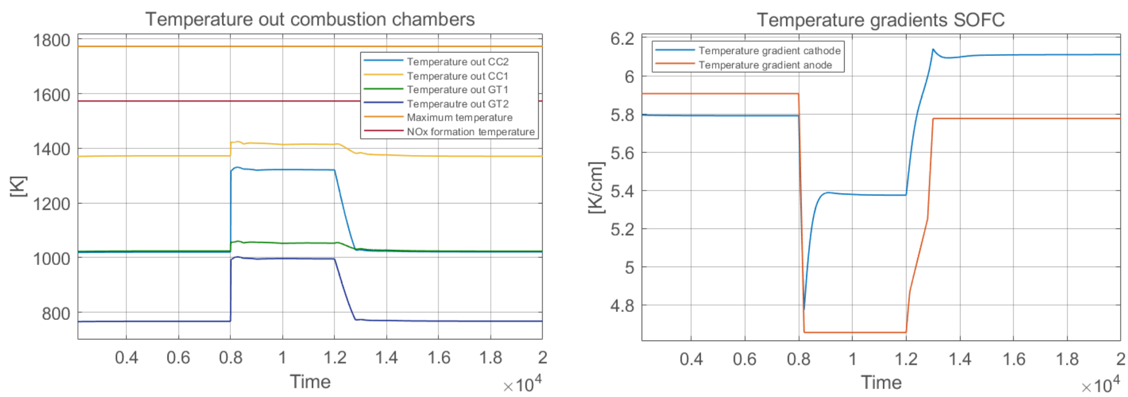


Figure 6.17: The temperature of the gases in the system and the temperature gradients in the SOFC.

In figure 6.17 the temperature of the gases in the system and the temperature gradient inside the SOFC is shown. On the left-hand side, the effect of the power step by the GT on the temperature, caused by the increase of fuel combustion, is shown. Compared to scenario II the maximum temperature of the gases is even lower and also does not exceed the $NO_x$ formation temperature. So the probability of $NO_x$ formation is also lower which is favourable for the emission requirements. In this scenario the temperature of the gases leaving the seconds combustion chamber does not even exceed the temperature of the gases leaving the first combustion chamber, which is the case in the other scenarios. The temperature gradients over the length of the anode and cathode, show the same behaviour as in scenario I and scenario II only with larger gradients because of a higher PEN temperature which ensures a higher outflow temperature.

## 6.5 | Efficiency Comparison with other SOFC-GT Power Units

In this section a comparison with SOFC-GT power units from the literature and the SOFC-GT system of this investigation is made. Because the SOFC-GT configurations described in section A.3 are mainly designed for the highest possible efficiency, and not so much for a fast response time, only a comparison could be made with the efficiency of these systems.

In general, other SOFC-GT configurations found in the literature have an efficiency between 45% and 70%, which is lower than the SOFC-GT power unit of this investigation, which is between 73% and 81% for stationary operation. The difference between the power unit of this investigation and the power units in the literature is the pressure. In this investigation an operational pressure of 2 MPa has been used, while in the literature a pressure range of 0.1 to 1 MPa is used. According to [72] higher efficiencies can be reached when the operational pressure is higher, and a heat source of sufficiently high temperature is freely available. This is the case in this study, since as much waste heat as possible and hot gases from the SOFC are used to increase the efficiency of the hybrid system. So, a higher efficiency is in line with other results from the literature.

A single stage version of the simulated configuration showed, via an extra simulation executed during this investigation, that operating at a pressure of 1 MPa indeed decreases the efficiency to around 71% for 'Maximum speed' operation. The efficiencies for 'Low speed and station keeping', 'Operations/Economic transit' and 'High speed transit' are decreased to 66%, 68% and 69%, respectively.

## 6.6 | Comparison with SOFC System

In this section a comparison with the standalone SOFC system of [5] and the SOFC-GT system of this investigation is made to demonstrate the differences between both power units. In section 1.2 is stated that the system lacks the ability to provide either adequate efficiency or load-following capabilities for naval applicability. So, the comparison is made between the efficiency and the dynamic behaviour of the SOFC-GT system and the SOFC system.

The results for this comparison are generated using the simulation model of the SOFC system from investigation [5]. The scenarios used to demonstrate the characteristics of the SOFC-GT power unit are also used to generate the results of the SOFC system displayed and discussed in this section, so a proper comparison is possible.

### 6.6.1 | Response Time Comparison with SOFC System

Figure 6.18 shows that the SOFC system is able to provide the power that is required in scenario I in approximately 1500 seconds. This is much longer than the response time of 15 seconds of the SOFC-GT without supportive components, which can be seen in figure 6.5.

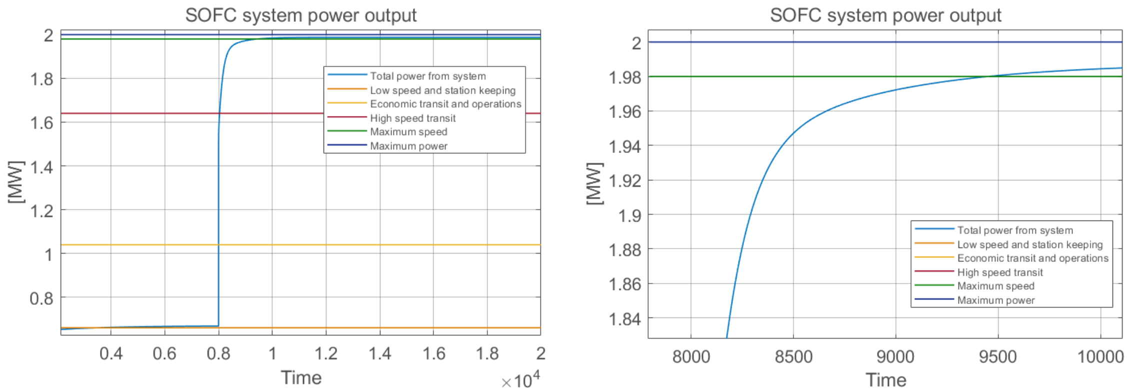


Figure 6.18: The power of the SOFC system in scenario I.

Figure 6.19 also shows that the SOFC system is able to provide the power that is required in scenario II. However, also in this scenario the time to reach the required power production is much longer than the 15 seconds of the SOFC-GT system, approximately 1000 seconds. The response time of the SOFC-GT power unit is shown in figure 6.11.

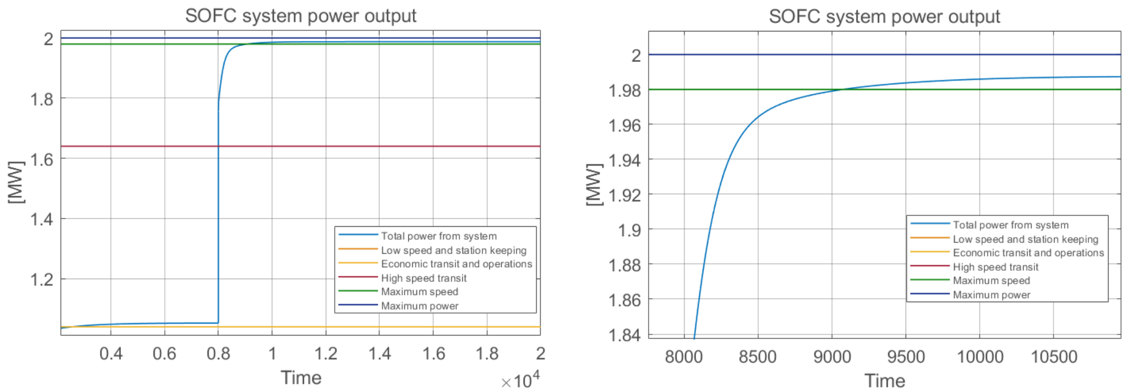


Figure 6.19: The power of the SOFC system in scenario II.

The response time of the SOFC in scenario III is shown in figure 6.20. It shows that the SOFC system is able to provide the power that is required in approximately 500 seconds. This is also much longer than the response time of the SOFC-GT power unit without supporting components, see figure 6.15.

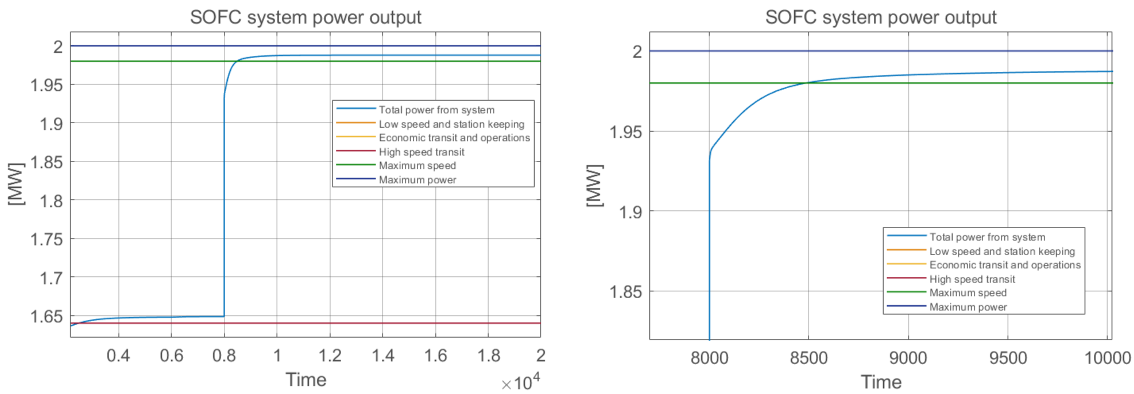


Figure 6.20: The power of the SOFC system in scenario III.

### 6.6.2 | Efficiency Comparison with SOFC System

Comparing the figures 6.21 and 6.22, showing the efficiency of the SOFC system, with the figures 6.7, 6.11 and 6.15, showing the efficiency of the SOFC-GT power unit, shows the improvement of the efficiency in the new configuration.

In the scenarios the lowest efficiency of the SOFC-GT power unit is approximately 35%, while the efficiency of the SOFC system does not exceed 25%, except for a very short period of time of less than a second. During stationary operation of the SOFC-GT power unit, with maximum operation of the SOFC, like in phase 1 and 5 of figure 6.1, the efficiency can reach up to 81%, so it can be stated that the efficiency of the SOFC-GT hybrid system is much better.

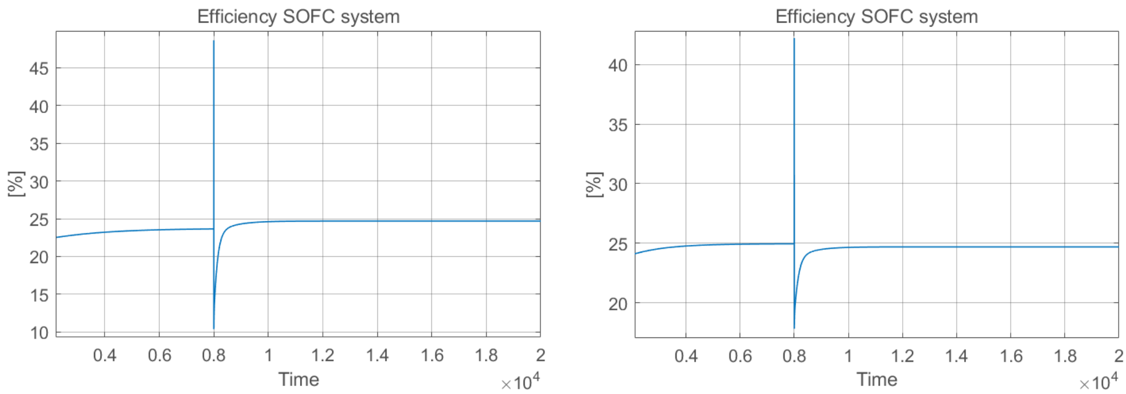


Figure 6.21: The efficiency of the SOFC system in scenario I (left) and scenario II (right).

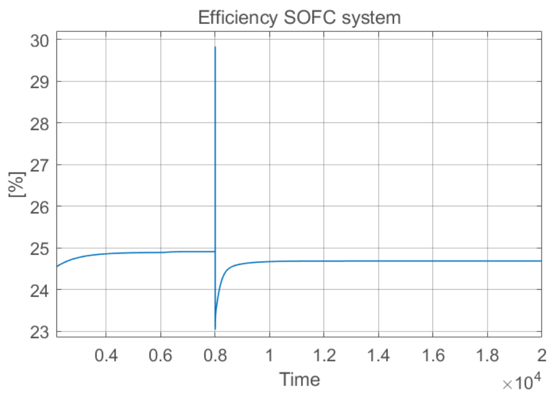


Figure 6.22: The efficiency of the SOFC system in scenario III.

# 7 | System Design Completion

The simulation model has provided several valuable insights on the operation of a methanol fuelled SOFC-GT power unit for naval applicability. In this chapter the final steps to the final design of the SOFC-GT are presented. This considers the verification and validation of the designed system as well as the final design itself. In this chapter the following sub-question will be answered.

- To what extent can the SOFC-GT hybrid power unit meet the technical criteria and fulfill the mission imposed by the RNLN?

Ultimately, this chapter will provide an answer to the main research question of this investigation.

- What are the design characteristics of a methanol fuelled Solid Oxide Fuel Cell - Gas Turbine hybrid power unit that meets the technical criteria for naval applicability on the support vessels of the Royal Netherlands Navy?

## 7.1 | Design Verification

This section provides the verification of the requirements, described in section 3.3 and the integration possibilities, described in section 4.6. The verification is done according to the results obtained by means of the simulation model, which are discussed in chapter 6.

### 7.1.1 | Requirements Verification

In the concept design of the power unit the combustion of AOG from the SOFC and the use of waste heat is considered, as well as the supportive components for peak-shaving and dynamic support. The comparison of the results of the power unit of this investigation with the results of [5] also shows that the efficiency is increased. In the scenarios the lowest efficiency of the SOFC-GT power unit is approximately 35%, while the efficiency of the SOFC system does not exceed 25%, except for a very short period of time. The increased efficiency and the use of supportive components means that the power unit meets requirement 1.1 and requirement 1.5.

The results show that the SOFC-GT power unit is able to provide the required power in 15 seconds, which is well within the 30 seconds of requirement 1.2. The results also have shown that power steps from all different operations of the support vessels are possible. Even the largest step, in scenario I, is no problem for the GT system. This makes it possible to operate the SOFC as constantly as possible, but a higher efficiency can be achieved by scaling up the power output of the SOFC. But in any case, that part of requirement 1.11 can be met.

The results show that the power unit can provide the required power in all operations, so also the maximum power required for 'Maximum speed' operation. In the scenarios the lowest efficiency of the SOFC-GT power unit is approximately 35%. This is just above the requirement but only during the largest power step. In stationary operation of the power unit the efficiency can reach up to 81%. So, it can be said that the power unit meets requirement 1.3 and requirement 1.4.
The hybrid system is modelled in such a way that it operates at a pressure of 2 MPa and thus automatically meets requirement 1.6. Furthermore, the results show that the maximum power required by the water pump and methanol pump is 29 W and 820 W, respectively. This is well below the maximum power of requirement 1.7, so here too the system suffices.

The temperatures at the exit of the combustion chambers and the temperature gradients in the SOFC are important for the safe operation of the power unit. The results show that the pre-reformer operates at a temperature of 520 K, because of the AOG fraction, and that the operating temperature of the SOFC does not exceed 1050 K. Furthermore, the maximum temperature of the inflow gases for the turbines is 1650 K and the maximum temperature gradient in the SOFC is 6.2 K/cm. This means that the operating temperature of the SOFC is lower than the maximum of 1173 K, the inlet temperature for the turbines is lower than the maximum of 1773 K and the temperature gradient in the SOFC is lower than the maximum of 10 K/cm. So, the system meets requirements 1.8, 1.9, 1.11, and 1.12.

The use of the PHE ensures that the methanol and water can be vaporized before entering the combustion chamber or the pre-reformer. This also holds for pre-heating the air and anode flow before entering the SOFC or the first combustion chamber. The results show that pre-heating the air flow indeed increases the efficiency, since the fuel consumption decreases as time elapses after the power step while the power output is kept constant.
Furthermore, the results show that in the temperature of the methanol during 'Low speed and station keeping' and Operations/Economic Transit' is larger than the 445 K of superheated methanol. This is to prevent the temperature of the methanol from decreasing to below the saturated vapour temperature during the increase of the fuel flow for the power step of the GT and is caused by the thermal inertia of the PHE.
To prevent excessive temperature in the pre-reformer this is compensated with a water temperature which is just below the 485 K of superheated water. The combined energy of the water and methanol is kept nearly constant as the results also show, so the energy flowing into the pre-reformer is also kept nearly constant. With this, the excess of energy in the methanol flow ensures that the shortage of energy in the water flow is compensated and that the water still evaporates. So, there can be stated that the power unit meets the requirements 1.10, 1.16, and 1.17.

Requirement 1.13 is also met because the power unit combusts the fuels of the AOG, including Hydrogen, in the first combustion chamber and methanol in both combustion chamber. In the design of the power unit the GT system has its own air and fuel supply, which means that it also complies with requirement 1.14.

The last requirement that needs to be verified is about the outlet temperature of the turbines. The gases shall leave the turbines before the saturated vapour pressure and temperature are reached and water droplets are formed. That means that the temperature after the first stage turbine has to be higher than 421.05 K and after the second stage turbine higher than 373.12 K [61]. The results shows that this is the case in all scenarios since the temperatures of the gases leaving the turbines are never below 750 K, with which the system also complies with requirement 1.15.

### 7.1.2 | Integration Possibilities Verification

The results of this investigation have shown, in scenario I, that the integration of the low-pressure air system with the SOFC-GT power unit is possible. The decrease of air flowing into the GT system, because some of it is used in the air system, is so low that it hardly affects the operation of the power unit. The power output decreases a little when the air system is used as well as the efficiency. However, the power decrease is so low that it can be compensated by battery power.

The simulation also has shown that there is sufficient heat available to provide the central heating and the warm water system with the required heat to reach the required temperatures. Especially during the power step of the GT system a lot of waste heat is available, but also during stationary operation this is the case. The smallest available water flow for the central heating is 1.2 $m^3/h$ after the heat for the warm water system has already been extracted. So, there can be stated that the SOFC-GT power unit can also be integrated with the warm water system and the central heating.

The power required by the water pump during all operation of the power unit is well below the maximum power of 76 kW of requirement 1.7. The maximum power required by the water pump is 29 W, so there is sufficient power available to provide the drinking water system with water by using the water pump of the power unit. So, also the integration of the power unit with the drinking water system is possible.

The simulation results also have shown that it is possible to increase the power of the power unit to 'Maximum speed' operation maximizing the power supply of the SOFC. As a result, the efficiency of the power unit can be above 73% in all stationary operations. This makes it possible to deliver a higher power for a longer period of time at a high efficiency, which in turn may offer the possibility for the support vessels to be part of microgrids.

## 7.2 | Design Validation

This section provides the design validation of the methanol fuelled SOFC-GT power unit according to the mission set by the RNLN. There will be determined if the system is fulfilling the stated mission and meets stakeholder expectations. For that reason, the validation process is done in cooperation with the relevant stakeholders, where in the results of the validation a distinction is made between contentment and concerns of these stakeholders about the system.[1, 32, 56, 73–75]

### 7.2.1 | Contentment

The system is well rated when it comes to the size and performance of the system. It is able to deliver the required power and can function with high efficiency. In addition, the maximum mass and volume, 43 tonnes and 81 $m^3$, is not considered a problem. The designed power unit will also fit since the engine room of the HOV is approximately 105 $m^3$ [56]. Saving space and mass for fuel storage capacity because of the high efficiency is a positive feature of the system and will compensate for the increase of mass and volume of the designed power unit. Furthermore, the designed system makes little use of batteries, which also benefits when it comes to mass, space, and money. However, some questions were raised about about the necessity of the GT system to be able to deliver the large power steps quickly.

Being able to operate the SOFC system and GT system separately ensures reliability of the entire system should one of the two fail, which is seen as positive. The fact that the temperature remains below the $NO_x$ formation temperature in almost all power steps is also something positive because it has advantages over emissions.
Lastly, the hybrid system produces a lot of waste heat that can be used elsewhere in the naval vessel. Using the waste heat for the warm water system and the central heating increases the efficiency of both the power unit and the support vessel since no longer extra fuel is required to produce heat for the central heating. Especially, during cold days this can make a lot of difference and therefore this feature of the power unit is considered positive.[32]

### 7.2.2 | Concerns

There are concerns about the feasibility of the system, since the SOFC is a new development that has not yet been extensively tested and developed for naval applicability. This creates uncertainties when it comes to the reliability and complexity of the system. From DMI there is the demand for naval vessels that are as reliable and simple as possible, which makes maintenance a lot easier. The designed system, at the moment, does not give certainty about these things and therefore their statement is that innovation is beautiful, but it has to be reliable and maintainable.

The maintenance of the GT is known and will not cause any problems, but this is different when it comes to the SOFC. The question is therefore whether specialist knowledge and skills are required to carry out maintenance on the SOFC. This investigation indicates, in section 2.1.6, that this will not be the case, but follow-up research and practice has to confirm this to convince DMI.
There are also mass flows in the system that need to be controlled for the system to operate. This means that a somewhat more complex operating system has to be used, which can also cause problems with maintenance because required knowledge may not be present with the crew or the maintenance team. This is also a bottleneck in the system according to DMI.

The sudden shutdown of the system in the event of an emergency is also a concern that has been raised. The GT can be stopped quickly and will not cause any problems, but for the SOFC this may be different and might cause some damage for example. The current research does not give a solution to this, so this is something that will have to be investigated in the future.

In addition, there is uncertainty about storing and handling methanol since it carries risks when it comes to personnel health, because methanol is toxic, and methanol burns with an invisible flame. The GMM study has shown that it is possible [10], but DMI still likes to see whether this is the case in practice. However, using methanol as fuel does provide possibilities for the water supply to be extracted from the exhaust gases. The use of water from the exhaust gases for consumption purposes (drinking water) or sanitary purposes (freshwater) may further increase efficiency and could be a replacement for the complex freshwater production system. However, research will have to show whether it is responsible to extract water from the exhaust gases. In any case, the simulation shows that at 'Low speed and station keeping' operation 200 liters of water per hour is net available in the exhaust gases.

### 7.2.3 | Other Remarks

It was indicated that there is currently a trend to switch from GT to Diesel engines, since these are more efficient. However, the gases from the SOFC have to be cooled, at the expense of efficiency, before they can be used in the Diesel engine. This was understood by DMI and therefore the use of a GT does not detract from the designed power unit.

During the validation process it was also indicated that in more and more harbours it is mandatory to use the electricity supply of the harbour. The vessels then do not have to use their own power unit for electricity, which saves emissions in the harbour environment. However, this compromises the use of the low-pressure air system and being part mircogrids. In the designed hybrid system, it has to be on to be able to supply air to the low-pressure air system. When electricity has to be taken from the harbour, the power unit does not work, and therefore the air system does not work, which can easily be solved by installing a compressor, nor can electricity be supplied to the harbour.

## 7.3 | Final Power Unit Design

After verification of the design in section 7.1 and the validation in section 7.2 the final design of the SOFC-GT hybrid power unit is presented in this section. This considers the final design configuration, the systems operation, the redundancy, and the technical specification data. The last of these four presents the details of the configuration of the power unit, such as the length of the PHE and the pressure ratios.

### 7.3.1 | Final Design Configuration

In this section of the report the final design of the SOFC-GT power unit is presented and the differences with the preliminary design will be discussed. The configuration is obtained in the iterative process of simulating the configuration, adjusting the configuration, and simulating again. The results discussed in chapter 6 and appendix F are obtained by using this configuration of the hybrid system.

The order of the water PHE and the methanol PHE has been switched in the final design. Since the methanol flow is larger than the water flow it requires more heat to reach the required temperature of superheated methanol. For that reason, it turned out to be more convenient to have the methanol PHE in front of the water PHE.

The exhaust gases leaving the GT contained so much waste heat that not only the air for the cathode, methanol and water could be pre-heated but also the anode flow and the air for the GT system. This allows higher temperatures of the anode flow to be achieved, preventing excessive temperature gradients in the SOFC during large load steps. For that reason, a PHE is placed between the pre-reformer and mixer for the anode to pre-heat the anode flow using the exhaust gases between the PHE for the air and the methanol. Furthermore, the air for the GT system also flows trough the PHE for the air increasing the inflow temperature of the air into the first combustion chamber. As a result, the efficiency of the GT system increases and therefore also the efficiency of the power unit. Afterwards there was still enough waste heat available for the warm water system and central heating.

To control the temperature of the methanol, water, and anode flow via the PHE bypasses of the exhaust gases flow is considered in the final design. Via these bypasses the amount of energy flowing into the PHE can be controlled. Since the amount of energy flowing through the PHE controls the output temperature of the temperature of the fluids flowing through the PHE can be controlled. This ensures that the temperature of the methanol and water does not become much higher than the temperature for superheated methanol and water. In addition, excessive temperatures of the anode flow, which have adverse consequences for the SOFC, can be prevented. The results have shown that, by using these bypasses, the temperatures in the system can be controlled sufficiently.

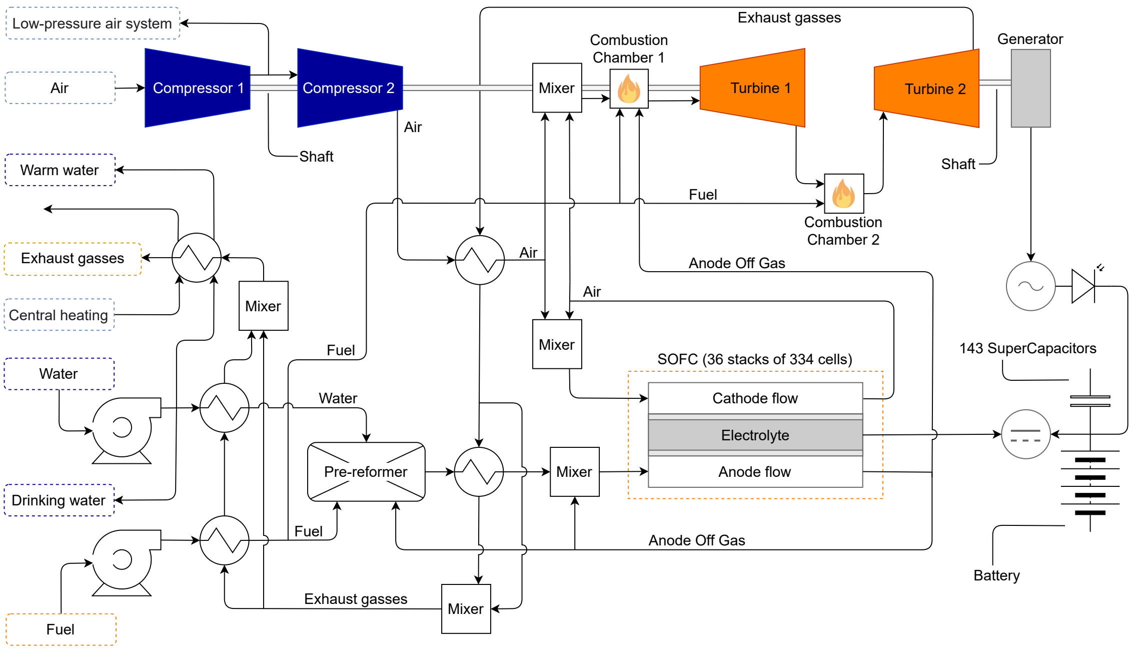


Figure 7.1: The final design of the SOFC-GT hybrid power unit.

## 7.3.2 | Technical Specification Data

In this section of the report the technical specifications of the components of the SOFC-GT power unit are discussed. These specifications are determined using the simulation model and the results discussed in chapter 6 and appendix F are obtained by using these specifications of the hybrid system. The mass and volume of the GT system and SOFC system are determined using the values from table 2.2.

In table 7.1 the specifications of the GT system and the pumps are displayed. The mass and volume of the GT system for each scenario is presented to show the influence of the required power step. It shows that the mass and volume of the GT system increases when the required power step increases, so the mass and volume of the entire power unit is also depending on the required power step. The mass and volume of the pumps do not depend on the scenario [76].

| Component | $p_{in}$ | $p_{out}$ | Scenario I | | Scenario II | | Scenario III | |
|---|---|---|---|---|---|---|---|---|
| | [MPa] | [MPa] | $m$ [kg] | $V$ [m$^3$] | $m$ [kg] | $V$ [m$^3$] | $m$ [kg] | $V$ [m$^3$] |
| Compressor 1 | 0.1 | 1 | - | - | - | - | - | - |
| Compressor 2 | 1 | 2 | - | - | - | - | - | - |
| Turbine 1 | 2 | 0.44 | - | - | - | - | - | - |
| Turbine 2 | 0.44 | 0.1 | - | - | - | - | - | - |
| Total GT system | - | - | 27,619 | 63 | 22,667 | 52 | 13,810 | 32 |
| Pump water | 0.1 | 2 | 125 | 0.063 | - | - | - | - |
| Pump methanol | 0.1 | 2 | 125 | 0.063 | - | - | - | - |

Table 7.1: The specifications of the GT system.

In table 7.2 the specifications of the SOFC system and the supportive components, the battery and the SC, are displayed. One battery is sufficient to provide the power difference during use of the low-pressure air system. When more power or longer power supply from the battery is required, for example when cornering or turning the vessel, more batteries would be required, resulting in larger mass and volume.

In total 143 SC, 1.3 kg [77] and 3.63 $dm^3$ [78] each, are required to be able to make the power step of scenario I. For smaller power steps also less SC would be required, resulting in a smaller mass and volume. However, in the final design there is chosen to use the required number of SC for the maximum power step of scenario I.

The SOFC system is connected as shown in figure 7.1. In previous research of [5] it was decided that the configuration will consist of 36 stacks with 334 cells each. These cells have a width of 10 cm and a length of 40 cm, resulting in a cell area of 0.04 $m^2$. The 36 stacks are divided into nine modules of four stacks which are installed parallel within that module.

| Component | $I$ [A/$m^2$] | $T_{in}$ [K] | $T_{operating}$ [K] | $V_e$ [V] | $U$ | $m$ [kg] | $V$ [$m^3$] |
|---|---|---|---|---|---|---|---|
| SOFC | 2100-4200 | 900-1000 | - | - | - | 7,783 | 7.25 |
| Pre-reformer | - | - | 520 | - | - | 30 | 2 |
| Battery [69] | - | - | - | 3.7 | 50 [kWh] | 250 | 0.1 |
| SC | - | - | - | 3.3 | 65,340 [J] | 186 | 0.517 |

Table 7.2: The specifications of the SOFC system and the supportive components.

In table 7.3 the specifications of the PHE are displayed. The PHE of this table are connected as shown in figure 7.1. The heat exchanger for the warm water system and the central heating is not considered in this table since this is only one of the integration possibilities.

| Type of PHE | $L$ [m] | $\tau_{plate}$ [m] | $\tau_{channel}$ [m] | $n$ [-] | $b$ [m] | $m$ [kg] | $V$ [$m^3$] |
|---|---|---|---|---|---|---|---|
| PHE Air | 0.175 | 0.0004 | 0.0008 | 700 | 2 | 765 | 0.294 |
| PHE Anode | 0.15 | 0.0004 | 0.0008 | 125 | 2 | 120 | 0.045 |
| PHE Methanol | 0.1 | 0.004 | 0.0008 | 250 | 2 | 1560 | 0.24 |
| PHE Water | 0.1 | 0.004 | 0.0008 | 95 | 2 | 595 | 0.09 |

Table 7.3: PHE specifications in the power unit.

All masses of the components taken together the total mass of the SOFC-GT power unit is 39,158 kg, considering the power step of scenario I. For the volume of the power unit this is 73.662 $m^3$. The pipes, valves, the heat exchanger for central heating and the warm water system and the like are not taken into account. To also include these components 10% is added to the total mass and volume of the hybrid system. The total mass of the SOFC-GT power unit then becomes 43,074 kg and the volume becomes 81.028 $m^3$.

If only the power step of scenario II is required, the total mass of the SOFC-GT power unit then becomes 37,627 kg and the volume becomes 68.928 $m^3$. For only the power step of scenario III the total mass then becomes 27,884 kg and the volume becomes 46.928 $m^3$.

A Diesel-electric system, as installed in the HOV, would have a mass of 11,765 kg and a volume of 31.596 $m^3$ for the required maximum power of 2 MW. For the largest version of the system, of scenario I, that is an increase of mass by 266% and an increase of volume by 165%. Furthermore, for the version of scenario II that is an increase of mass by 219% and an increase of volume by 118% and for the scenario III version an increase of mass by 137% and an increase of volume by 49%. This shows that the increase of mass and volume of the power unit, compared to the current power unit type of the HOV, is also depending on the required power step.

### 7.3.3 | Power Unit Operation

The operation of the design of the SOFC-GT power unit, determined via the simulation model, will be explained in this section. Compared to the preliminary operation of section 4.7.1 there are some changes in the operation of the hybrid system. A schematic operation of the power unit and the power production of its components is provided in figure 7.2.

The power supply by the SOFC system is no longer constant but varies in the operation of the power unit. Using only the GT system during the power step turned out to be very inefficient compared to using as much power from the SOFC as possible. For that reason, the power supply of the SOFC is no longer constant. However, the power steps for the SOFC cannot be made in a very short amount of time considering the durability. The result is that the minimal amount of power produced by the combination of the SOFC system and GT system in stationary operation is 'Low speed and station keeping' while the maximum amount of power produced is 'Maximum speed'. It has to be noted that during stationary operation as much power as possible is produced by the SOFC so the efficiency is as high as possible.

The GT system assists the power unit to reach the power steps from all operations to any power level, which is displayed in the scenarios of chapter 6, in 15 seconds. The GT system responds to this power step by increasing the air flow and combustion of fuel in the second combustion chamber. During the slow power step of the SOFC the power output of the SOFC increases and the power output of the GT system decreases, so the SOFC takes over the power supply again. When the SOFC reaches the required power supply, the power unit again operates in stationary operation, in which the GT system still combusts the residual fuel from the SOFC in the first combustion chamber and expands the gases in the turbines so it produces power to drive the compressors and some electrical power to increase the efficiency of the hybrid system.

The SC assists the GT system during the first 15 seconds of the power step, since it takes some time to increase the power from the GT system. To make power available almost immediately, the SC provides the difference in power supply by the power unit and the power request of the naval vessel as long as the GT system is still increasing power supply. During the power step down of the GT or the SOFC the power supply does not decrease immediately to the new level, so the SC will be charged during this time with the difference in power supply by the power unit and power request of the naval vessel.

The battery assists the power unit during longer and smaller load steps, for example during the use of the low-pressure air system when the power from the GT system decreases due to a decrease in mass flow. When in stationary operation the power request decreases, the power supply by the SOFC does not immediately decrease, so the battery will be charged with the difference in power supply of the SOFC and power requested by the naval vessel.

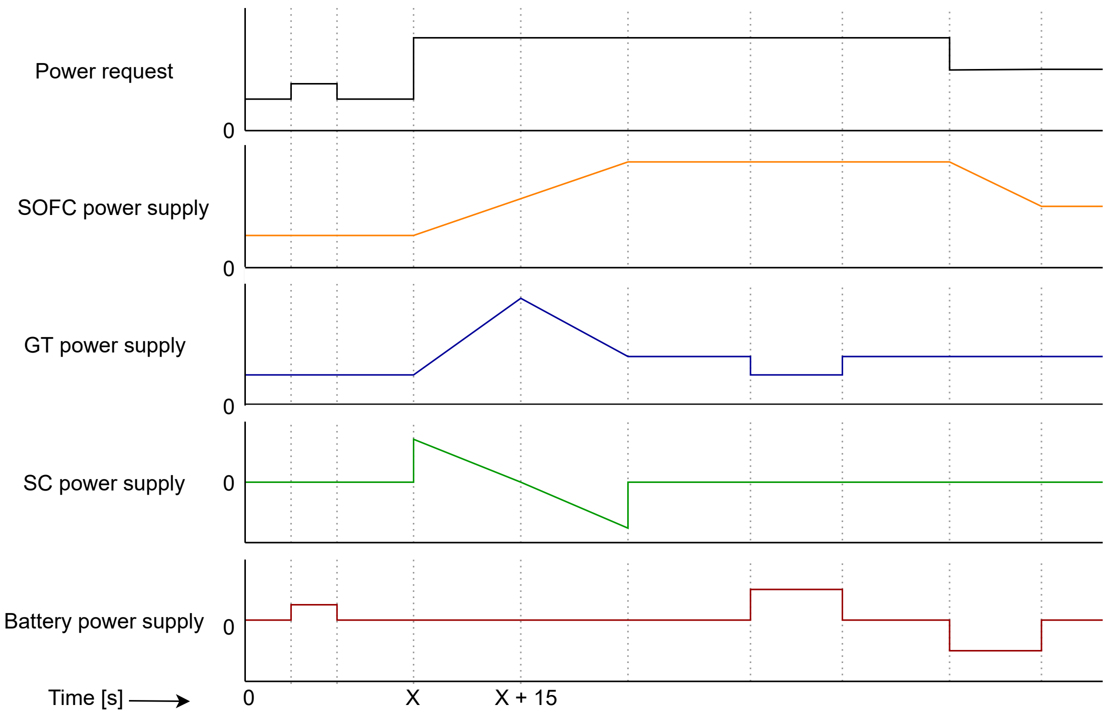


Figure 7.2: The schematic operation of the power unit.

The bypasses of the PHE are used to control the temperature of the methanol, water, and anode flow. When the energy in the exhaust gases increases due to more combustion of fuel, the bypass of the exhaust gases is used to redirect a fraction of the exhaust gases to keep amount of energy flowing through the PHE constant and therefore also the outflow temperature of the cold flow. When the cold flow through the PHE increases the fraction of the exhaust gases flowing through the PHE is increased to increase the amount of energy flowing through the PHE and keep the outflow temperature of the cold flow constant.

Lastly, the mixers for the anode and cathode are used to control the temperature of the flows by increasing or decreasing the flows leaving the SOFC and flowing into to mixers. This is still the same as in section 4.7.1, however in the operation of the power unit, described in this section and determined after the simulation, the inflow temperatures in the SOFC will vary which will lead to greater use of the control of the mixing chambers.

### System Redundancy

For the application of the SOFC-GT to a naval vessel, it is important that both systems can operate independently of each other. In that case, the vessel will be able to continue to operate at any time, perhaps to a reduced extent, but failure will not occur in the failure of either system. By applying the bypasses and mixers, both the SOFC system and the GT system can operate separately. The mixers ensure that the temperature of the inflow gases for the SOFC is maintained in the event of the turbine failure and therefore preheating through the PHE. The bypasses ensure that excessive temperatures of the flows to the SOFC system are prevented when the SOFC system fails. The gases can then flow along the PHE instead of through them so that there will be no heat transfer.

The only tight link that both systems have with each other is the compressors, which are important for both since air has to be compressed for the systems to operate. Given the large power required by the compressors to supply air for the GT system and the SOFC system, it is not possible to use one separate compressor. This would cause the maximum power of requirement 1.7 to be exceeded. However, by using several compressors it should be possible to supply at least the smallest consumer with air, the SOFC system. The GT system would then not be used because the compressors are not used. The residual fuel could possibly still be burned so the flows can be preheated with the waste heat. Another possibility would be to use a motor next to the first turbine, like in [18] described in section 2.1.1, which can provide support when the GT system is unable to compress sufficient air. It would then still be possible to partially use the GT system to burn the residual fuel to produce some power to drive the compressors. The waste heat can still be used to preheat the flows.

# 8 | Discussion

The design and simulation results of the methanol fuelled SOFC-GT power unit are based on assumptions, the simulation results from [5], system characteristics, which consist partly of estimations, which are most certainly not 100% correct, and theoretical results obtained in the literature study. Therefore, the simulation results and system characteristics obtained in this research may differ from the reality. In this chapter there is stated at what parts of the research some uncertainty is present about estimations or practicability and to what extent they detract from the results and conclusions of this study.

## 8.1 | Reviewing Assumptions

To provide a proper answer to the main research question first the assumptions made in this study have to be reviewed. When the assumptions are not correct this influences the validity of the results obtained in the previous chapters. In this section the results of reviewing the assumptions stated in section 5.3.1 will be presented, considering among other things the ideal gas law. It has to be noted that reviewing the assumptions already has been carried out during the research to ensure the validity of the study.

### 8.1.1 | Ideal Gas Law

The use of the ideal gas law in the SOFC-GT hybrid system is convenient since it simplifies the calculations in the model significantly. The validity of the assumption that the ideal gas law holds, under the circumstances defined in power unit has to be tested. The assumption of ideal gas in the pre-reformer and SOFC, at 500 K and 2 MPa, is verified by [5]. In this section the assumption of ideal gas in the GT and compressors is verified.

Using the equations below the reduced temperature and reduced pressure could be determined, respectively [61]. The results of these reduces parameters are displayed in table 8.1. The pressure in the system is 2 MPa, so this value is used to determine the reduced pressure. The temperatures in the system for calculating the reduced temperature are 1000 K and 250 K. The last of these two temperatures is used to verify the assumption of ideal gas during compression of the air, consisting of Nitrogen and Oxygen, with the results shown in the last two columns of table 8.1.

$$T_r = \frac{T}{T_{cr}} \tag{8.1.1}$$

$$p_r = \frac{p}{p_{cr}} \tag{8.1.2}$$

Using the critical parameters, the Nelson–Obert generalized compressibility chart, both provided by [61], and the data from [66] the compressibility factors of the various gases could be determined. The results are displayed in table 8.1.

For ideal gases, the value of the compressibility factor, $Z$, is 1 [61]. The results in table 8.1 show that the assumption of ideal gas for the flows in the system is a proper assumption. The values of the compressibility factor are all close to 1, so the assumption of ideal gas is valid.

| Substance | $T_{cr}$ [K] | $p_{cr}$ [MPa] | $T_r$ [-] | $p_r$ [-] | $Z_{1000K}$ | $T_r$ [-] | $Z_{250K}$ |
|---|---|---|---|---|---|---|---|
| Methanol | 513.2 | 7.95 | 1.95 | 0.25 | 0.9818 | - | - |
| Hydrogen | 33.3 | 1.30 | 30.03 | 1.54 | 1.0042 | - | - |
| Water | 647.1 | 22.06 | 1.55 | 0.09 | 0.995 | - | - |
| Carbon Monoxide | 133 | 3.50 | 7.52 | 0.57 | 1.0045 | - | - |
| Carbon Dioxide | 304.2 | 7.39 | 3.29 | 0.27 | 1.0042 | - | - |
| Methane | 191.1 | 4.64 | 5.23 | 0.43 | 1.0071 | - | - |
| Oxygen | 154.8 | 5.08 | 6.46 | 0.39 | 1.0053 | 1.61 | 0.9736 |
| Nitrogen | 126.2 | 3.39 | 7.92 | 0.59 | 1.0067 | 1.98 | 0.9857 |

Table 8.1: The critical en reduced parameters to determine the compressibility factor.

### Constant Specific Heat

When a gas is ideal then it is both thermally and calorically perfect [65], and when a gas is calorically perfect then the specific heats are constant [64]. So, with the validity of the ideal gas law also the assumption that the specific heat at constant pressure, $c_p$, is constant during a process is justified.

Furthermore, table 8.2 shows the error of calculating the specific heat at constant pressure [61]. The maximum error is for methane and has a value of 1.33%, which is small compared to the losses caused by the efficiencies of the components. Moreover, the most common substance in the system, Nitrogen, has an error of only 0.59% and the average values of the error are for all substances below 0.6%. So, it is expected that calculating the specific heat at constant pressure does not detract from the outcome of this investigation.

| Substance | Maximum error [%] | Average error [%] |
|---|---|---|
| Methanol | 0.18 | 0.08 |
| Hydrogen | 1.01 | 0.26 |
| Water | 0.53 | 0.24 |
| Carbon Monoxide | 0.89 | 0.37 |
| Carbon Dioxide | 0.67 | 0.22 |
| Methane | 1.33 | 0.57 |
| Oxygen | 1.19 | 0.28 |
| Nitrogen | 0.59 | 0.34 |

Table 8.2: The maximum and average errors of calculating the specific heat a constant pressure.

### Homogeneous Mixing

The van der Waals equation is an improvement of the ideal gas equation of state, equation 5.3.1, by including the volume occupied by the molecules and the intermolecular attraction forces [61, 79]. However, since the ideal gas law is valid, it can be concluded that the intermolecular attraction forces can be disregarded. So, the molecules will not attract each other strongly and can therefore move freely through the available space. From that can be concluded that the validity of the ideal gas law justifies the assumption of homogeneous mixing.

## 8.1.2 | Dynamic Pressure Effects

The assumption that the dynamic pressure effects can be neglected since the gases move through the system at low speeds also has to be tested. First the velocity of the gases flowing through the system has to be determined using the ideal gas law [65]. For the anode flow, which has to flow from the SOFC to the GT, the result is the following.

$$\dot{V} = \frac{\sum \dot{N} \cdot R \cdot T}{p} = 0.06 \text{ m}^3/\text{s} \tag{8.1.3}$$

The average density of the gas flow is also required to determine dynamic pressure and can be calculated as follows from the equation below. For the anode flow the result is the following.

$$\rho = \frac{\dot{V}}{\sum \dot{N} \cdot M} = 0.0019 \text{ kg/m}^3 \tag{8.1.4}$$

Using the results from the equations above the dynamic pressure can be determined via Bernoulli's law [61, 64], which is displayed below.

$$\Delta p = \frac{1}{2} \cdot \rho \cdot v^2 \tag{8.1.5}$$

Using this equation there could be determined that the velocity of the flow has to be 1450 m/s in order to obtain a pressure decrease of 0.1%. For that reason, and the validation of this assumption within the SOFC by [5], can be concluded that this assumption is valid.

### 8.1.3 | Kinetic and Potential Energies

In devices that involve shaft work, for example GT, compressors, and pumps, the kinetic and potential energy terms in the energy equation are usually very small relative to the other terms. Therefore, the assumption that the changes in kinetic and potential energies of the working fluid is reasonable. Furthermore, it is a commonly utilized simplification in the analysis of power cycles and therefore does not detract from the results of this study.[61]

### 8.1.4 | Isentropic Flow

Since the fluid flows through many devices, for example the GT, and compressor, the flow quantities vary primarily in the direction of the flow . Furthermore, there is no work and heat transfer involved in the flows between components of the hybrid system due to proper insulation. Therefore, the flow can be approximated as isentropic flow with good accuracy.[61]

## 8.2 | Reviewing Approximations

### 8.2.1 | Dimensions

The data obtained from the literature study, to determine the dimension of the SOFC-GT power unit, is case specific data, it is determined in the context of that specific study. As a result, it is probably not possible to copy this data one-on-one and use it in this research. So, the mentioned dimensions and masses of the hybrid system and its components will probably be different in reality. However, the aim of this research is not to give the best possible representation of the masses and dimensions of the power unit, but to show the performance of the system. Therefore, the use of data from other studies has limited effect on the outcome of this study.

### 8.2.2 | Efficiencies

The efficiencies of the components are estimated using the following sources [61, 63]. Since the components that would be used for this hybrid system are not known and therefore not tested, the true value of the efficiency is also not known. From that follows that the true values of the power output can deviate from the values determined using the simulation model. However, since the sources used are scientific and widely used the true value of the efficiency will probably not deviate that much. Therefore, there is expected that the results of the simulation model are valid and simulate the reality with good accuracy.

### 8.2.3 | Parameter Rating

In order to determine what concept is best suitable for modelling and optimization, rating of the concepts, on a scale of 1-3, has been used. Because this is a very subjective way of assessing, it was decided to use this scale in which the points to be distributed are very close to each other. As a result, the focus is not on how well the concept scores, but more on which concept scores best. In this way, an attempt has been made to make the concept as objective as possible. The result also shows that one concept scores considerably better than the others. Hence, it can be said that this does not detract from the results of this study.

### 8.2.4 | Power Assistance

The simulation of the battery and SC was outside the scope of this investigation and is therefore not very accurate. This also holds for the efficiency of the SC. Therefore, the results of power assistance in the simulation model will deviate from the reality. However, the power assistance by the battery and SC is not the main part of this investigation and is also only a small part of the simulation. For those reasons, the general results of this investigation can be considered as representative.

### 8.2.5 | Controlling Manually

The control of the GT and SOFC, and the other components is done manually during the simulation of the hybrid system. The response time of the GT system is based on [14, 15] and the response time of the SOFC is based on reliability considerations, slow increase of the power production increases lifetime. With this there is attempted to present a realistic and well-founded picture of a fast and responsible response time. Furthermore, the influence of controlling the hybrid system manually is visible in the results. However, the characteristics and dynamic behaviour of the SOFC-GT power unit during power steps are clearly visible. Using controllers to operate the hybrid system will improve the results and will show the exact theoretical operation of the power unit. However, since the characteristics and dynamic behaviour are clearly visible, controlling the power unit manually does not detract from the outcome of this investigation.

## 8.3 | Reviewing Systems Engineering Process

The application of the SE process does not detract from the thermodynamic results of this investigation but was important for the design of the SOFC-GT power unit. For that reason, it is also important to review the application of the SE process. The stage of project 'Replacement Support Vessels' prevented the use of SE from being applied correctly, since the requirements were still adjustable. Because of this flexibility certain decisions made in the design process are still adjustable, such as the integration possibilities. In correct application of SE the integration possibilities, discussed in section 4.6, become requirements when they are approved by the client. In correct application of the process and a more advanced stage of the project, the final design of the system might look differently. However, the designed power unit is not to be built yet, so in the building process SE can be reapplied. In the current investigation, where the performance of the power unit is only demonstrated via simulation, the SE process as it is applied does not detract from the outcome.

## 8.4 | Completion

In general, the assumptions and approximations made in the investigation turned out to be valid and reasonable. They are based on other investigations, information found in the literature or are conservative to prevent an unrealistic outcome. Furthermore, in this chapter the validity of the assumptions is proven using widely accepted scientific information. Finally, the applied SE process is used properly as far as this investigation made that possible. Everything discussed in this chapter taken together the results of this investigation, the simulation of the SOFC-GT power unit and the final design of that power unit, can be considered as representative.

# 9 | Conclusion

In this chapter the final conclusions of this investigations will be presented and discussed. This considers the performance of the hybrid system, the applicability and integration as well as system structure. The conclusion made in this chapter are based on the results of the simulation, chapter 6 and appendix F, the verification, validation and the final design of the SOFC-GT power unit in chapter 7.

## 9.1 | Performance

In general, it can be said that a methanol fuelled SOFC-GT power unit can meet the requirements of power supply, fast response time, and high efficiency for the operational profile provided by the RNLN in table 3.1. The response time to power steps is 15 seconds and the efficiency during stationary operation, at 2 MPa, can reach up to 81%, with a minimum of 35% during the largest load step. Compared to the SOFC system the response time is decreased from 500 seconds to 15 seconds and the efficiency is increased from 25% to 81%. The high efficiency is among other things obtained by the combustion of the residual fuels in the AOG. So, the use of a GT system positively influences the performance of the power unit.
By using supportive components for peak-shaving and dynamic support the response time of the system is even further increased, because due to the SC power is available almost immediately. The battery can assist during smaller power steps preventing the GT system from making unnecessary and many power steps. The final configuration of the power unit has a mass of 43 tons and a volume of 81 $m^3$.

Besides, the power unit can also meet other requirements for naval applicability. This concerns the maximum temperatures in the system, 1123 K for the SOFC and 1772 K for the GT, which are not exceeded as well as the maximum allowable temperature gradient of 10 K/cm in the SOFC. Furthermore, there is sufficient waste heat available to provide the power unit with the heat required to pre-heat the methanol, water, air, and anode flows in the system. Moreover, the results show that the maximum power required by the water pump and methanol pump is well below the maximum power of 76 kW that can be provided by the ships electrical system.

Also, the temperatures of the gases leaving the turbines do not go below the minimum temperature, so no water droplets are formed, which is suitable for the maintenance of the system. At last, due to the separate air and fuel supply to the GT system it is possible to operate the SOFC as constant as possible. The GT system will make the power steps when the naval vessel requires it. However, considering the efficiency it is more convenient to increase the power output of the SOFC. Considering the durability of the SOFC this power step cannot be made fast, but the GT system is available to compensate for this.

## 9.2 | Applicability and Integration

The validation process has shown that the stakeholders are satisfied with the design of the system and its performance. Mainly the high efficiency and the amount of residual heat that can be used elsewhere were seen as positive. The concerns expressed relate only to the implementation of the system, since the SOFC is a new development that has not yet been extensively tested and developed for naval applicability, and therefore do not affect the value of the designed system in this investigation. It can therefore be concluded that the power unit meets the mission and expectations of the RNLN.

The results of this investigation also show that the power unit can be properly integrated with the naval vessel. Just 0.04% of the maximum pump power is used to supply the power unit with water, so there can be assumed that enough power is left for the water pump to supply the drinking water system and the warm water system with pressurized water. This cannot be said with certainty because it is not known what the maximum flow rate of the drinking water system is. In addition, the use of air from the power unit for the low-pressure air system is possible because it has only a very small influence on the hybrid system. There is also enough waste heat left to provide the warm water system with heat, after which at least enough heat remains to supply the central heating with a water flow of 1.2 $m^3/h$. Finally, the power unit can supply any power with a high efficiency through the SOFC, which also provides the opportunity to make the support vessel part of mircogrids.
The validation process also has shown that the power unit may be even more integrated with the vessel by supplying water from the exhaust gases, at least 200 liters per hour, if this proves to be responsible.

## 9.3 | System Structure

Looking at the power step that the GT must take in order to have power available as soon as possible, it can be said that there are two different choices when it comes to the execution of the SOFC-GT power unit. In the event that large power steps need to be available as soon as possible, the GT system within the power unit becomes so large and heavy that it can be said that the SOFC system is used as a supporting component to increase efficiency. In the other case, the GT is the supporting component and serves to provide only for the rapid bridging of small power steps.
Depending on the profile of the naval vessel, one version or the other can be chosen. For ships operating in the higher spectrum of violence, for example the Luchtverdedigings- en Commando Fregat (LCF), it can be chosen to add a SOFC as a supporting part. This increases efficiency and allows the ship to better meet the requirements when it comes to operational range. For ships such as the support vessels, it can be said that a smaller GT system will be sufficient to quickly make small power steps and thus make the ship more operationally deployable.

## 9.4 | Strongly Coupled Processes

The results of the investigation also have shown that the coupling between different temperatures and processes in the system can be very strong. A higher methanol temperature directly influences the pressure in the pre-reformer which compensates for this by increasing the methanol inflow into the pre-reformer. This again influences the utilization ratio in the SOFC, the Hydrogen fraction in the AOG, and the power output of both turbines.
This also holds for the inflow temperature of the gases for the SOFC. A higher inflow temperature increases the power output of the SOFC and decreases the temperature gradients inside the SOFC. The temperature of the exhaust gases influences the fuel consumption via the PHE and therefore also the efficiency of the system. The last example is the thermal inertia of the PHE strongly influences the operation of the power unit since the temperature of the pre-heating lags the required temperature of the flows, so that the mixing chambers have to allow a larger fraction leaving the SOFC to flow back. This also holds for pre-heating the air for the GT system, due to the thermal inertia of the PHE the fuel consumption is larger and the efficiency is lower in the beginning of the power step.

## 9.5 | Operating Pressure

A comparison with a single stage version of the SOFC-GT power unit used in this investigation showed that a higher operating pressure increases the efficiency of the system. This is also confirmed by the literature [72]. The final design of this investigation operates at a pressure of 2 MPa and can reach efficiencies up to 81%, with a minimum efficiency of 73% for 'Low speed and station keeping' operation. In general, other SOFC-GT configurations found in the literature, operating at a pressure of 1 MPa or lower, have an efficiency between 45% and 70%. The single stage version of the simulated configuration confirms, via a simulation, that operating at a pressure of 1 MPa indeed decreases the efficiency to around 71% for 'Maximum speed' operation. The efficiencies for 'Low speed and station keeping', 'Operations/Economic transit' and 'High speed transit' are decreased to 66%, 68% and 69%, respectively.

# 10 | Recommendations

The investigation also has created valuable content to be used in further research. The created simulation model is modular in nature and can be used in these follow-up investigations. In this chapter of the report the recommendations for follow-up research and the importance considering the results of this investigation will be discussed.

## 10.1 | System Controlling

In the simulation of the SOFC-GT power unit several parameters had to be controlled manually. This considers the inflow of the anode and cathode mixer, the molar air flow to the GT and air system, the molar fuel flow to the combustion chambers, the inflow temperature of the cathode and anode of the SOFC, the bypass ratios of the PHE and the current density for the SOFC. Since all components in the system are closely coupled changing one of these parameters influences the entire operation of the system. Therefore, it is difficult to control the system manually and controllers are required to optimize the operation of the SOFC-GT power unit. For follow-up research it is advised to investigate the possibility to equip the hybrid system with a control system.

In case of the power unit of this investigation, which is design for naval applicability, it is important to consider the complexity of the control system. From DMI there is the demand for naval vessels that are as reliable and simple as possible, which makes maintenance a lot easier. A complex controlling system can cause problems with maintenance because required knowledge may not be present with the crew or the maintenance team.

## 10.2 | SOFC Maturing

Since the SOFC technology is still in development the lifetime, durability, reliability, compactness are uncertain factors in the operation of the SOFC, and therefore also in the operation of hybrid systems. As the SOFC technology matures, it will probably become clear in the future if and how these factors will influence the system. Because of the uncertainty the following two recommendations are discussed in this section and consider the optimal SOFC operation and the reliability.

### 10.2.1 | Optimal SOFC Operation

In the simulation of the SOFC-GT power unit there is tried, to the best of knowledge, to operate the SOFC in optimal conditions. Optimal operation of the SOFC will increase the efficiency, lifespan, and reliability and will reduce maintenance. Furthermore, the safety will be increased since the failure modes can be avoided. However, the optimal operation of the SOFC is not exactly known, and literature does not have an unequivocal answer to this either. Therefore, there is recommended to investigate this in follow-up research. It is important that this follow-up research also considers the possibility to increase and decrease the power supply by the SOFC in a responsible manner, considering the lifespan and reliability. In addition, it has to be investigated what the minimum power is that the SOFC can deliver when it operates idle and whether the SOFC can handle an operating pressure of 2 MPa. Finally, it is not entirely clear what happens with the methanation reactions inside the pre-reformer and the PHE when the temperature is well above 520 K, approximately 800 K. This is also something that has to be investigated in future research of the optimal SOFC operation.

### 10.2.2 | Reliability

In line with optimal operation of the SOFC is the reliability of the SOFC system. Literature states that the GT system have proven its reliability and will therefore not negatively influence the power unit. However, the reliability of the SOFC is not known and therefore no definitive answer can be given about the reliability of the SOFC-GT power unit, despite this research has shown that system redundancy can be applied. Since the reliability of the power unit is very important for naval applicability there is recommended to investigate the reliability of the SOFC. This also concerns the effect of a sudden shutdown of the SOFC system in the event of an emergency and the effect of operating the SOFC with filtered salt air.

## 10.3 | Hydrogen-Methanol Mixture

The fuels used in this investigation, a mixture of methanol and Hydrogen, are not widely used in GT application and therefore there is some uncertainty about the possibility to use these fuels together in the combustion chamber of the GT system. In practice methanol is used as fuel in GT systems, see section 2.1.4, and Hydrogen can be combined with other fuels. However, the practical use of the Hydrogen-methanol is, to the best of knowledge, not known. For that reason, there is recommended to investigate the possibility to use a combination of Hydrogen and methanol in a GT.

## 10.4 | Response Time Heat Exchangers

Due to the mixing chambers and the bypasses the influence of the response time of the PHE has dramatically decreased. However, the PHE still have influence since the thermal inertia makes it difficult to control the bypasses of the PHE and increases the time that extra fuel is required to make a power step. Because of this the temperature of the methanol and water can become excessive or insufficient and the efficiency of the system is lower for a longer period of time, respectively. Therefore, improving the response time of the PHE is a recommendation for follow-up research.

## 10.5 | Water from Exhaust Gases

Using methanol as fuel does provide possibilities for the water supply to be extracted from the exhaust gases because of the clean combustion of methanol. Extracting water from the exhaust gases for consumption purposes (drinking water) or sanitary purposes (freshwater) may further increase efficiency and could be a replacement for the complex freshwater production system. The simulation has shown that a least 200 liters of water per hour is net available in the exhaust gases, which is sufficient according to the stakeholders. However, research will have to show whether this is responsible and is therefore recommended for follow-up research.

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# A | Background Information

## A.1 | Replacement Project

This section will provide more information and context about the project 'Replacement Support Vessel', what this research is derived from and wants to contribute to. Furthermore, more information will be provided about the current fleet of support vessels and the replacement capacity.

### A.1.1 | Current Fleet of Support Vessels

#### Hydrographic Survey Vessels

The main task of the two hydrographic survey vessels is to do hydrographic survey work which means mapping changes in the waterways and the seabed. The vessels are efficient in use, operate with a relatively small crew, and are equipped with advanced recording systems. Specialized software combines GPS and sonar data to create detailed 3D maps which the Hydrographic Service uses to make sea charts. The RNLN does this hydrographic survey work in the waters of the entire Dutch continental shelf and around the Netherlands Antilles and Aruba. In order to be able to operate in shallow waters, both ships have access to a recording sloop which are equipped with almost the same sensors as the vessels.

| | |
|---|---|
| Water displacement: | 1,875 tons |
| Length: | 75.0 meters |
| Width: | 13.1 meters |
| Draft: | 4.0 meters |
| Propulsion [80]: | 3x Caterpillar C32Tta (diesel-electric) |
| Power: | 1,564 kW total |
| Speed: | 12 knots |
| Crew: | 18 men |

Table A.1: The specifications of the hydrographic survey vessels


Figure A.1: A picture of Zr.Ms. Luymes, one of the two hydrographic survey vessels.

### Multi-purpose Logistics Support Vessel

The vessel Zr.Ms. Pelikaan supports the deployment of the MoD in the Caribbean during operations and exercises of the Marine Corps and the coastguard of the Netherlands Antilles and Aruba. The vessel will also provide assistance to the RNLN station ship in the Caribbean which concerns law enforcement, coast guard operations and the fight against drugs. It is also used at the request of civil authorities, for example for emergency aid. The vessel is equipped with a crane to place containers in the cargo hold.

| | |
|---|---|
| Water displacement: | 1,150 tons |
| Length: | 65.4 meters |
| Width: | 13.2 meters |
| Draft: | 4.0 meters |
| Propulsion: | 2 × Caterpillar 3516 BTA diesel engine |
| Power: | 1491 kW total |
| Speed: | 14.5 knots |
| Crew: | 13 men |
| Accommodation for: | 77 passengers |

Table A.2: The specifications of the multi-purpose logistics support vessel Zr.Ms. Pelikaan


Figure A.2: A picture of multi-purpose logistics support vessel Zr.Ms. Pelikaan.

### Submarine Support Vessel

The submarine support vessel Zr.Ms. Mercuur accompanies submarines on exercise and functions, among other things, as a sailing maintenance shed for torpedoes. After a training torpedo has been launched and surfaced at the end of its orbit, the Mercuur crew takes it out of the water and prepares it for the next launch. The vessel also acts as a target for the submarines, firing not at but under the ship. The vessel itself also has a torpedo launch tube for testing torpedoes.

| | |
|---|---|
| Water displacement: | 1,400 tons |
| Length: | 64.8 meters |
| Width: | 12.0 meters |
| Draft: | 4.3 meters |
| Propulsion: | 2× MAN 6L-20/27 diesels |
| Power: | 1217 kW total |
| Speed: | 14 knots |
| Crew: | 39 men |
| Armament: | 1 underwater launch tube for Mark 48 torpedoes |

Table A.3: The specifications of the submarine support vessel Zr.Ms. Mercuur.


Figure A.3: A picture of submarine support vessel Zr.Ms. Mercuur

### Diving Support Vessels

The mining service of the MoD has 5 diving vessels: Argus, Cerberus, Hydra, Nautilus and dive training vessel Soemba. The divers of the Diving and Dismantling Group in particular use them as a platform for their work. Among other things, the divers clear explosives in Dutch coastal and inland waters and perform underwater maintenance and repairs on naval vessels. The diving vessels all have modern means of communication and a recompression tank for several people. The Hydra and Nautilus have been extended by 10 meters and are equipped with a bow thruster. As a result, they can also accommodate 22 students from diving courses. The Soemba was built for the Royal Netherlands Army (RNLA) diving training but has entered the service of the navy when the RNLA and RNLN diving courses merged.

| | Argus/Cerberus | Hydra/Nautilus | Soemba |
|---|---|---|---|
| Water displacement: | 222.8 tons | 340 tons | 410 tons |
| Length: | 27.94 meters | 38.47 meters | 42 meters |
| Width: | 8.76 meters | 8.6 meters | 9.50 meters |
| Draft: | 1.50 meters | 1.50 meters | 1.50 meters |
| Propulsion: | 2x Volvo Penta TADM 122A | 2x Volvo | 2x DAF 1160 DKV |
| Power [81]: | 2x 280 kW | 2x 280 kW | 2x 175 kW |
| Speed: | 10.5 knots | 10.5 knots | 8 knots |
| Crew: | 6 men | 8 men | 4 men |
| Passengers: | - | 22 passengers | 17 passengers |

Table A.4: The specifications of the diving support vessels.


Figure A.4: A picture of Zr.Ms. Nautilus, one of the five diving support vessels.

### Naval Education Vessel

The Van Kinsbergen is used to provide future naval officers with practical nautical skills as supplement to theory and (bridge) simulator lessons. These skills are necessary to be able to work as an officer on the bridge of a RNLN ship. In addition to the normal navigation bridge, the vessel has a fully equipped secondary training bridge which makes it suitable for practicing safe mooring and mooring manoeuvers. Besides the education vessel is equipped with a Rigid Hull Inflatable Boat (RHIB).
The vessel sails approximately 200 days per year and is also deployed during the annual sailing period, a longer training voyage of about 5 weeks, together with a flotilla mine hunters. The area of operation of the naval training vessel is the North Sea as far as Southern Norway, the Baltic Sea west of Bornholm, the English Channel and the coastal waters around Ireland and Great Britain.

| | |
|---|---|
| Water displacement: | 670 tons |
| Length: | 41.5 meters |
| Width: | 8.6 meters |
| Draft: | 3.3 meters |
| Propulsion [82]: | 2x Caterpillar 3508B DI-TA ELEC |
| Power [82]: | 2x 578 kW |
| Speed: | 24 knots |
| Crew: | 2x5 men (5 civilians, 5 military) |
| Students: | 16 men |

Table A.5: The specifications of the naval education vessel Van Kinsbergen.


Figure A.5: A picture of naval education vessel Van Kinsbergen.

## A.1.2 | Replacement Support Vessels

The ten support vessels will reach their end-of-life in phases between 2023 and 2034, as already briefly mentioned in section 1.1.4. In May 2020, the A-letter of the project "*Replacement of Support Vessels CZSK*" already announced the intended replacement of this capacity. In this section the content of this letter will be discussed in more detail to provide context of the replacement project.[83]

The project is part of the investment program of the "*Defensienota 2018 – Investeren in onze mensen, slagkracht en zichtbaarheid*" and the Defense Projects Overview. The support vessels provide with their specific tasks a contribution to the 'remaining safe' of the Kingdom of the Netherlands and to the 'safe connection' of the supply and removal lines from the Netherlands. Because it concerns vessels with comparable properties and in order to be able to utilize economies of scale, the replacement of these vessels is considered as one project and involves an investment between the €250 million and €1 billion.

DMO and CZSK want the support vessels to be built 'Commercial of the Shelf, unless' with almost exclusively civil building standards and only military additions where inevitable. To optimize engineering and maintenance, family design, as already mentioned in section 1.1.4, is preferred over specific replacements per existing vessel type. This is possible due to equivalent requirements in terms of seaworthiness, maneuverability, and control [6]. In the design this primarily concerns the construction method of the hull, the layout of the vessel and all generic systems. This approach may provide economies of scale for the closing acquisition contracts, as well as operating benefits in the field of, among others training and Integrated Logistic Support (ILS). The support vessels will be designed for a lifespan of 30 years, as all vessel of the RNLN, during which a Mid-life Update (MLU) is performed [6].

Currently, the process is in phase B, in which more concrete thought about design and construction is being carried out by the DMO and CZSK itself. There will be further investigated how the replacement capacity can be acquired efficiently and effectively and the acquisition strategy will be determined.

What already has been established is that the design of the replacement support vessels will be based on the layout of the HOV, the most recent to come into service. The vessels will be delivered with a fully electric propulsion and distribution system, which may be fuelled, in case of seagoing support vessels, with a methanol ICE to implement the DEOS [5, 56]. Since both, the electrical system, and the methanol containment- and supply-system will be present, this also provides the opportunity of implementing the SOFC-GT power unit during the (MLU).

### A.1.3 | Replacement Capacity

The capacity of the replacement support vessels will largely fulfil the same needs as the existing capacity as described in section A.1.1. As a result, the target and the concept of operations hardly differ from the current fleet. The support vessels are usually deployed independently, regularly to support civil authorities, but where appropriate also in an (inter)national context. This section provides an overview of the principal design characteristics, specific tasks that must be performed by the replacement capability and the operational profile.

The principal design characteristics of the seagoing support vessels, as established by the DMO and CZSK, are shown in figure A.6 and table A.6. This will already give a small overview of the general requirements for the support vessels and the power unit. The seagoing support vessels will provide training, submarine support, hydrography functions, and Caribbean support which will be explained more extensive in the next paragraphs [6].

Figure A.6: Artist impression of the principal design characteristics of the seagoing support vessels.[2]

| Parameter | Value |
|---|---|
| High speed transit | 12 knots |
| Maximum speed | 15 knots |
| Installed power | 5000 kW |
| Range at transit speed | 5000 Nautical Miles |
| Displacement | 2400 tons |
| Payload | 800 tons |
| Design life | 30 years |
| Autonomous operation | 14 days |
| Operational Days | 200 days per year |

Table A.6: Principal design characteristics of the seagoing support vessels [6]

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The core task of the naval education vessel is to support the practical part of the training courses for junior naval officers and non-commissioned officers, which includes practicing with propulsion, navigation equipment and deck systems. The replacement capacity will be larger than the current naval education vessel, so it will have better characteristics for sailing on the North Sea and better meets the training needs since there will be more room for students.
The replacement capacity of the submarine support vessel will be used to support the readiness process of submarines. It will function as a target, safety platform and torpedo recovery unit, take on board and maintain torpedoes. In case of calamities with a submarine, the vessel must be able to assist in a rescue operation, which includes underwater communication and the ability to accommodate a submarine crew after a rescue operation has been carried out. In addition, the vessel has to be able to be used for various civil-military tasks, as a diving platform or for scientific research.

The replacement capacity of the HOV will have the ability to continue the tasks of hydrography, compiling and updating sea charts, in the Dutch part of the North Sea and in the Caribbean. In this way, the MoD contributes to safe navigation on the maritime access routes. Proper knowledge of the maritime environment is also important in deployment areas to be able to deploy military units effectively.

The primary task of the support vessel in the Caribbean is to transport equipment and personnel between the islands. In addition, the replacement capacity will have functions for Humanitarian Assistance and Disaster Relief, support of diving operations and training, and for limited hydrographic tasks in the Caribbean. There is also a need for a modest increase in transport capacity in the context of providing emergency aid.

The diving vessels act as a diving platform for the purpose of clearing explosives in coastal and inland waters, supporting civil authorities, conducting underwater maintenance on naval vessels and diving training. The replacement capacity will have the ability to perform the same tasks but is not part of the family formation of seagoing support vessels. They will have their own family formation in the diving support vessels [2].

## A.2 | SOFC System

In this section the working principles and governing equations of the components of the methanol fuelled SOFC system will be explained, which considers the pre-reformer and SOFC. The details of the SOFC and pre-reformer are not within the scope of this investigation, however it is found important that the basic principles are known.

### A.2.1 | Pre-reformer

Before the methanol can be used in the SOFC it is reformed, converted into a hydrogen rich mixture, which can be done within the SOFC or in an external pre-reformer, which is a slender, tubular reaction vessel. These two types of reforming are called Internal Reforming (IR) and External Reforming (ER) respectively. In this methanol reforming process, a series of reactions can occur by combining the flows of methanol and steam at a certain temperature. In this research a pre-reformer will be used, as will be explained in section 4.1, to enable these reforming reactions given below.[5]

$$\text{MSR:} \quad CH_3OH + H_2O \rightleftharpoons CO_2 + 3\,H_2 \qquad \bar{h}_r^\circ = +49.7 \;\; \text{kJ/mol}$$

$$\text{MDR:} \quad CH_3OH \rightleftharpoons CO + 2\,H_2 \qquad \bar{h}_r^\circ = +90.7 \;\; \text{kJ/mol}$$

$$\text{WGS:} \quad CO + H_2O \rightleftharpoons CO_2 + H_2 \qquad \bar{h}_r^\circ = \text{-}41.2 \;\; \text{kJ/mol}$$

The first two reforming reactions are endothermic while the third reforming reaction is exothermic. However, as can be derived from the reaction equations above, MSR is the superposition of MDR and WGS. From that can be concluded that the overall nature of the reforming process is endothermic.[5]

In the reforming process also some methanation reactions can occur, which are unfavourable due to their exothermic nature and the risk of overheating the pre-reformer. However, research has concluded that these methanation reactions can almost entirely be avoided when the pre-reformer is operated below 520 K [5]. For completeness also these reactions will be considered in this research and are therefore mentioned below.

$$\text{MCMO:} \quad CO + 3\,H_2 \rightleftharpoons CH_4 + H_2O \qquad \bar{h}_r^\circ = \text{-}206 \;\; \text{kJ/mol}$$

$$\text{MCDO:} \quad CO_2 + 4\,H_2 \rightleftharpoons CH_4 + 2\,H_2O \qquad \bar{h}_r^\circ = \text{-}164 \;\; \text{kJ/mol}$$

### A.2.2 | Solid Oxide Fuel Cell

The SOFC consist of four main components, see also figure A.7: the anode, cathode, solid electrolyte, and an electrical conductor. The operating temperature of the cell is between 650 °C and 1100 °C. This high temperature enables the reactions without the use of catalysts.

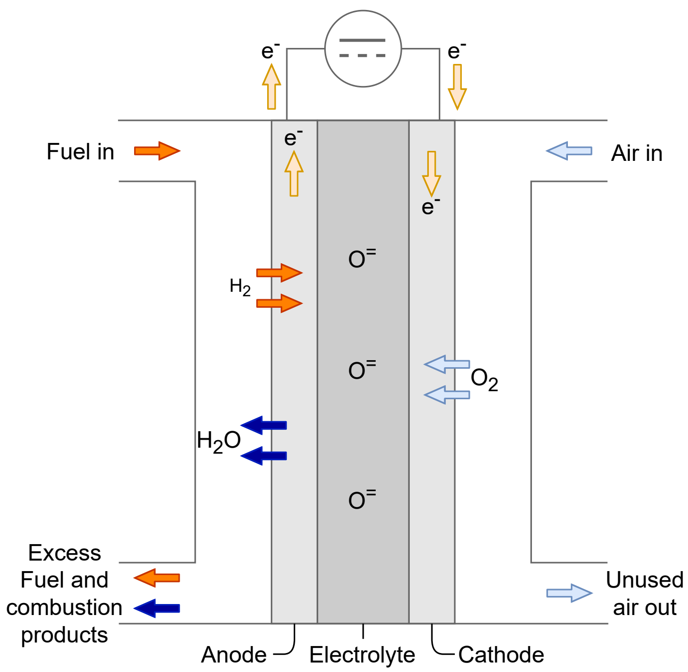


Figure A.7: The components and general working principle of the SOFC including the chemicals involved.

The working principle, as will be explained in this section [5], is also made visible in figure A.7. Compressed air, $O_2$ and $N_2$, enters at the cathode side of the SOFC, where the following reaction occurs.

$$O_2 + 4\,e^- \longrightarrow 2\,O^{2-}$$

The exhaust product that leaves the cathode is unused air. The $O^{2-}$ ions travel through the electrolyte, a sort of barrier between the anode and the cathode that inhibits electrons ($e^-$) to pass through, to the anode. There also the reaction products leaving the pre-reformer enter the SOFC and the following reactions with $H_2$, $CO$, and $O^{2-}$ occur.

$$H_2 + O^{2-} \longrightarrow H_2O + 2\,e^-$$

$$CO + O^{2-} \longrightarrow CO_2 + 2\,e^-$$

The exhaust products that leave the anode are mostly $H_2O$, $CO_2$, and the residual $H_2$ fuel. Other possible exhaust gases are $CO$, $CH_3OH$ and $CH_4$. The electrons that are separated from the $O^{2-}$ cannot pas trough the electrolyte and therefore have to pas through the electrical conductor to return to the cathode. In this way an electric current is created which is able to provide power to the consumers.

The MDR, discussed in section A.2.1, can be largely prevented when sufficient water is added to the pre-reformer. The water that does not react in the pre-reformer flows through the anode and enables WGS, so the second reaction at the anode, $CO + O^{2-} \longrightarrow CO_2 + 2\,e^-$, in reality hardly occurs.[5]

### Cell Temperature

The heat flows that contribute to the operating temperature of the SOFC and the temperature of the outflow gases are made visible in figure A.8.
The inflow gases, at both anode and cathode, are heated to certain temperatures in the operating temperature range before entering the SOFC. Inside the gas channels of the cell the convective heat flow, in which the gases participate, and radiative heat flow make their contribution to the temperature. The heat created in the electrolyte is caused by the reversible losses, increase of entropy, and irreversible losses, which are the activation losses, ohmic losses and concentration losses. The ohmic losses are caused by the resistance of the Oxygen ions ($O^{2-}$) passing trough the electrolyte. The concentration losses are caused by the distribution of positive and negative ions at the surface of the electrolyte hindering the process in the cell.[5]

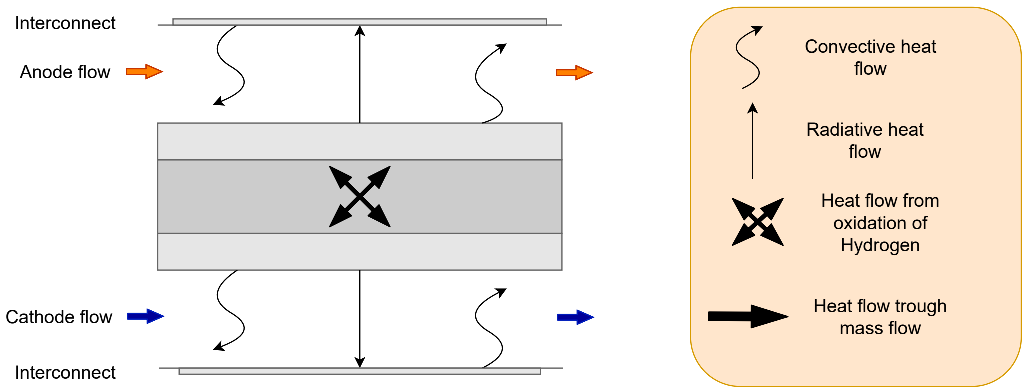


Figure A.8: An overview of the configuration of a single cell, gas flows and the different heat flows inside the cell. Adapted from [5].

## A.3 | Configurations

Hybrid SOFC-based power units are a much-investigated subjects when it comes to improvement of efficiency resulting in many possible configurations found in the literature. In this section an overview of the reviewed configurations will be provided to gain insight in the possibilities for these hybrid power units. A distinction has been made between the configurations of methane and methanol fuelled power units. The methane fuelled hybrid systems are used as inspiration for the possible SOFC-GT configurations discussed in chapter 4 while the methanol fuelled power units show what already has been investigated.

Before discussing the different configurations, it is important to know the difference between direct and indirect coupling since this will be mentioned often. In figure A.9 the difference is displayed in an example.

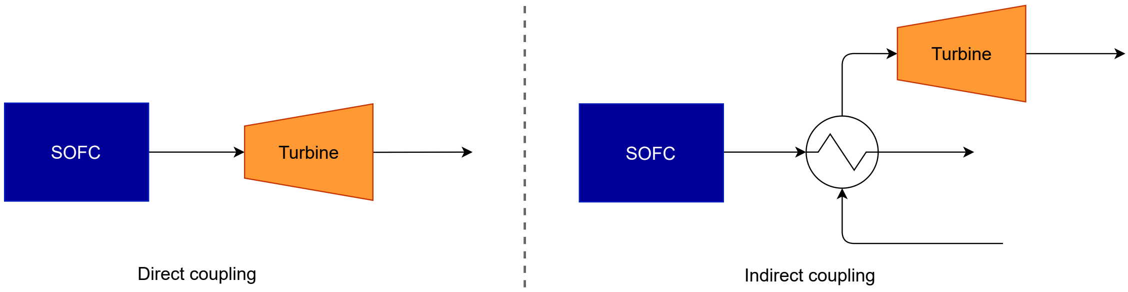


Figure A.9: Schematic view of directly and indirectly coupled components.

### A.3.1 | Methane Fuelled

The most simple configurations for the hybrid power units consist of a SOFC with internal reformers and a single shaft connected compressor and GT [59], see figure A.10. Variations on this simple configuration is using an external reformer [3], a segregated compressor and GT or a combination of a single shaft connected compressor and GT with an extra compressor for the fuel flow. In this configuration the remaining fuel leaving the SOFC is combusted and the flue gas is expanded through the turbine to produce power, so the SOFC is directly coupled to the GT. The fuel and steam used in this configuration are compressed by pumps which are not mentioned in the figure as well as heating the water to steam.

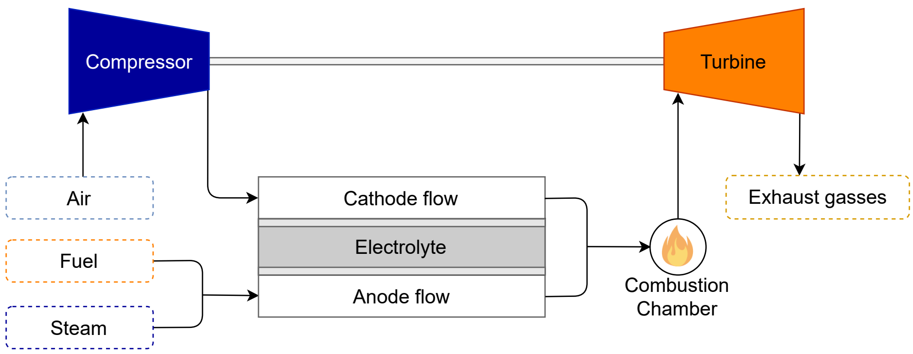


Figure A.10: Schematic view of the simple SOFC-GT hybrid system.

Since the efficiency of the simple SOFC-GT power unit is not extremely high configurations variations are investigated using recirculation. Outflow gases form the anode and cathode are reused to increase the temperature of the inlet gases without external heating. The inlet gases for the anode are mixed with the outflow gases of the anode before being used in the SOFC. The same principle holds for the inlet and outflow gases of the cathode. This recirculation can be done using high-temperature blowers, as is done in many investigations, but ejectors are more reliable and low cost in maintenance.[84]

To increase the efficiency any further, more complex configurations, called a Combined Cooling, Heating and Power system (CCHP), are investigated in the literature. One of those configurations consist of a supercritical $CO_2$ ($SCO_2$) Brayton cycle, transcritical $CO_2$ ($TCO_2$) Brayton cycle, Organic Rankine Cycle (ORC), SOFC-GT hybrid system and Liquefied Natural Gas (LNG) cold energy utilization. The cycles in this configuration produce electricity and are connected to each other by the transfer of heat via HE, so called indirectly coupled setup. The waste heat from this system is used for heating and the LNG is utilized in the SOFC-GT, for the air conditioning and to produce ice.[85]

A more simple version of the configuration discussed in the previous paragraph is the SOFC-$SCO_2$ Brayton cycle Hybrid System (SSHS). In this configuration the SOFC and $SCO_2$ Brayton cycle are indirectly coupled and the hot gases leaving the SOFC are used to heat the $SCO_2$ and pre-heat the inlet flows for the cell. Variations on this type of configuration contain recirculation of the outflow gases.[86]

Another configuration is the so called SOFC-GT-VARS-ORC in which all components are indirectly coupled. In basis this system is a Brayton cycle with intercooling and reheating. Air is pressurized in the Low-Pressure Compressor (LPC) and the heat from the intercooling is used in the Vapour Absorption Refrigeration System (VARS) to produce pure ammonia vapour ($NH_3$), which is used as refrigerant to produced cold. The cooled air from the intercooling is again pressurized in the High-Pressure Compressor (HPC) before it enters the SOFC. A third compressor is used to pressurize the fuel. The gases leaving the combustion chamber are expanded in the High-Pressure Turbine (HPT), reheated, and expanded in the Low-Pressure Turbine (LPT). The waste heat from the GT is used in the ORC and to pre-heat the inlet gases for the SOFC.[87]

The simpler version of the configuration discussed in the previous paragraph consist of only the SOFC-GT-VARS without intercooling and reheating. In this configuration the waste heat from the GT is used to pre-heat the inlet gases and for the production of pure ammonia vapour. Also, before entering the combustion chamber the outflow gases of the SOFC are further pressurized with a second compressor. Moreover, the combustion chamber has an additional air flow, provided by an extra compressor, and fuel flow to provide extra mass flow to the GT for extra power supply.[88]

There are also studies that were not only aimed at improving the efficiency but also the performance of the SOFC-GT power unit. In one of those configurations a module of Supercapacitors (SC) are included to respond to fast disturbances or load variations [20].
A second option to improve the performance is using a Generator/Motor (G/M) and a battery as energy buffer. In this configuration the combustion chamber has an additional fuel flow to provide extra power when required and allowing the SOFC to operate at a relatively constant load condition. The G/M can assist as motor when the compressor does not have enough turbine power for air delivery. Because of the step-up and step-down load variations the motoring mode operation of the G/M can also be used to absorb the excessive power during load step-down transients, which reduces the battery requirements.[18]

A totally different configuration, specifically designed for maritime applications, uses an Internal Combustion Engine (ICE) in combination with a pre-reformer and SOFC system. In this system the AOG from the SOFC, air, and fuel are combusted in the ICE. Before entering the ICE the AOG has to be cooled, which is done with a water cooler and by using the heat to pre-heat the water and fuel for the pre-reformer. The waste heat of the ICE is also used for pre-heating the water for the pre-reformer, while the waste heat from the cathode outflow is used to pre-heat the air for the cathode.[14]

### A.3.2 | Methanol Fuelled

Unlike methane fuelled hybrid systems, methanol fuelled SOFC-GT have been little researched. Therefore, there are only two configurations, both CCHP, that will be discussed in this section of the report.

The first configuration consists of a solar collector driven methanol pre-heater, pre-reformer, SOFC, GT and indirectly coupled steam cycle. The waste heat leaving the GT is used for pre-heating the cathode flow and to produce steam for the steam cycle. This steam is expanded in the Steam Turbine (ST) to produce electricity. The waste heat leaving the ST is used in the indirectly coupled absorption refrigeration and absorption heat pump units to produce heat and cold.[89]

The second configuration is very similar to the previous one but does not contain a ST. Furthermore, in this configuration the air for the SOFC is humidified which implies that this configuration does not contain a GT but a Humid Air Turbine (HAT). The steam leaving the HAT is used to pre-heat the water for the humidifier and for the absorption refrigeration and absorption heat pump units. The waste steam leaving these units is again used in the humidifier, which means that in this configuration both cycles are directly coupled.[90]

Outside the scope of this investigation is the GT cycle with methanol fuelled Chemical-Looping Combustion (CLC). However, the interesting component of this configuration is the condenser which separates the $CO_2$ from the $H_2O$ for $CO_2$ capturing.[91]

## A.4 | Knowledge Gaps Outside the Scope

The literature study also identified knowledge gaps that are outside the scope of this investigation. Knowledge gaps have been identified in the areas of compactness, durability, safety, maintenance and reliability of SOFC-GT power units. However, these are important for the performance of the SOFC-GT and therefore mentioned in this section of the report. In chapter 10 the importance of follow-up research for these knowledge gaps and related recommendations will be provided.

The literature also does not provide much information about reliability of the SOFC system. Therefore, it is important to consider this subject during the design of the SOFC-GT power unit. When carefully designing the hybrid system the reliability can be improved. However, some additional research about this subject will be required to obtain certainty.

The possibility to use a combination of Hydrogen and methanol as fuel in a GT is also unknown. Since methanol will be used as fuel for the SOFC and, possibly, GT and residual Hydrogen fuel leaves the SOFC, it is important to investigate whether it is impossible to combust the two fuels in the GT.

The literature provides little information about the optimal operation of the methanol fuelled SOFC and has to be investigated because of the durability, maintenance, and reliability. Optimal operation of the SOFC will increase the efficiency, lifespan, and reliability and will reduce maintenance. Furthermore, the safety will be increased since the failure modes can be avoided.

Lastly, the literature states in section 2.1.1 that the dynamic behaviour of the power system is limited by the response time of the HE. Using a GT will enhance the dynamic behaviour but is no solution for the slow response time of the HE itself. Improving this response time is, to the best of knowledge, unknown and therefore requires further investigation.

## A.5 | The Essence of Systems Engineering

In this section the process will briefly be explained in order to give a clear overview of the method and the steps taken in the investigation. The information provide in this section is provided by [53,54,60,92]. Before SE will be explained it is important to know the definition of a system. Simply stated, a system is a composition of integrated components, people, products, and processes, that provide a capability to satisfy a stated need, purpose or objective [53, 92].

In a system there are points of interaction between functions, subsystems or components, called interfaces. Moreover, the systems itself has interfaces with the stakeholders and the context it is operating in. Through these interfaces the overall functionality of the system is an interplay between the separate and in relation to each other functioning of the subsystems and components. Analogously, the system shows its full potential and behaviour when it is fully assembled and is used in the respective context.

When a system is being designed it has to comply to its mission and all the interfaces involved. The SE process is developed, initially for military purposes, to investigate the identified mission and interfaces, and to develop a suitable solution. The development process starts with the identified mission and deals with more but smaller details. Ultimately all these separate parts have to be integrated to create a coherent working system. This will be explained more extensive in the next section.

## A.6 | The V-model

SE can best be described on the basis of the V-model, presented in figure A.11, which is widely used in the literature. The process starts at the left top of the V with the mission of the system, goes to the bottom and ends at the right top with the validated system. The left side of the V shows the development and decomposition of the system into subsystems and components, which will be described in sections A.6.1 and A.6.2. The right side of the V shows the integration of the components and subsystems and the validation and verification of the system and subsystems, which will be described in sections A.6.3 and A.6.4.

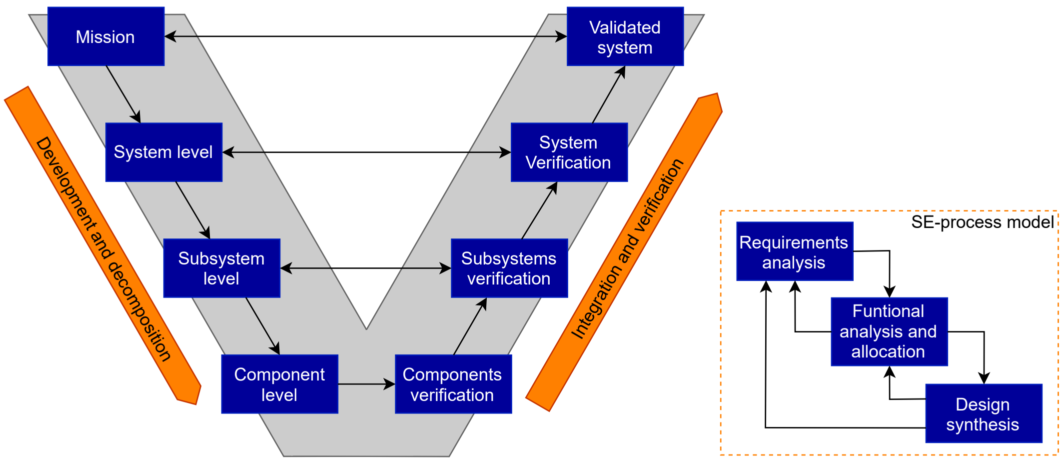


Figure A.11: The V-model presenting the SE process: the decomposition of the system into subsystems and components and the subsequent building of the system.

In every phase of the V model, presented by the blue blocks in the V, the SE-process model, right side of figure A.11, is executed. The feedback loop between 'Requirements analysis' and 'Functional analysis and allocation' ensures that the functions match the requirements. The feedback loop between 'Functional analysis and allocation' and 'Design synthesis' ensures that the design of the system or subsystem matches the functions. The arrow from 'Design synthesis' to 'Requirements analysis' is the verification of the design and ensures that the design of the system or subsystem and the requirements ultimately match. By using this SE-process model it is ensured that each phase in the V-model is successfully completed before moving on to the next phase.

### A.6.1 | System Level

At this level of the investigation the mission of the system and the requirements are determined. These requirements can be provided by the customer, the interfaces, the literature or have to be translated from the mission of the system. Considering these requirements the functions of the system will be determined and a series of concept system designs will be created. Weighting factors will ultimately be used to choose which concept system best meets these requirements

### A.6.2 | Subsystem Level

At this level the system design will by divided into subsystems and interfaces between these subsystems in the next level. The subsystems are also systems, largely independent from the other subsystems, and perform a set of functions that are described in the system design. For the subsystems also requirements have to be determined which again can be provided by the customer, the interfaces, the literature or have to be translated from the mission of the system. After that functions of the subsystems will be determined and subsystem designs will be made from the requirements. If this is the lowest level of the V then also the components for the subsystems are determined at this stage.

### A.6.3 | Integration

After all the components are determined these have to be integrated into subsystems. After that the subsystems have to be verified, which will be explained in section A.6.4. Then the subsystems have to be integrated into the system in order to subsequently be validated and also verified. Note that the number of integration steps increases when the system becomes larger and the subsystems also consist out of subsystems.

### A.6.4 | Verification and Validation

To determine whether the system and subsystems meet the requirements they have to be verified, presented by the arrows between the left and right sides of the V in figure A.11. The verification methods relevant for this investigation are reviewing and simulation. As mentioned in section A.6.3 the verification steps have to be taken between every integration step. In this way it is easy to determine where the system or subsystem is experiencing problems and where adjustments need to be made. Validation of the system is the last step and determines, from the stakeholders perspective, if the system is able to fulfil its mission, which therefore will be done in consultation with the stakeholders.

### A.6.5 | Feedback Loops

Between every step in the process feedback loops, shown in figure A.12, have to be executed. In the development phase, left side of the V, these feedback loops are small verification steps to determine if the solution still meets the requirements before moving to the next development step. In the integration phase, the right side of the V, these feedback loops are also small verification steps but here they determine what adjustments have to be made to the subsystems or system before moving to the next integration step.

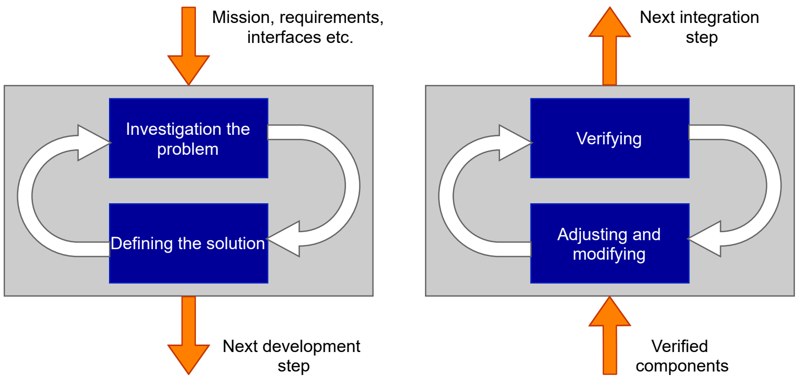


Figure A.12: A display of the feedback loops in the SE process.

In figure A.12 the left loop represents the development feedback loop with the downward arrow designing the solution and the upward arrow verifying the solution. The right loop represents the integration feedback loop with the downward arrow verifying the system or subsystem and the upward arrow integrating the system, subsystem or adjustments.

# B | Functional Diagrams

## B.1 | System

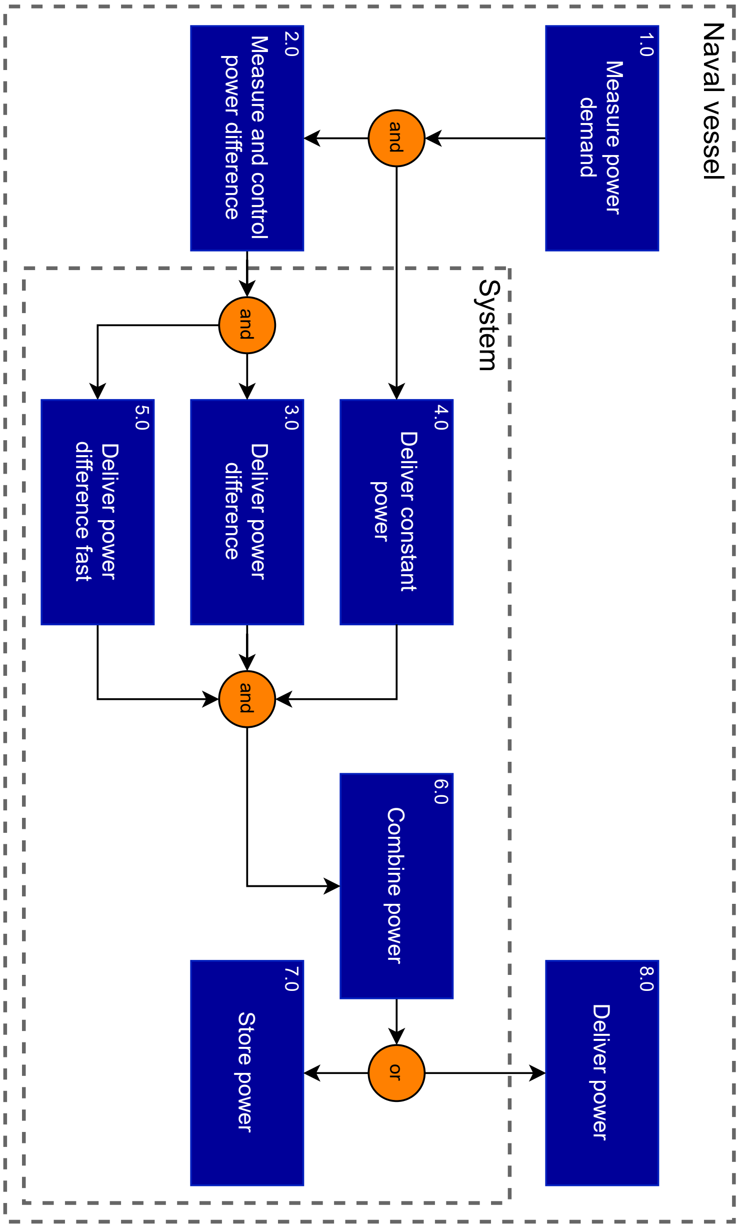


Figure B.1: The Functional Flow Block Diagram of the system and the functions to be performed.

## B.2 | Subsystem 3.0

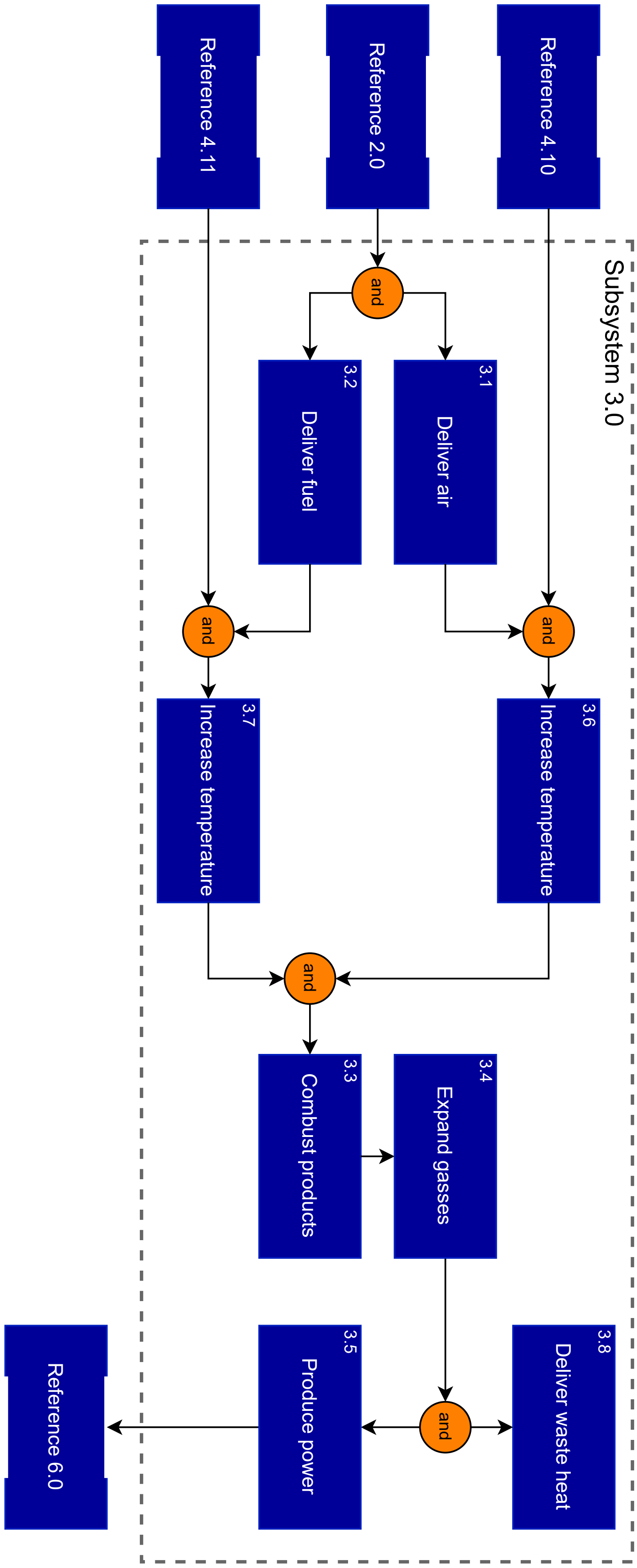


Figure B.2: The Functional Flow Block Diagram of subsystem 3.0 and the functions to be performed.

## B.3 | Subsystem 4.0

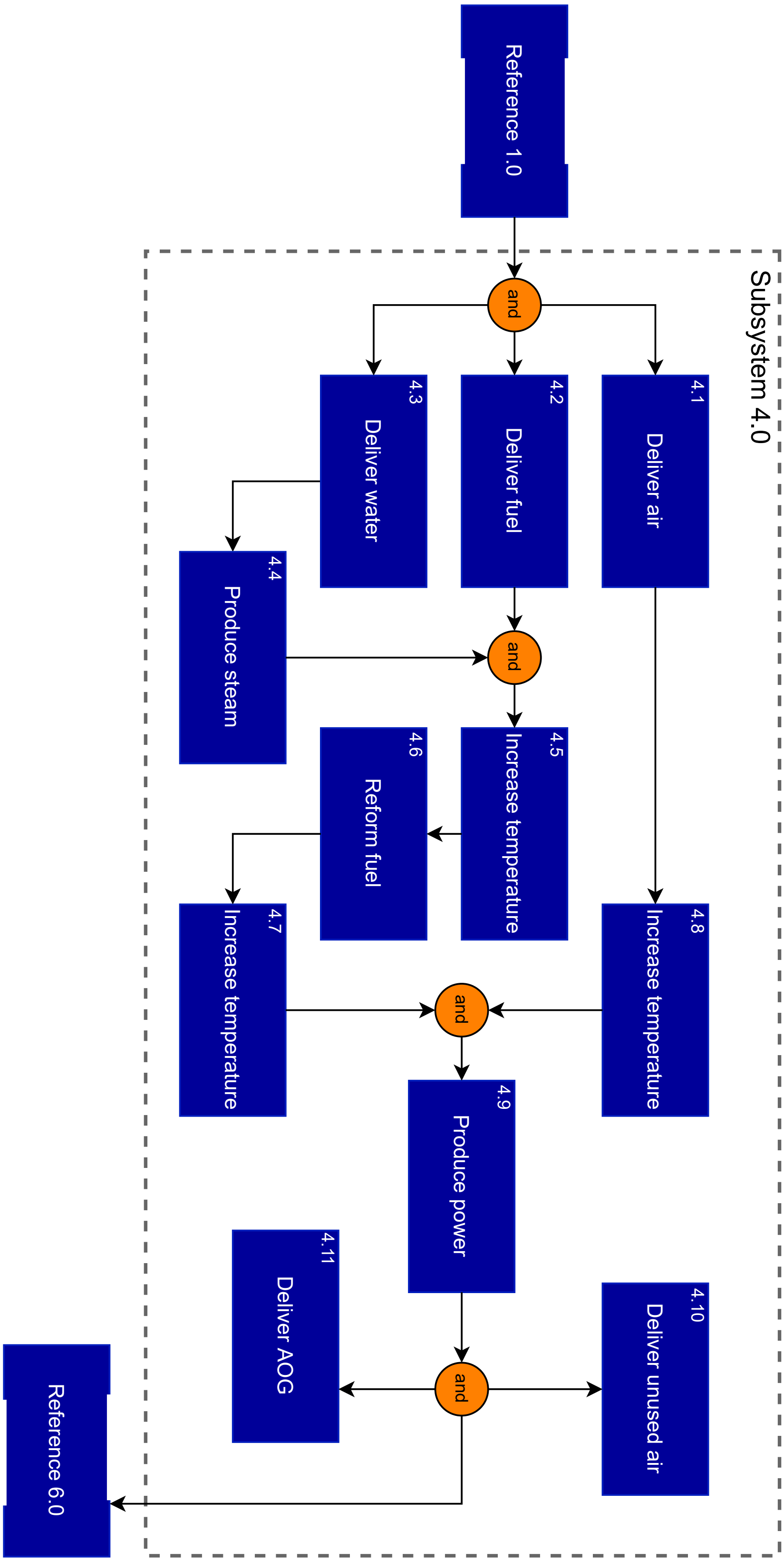


Figure B.3: The Functional Flow Block Diagram of subsystem 4.0 and the functions to be performed.

# C | Allocation Sheet

This Requirements Allocation Sheet (RAS) documented the connection between the determined functions, requirements, performance, and the physical system. It provides traceability between the determined functions, the requirements, and the choice of components. The function numbers in the FFBD of figures B.1, B.2 and B.3 match the function numbers in this sheet.[53]

| Function name (function number) | Functional performance and design requirements | Component identification |
|---|---|---|
| Measure power demand (1.0) | The amount of power required by the ship's electrical system has to be determined in order to deliver this amount. | Integrated Monitoring Control System (IMCS) of the ship |
| Measure and control power difference (2.0) | Determine the difference between the constant power supply of the SOFC and the required power. | IMCS of the ship |
| Deliver power difference (3.0) | Deliver the power difference between the required power and the constant power supply delivered by the SOFC.<br>Requirement 1.2: The dynamic behaviour of the power unit in load following conditions shall be enhanced, so the response time to load steps will be shorter than 30 seconds. | See components subsystem 3.0 |
| Deliver constant power (4.0) | Deliver a constant power supply to the ship's electrical system. | See components subsystem 4.0 |
| Deliver fast power (5.0) | Provide the ship's electrical system with fast power during the time the GT is accelerating. | Component 8: Battery pack and (super)capacitors |
| Combine power (6.0) | Combine the AC power of the generator and the DC power of the SOFC. | Component 10: Electronic control system |
| Store power (7.0) | Store electrical energy for fast delivery of power and to increase efficiency.<br>Requirement 1.5: The power unit shall contain supportive components for peak-shaving and dynamic support. | Component 8: Battery pack and (super)capacitors |

| Function name (function number) | Functional performance and design requirements | Component identification |
|---|---|---|
| Deliver power (8.0) | Distribute the electrical power to the ship's systems.<br>Requirement 1.3: The power unit shall provide power up to 2000 kW, with the operational profile of table 3.1.<br>Requirement 1.4: The naval vessel shall be able to operate autonomously for 21 days. With an average power percentage of 59% of 2 MW this results in a minimum power unit efficiency of 34%. | Component 10: Electrical system |
| Deliver air (3.1) (4.1) | Compress the air to 2 MPa and transport air to the SOFC and GT.<br>Requirement 1.6: The system shall be operated at a pressure of 2 MPa.<br>Requirement 1.14: The GT system shall have its own air and fuel supply to respond adequately to load steps. | Component 4: Compressor(s) |
| Deliver fuel (3.2) (4.2) | Pressurize the fuel to 2 MPa and transport fuel to the SOFC and GT.<br>Requirement 1.6: The system shall be operated at a pressure of 2 MPa.<br>Requirement 1.7: The available electrical power supply will be 76 kW for the pumps.<br>Requirement 1.14: The GT system shall have its own air and fuel supply to respond adequately to load steps. | Component 4: Pump(s) |
| Combust products (3.3) | Combust the fuel to release the chemical energy and increase the temperature and enthalpy.<br>Requirement 1.1: The residual fuel in the AOG and air from the cathode shall be combusted.<br>Requirement 1.12: The temperature of the inflow gases for the GT shall be lower than 1773 K to prevent the GT from over-heating.<br>Requirement 1.13: The GT shall be able to combust Hydrogen and methanol. | Component 9: Combustion chamber |
| Expand gases (3.4) | Translate the pressure and temperature to rotational speed.<br>Requirement 1.15: The gases shall leave the GT before the saturated vapour pressure and temperature are reached and water droplets are formed. | Component 1: Turbine |
| Produce power (3.5) | Translate the rotational speed of the turbine to electrical power. | Component 7: Generator |
| Deliver waste heat (3.8) | Transport the hot gases from the GT to another component where heat is required.<br>Requirement 1.1: The waste heat shall be used elsewhere in the naval vessel to increase the efficiency of the power unit. | Component 5: High-temperature blowers or ejectors. |

| Function name (function number) | Functional performance and design requirements | Component identification |
|---|---|---|
| Deliver water (4.3) | Pressurize the water to 2 MPa and transport water to the SOFC.<br>Requirement 1.6: The system shall be operated at a pressure of 2 MPa. | Component 4: Pump(s) |
| Produce steam (4.4) | Add energy to the gases to increase the temperature so the water vaporizes and steam is produced.<br>Requirement 1.10: Steam shall be pre-heated and vaporized before entering the pre-reformer to reduce the amount of AOGRC used to control the temperature of the pre-reformer. | Component 3: Heat exchanger or heater |
| Increase temperature (3.6)(3.7) (4.5)(4.7)(4.8) | Add energy to the gases to increase the temperature, to the required temperature, and enthalpy.<br>Requirement 1.9: The air supplied to the cathode and anode of the SOFC shall be pre-heated so the temperature gradient between the inlet and outlet of the SOFC is lower than 10 K/cm, resulting in a maximum temperature difference of 400 K.<br>Requirement 1.10: Methanol shall be pre-heated and vaporized before entering the pre-reformer to reduce the amount of AOGRC used to control the temperature of the pre-reformer.<br>Requirement 1.16: Methanol needs to be vaporized before combustion to provide proper mixing of the fuel and the air and therefore a clean and efficient combustion.<br>Requirement 1.17: The air and fuel inflow will be pre-heated before entering the combustion chamber to reduce the fuel consumption and increase efficiency. | Component 3: Heat exchanger(s) or heater(s) |
| Reform fuel (4.6) | Produce Hydrogen from $CH_3OH$, which can be used in the SOFC.<br>Requirement 1.8: The pre-reformer shall operate at a temperature of 520 K, by using a fraction of the AOG, to prevent methanation. | Component 6: Pre-reformer |
| Produce power (4.9) | Produces electrical power from the chemical reaction of Hydrogen and Oxide.<br>Requirement 1.11: The SOFC should be operated between 873-1123 K and as constant as possible to ensure a longer lifetime. | Component 2: Solid Oxide Fuel Cell |
| Deliver unused air (4.10) & deliver AOG (4.11) | Transport the gases leaving the SOFC to other components in the system. | Component 5: High-temperature blowers or ejectors |

Table C.1: The RAS translating the functions and requirements to components.

# D | Argumentation

In this appendix of the report the weight factors and the scores of the different concepts are explained in more detail. Every section in this chapter contains the explanation of the parameter and the weighting factor and the score per concept configuration to the parameters including an explanation.

## D.1 | Durability

The durability of the power unit, and especially the SOFC, is considered in this parameter. The GT and ORC are not threat for the durability so these parameters considering the SOFC is what counts most. Since the durability of the GT cannot be influenced that much they are considered mostly, paying attention to the temperature differences of the inflow gases. This is according to the information obtained from the literature study. The reliability of the SOFC still has to be investigated and cannot be guaranteed in this investigation and therefore is not considered in this section although the reliability also depends on temperature differences.
The concepts will be rated according to the temperature differences of the inflow gases. The more constant the temperature of the inflow gases are the less the risk of fracture inside the SOFC and degradation of the SOFC, so the higher the score.

The inflow gases for the SOFC of concept 'Regeneration' are pre-heated by the gases leaving the GT. Since the turbine outlet temperature of the gases is depending on the amount of power required by the ship, the heat transfer in the HE varies with this. Therefore, the temperature of the inflow gases will also vary which will have a negative influence on the durability of the SOFC. This concept scores 2 points for that reason.
The temperature of the inflow gases for the SOFC of concepts 'Multistage' and 'Rankine' can be kept constant with the amount of AOG and gas from the cathode flowing into the mixers. For that reason, these concepts score 3 points.

## D.2 | Maintenance

Onboard of a naval vessel maintenance must be executed as quick and smooth as possible. The concepts are also graded to this parameter and will be rated according to the size of the parts, the difference in parts and the expected maintenance problems. The smaller the parts, the less different parts, and the less expected maintenance problems the higher the score.

Concepts 'Regeneration' and 'Rankine' consist of a larger compressor and GT which makes maintenance and replacement of components more difficult. Furthermore, spare parts will be larger and heavier. Moreover, due to the single-stage expansion the temperature at the end of the turbine will be lower resulting in the possibility of water droplet formation, which is unfavourable for the GT. Furthermore, concept 'Rankine' consists of an entire extra power cycle and therefore contains more different parts making maintenance also more difficult. This results in a score of 2 points and 1 point for the concepts 'Regeneration' and 'Rankine', respectively.
Concept 'Multistage' consist of multiple smaller compressors and turbines making maintenance and replacements easier. Besides, the spare parts will be lighter and smaller. Due to the multistage expansion the temperature at the outlet of the turbine will be higher mitigating the risk of droplet formation. All this considered this concept is the best option considering maintenance and therefore scores 3 points.

## D.3 | Controllability

To be as efficient as possible it is important to control the power supply as accurate as possible. This parameter considers this possibility for the concepts according to the influence of temperature differences and the thermal inertia of the concept systems. The response time is also important for the performance of the naval vessel but in case of this parameter all concepts score the same because of the GT, batteries and SC. For that reason, the concepts are rated according to the possibility of power control for every separate subsystem. The less influence other subsystems have the higher the score of that specific concept.

In concepts 'Regeneration' and 'Rankine' the temperature of the inflow gases for the SOFC and the heat transferred to the ORC cannot be controlled precisely, respectively. Both factors are depending on the outlet temperature of the turbine gases. Since the power produced by the SOFC and the ORC is depending on the temperature this means that the power cannot be controlled precisely. Furthermore, both concepts use HE to pre-heat the inflow gases for the SOFC and transfer heat to the ORC, respectively. Therefore, the responses to change in outlet temperature of the GT is also slow for both concepts due to thermal inertia. So, both concepts score 1 point for this parameter.
Concept 'Multistage' does not have this problem since the amount of AOG and flow from the cathode can precisely control the temperature of the inflow gases. This means that also the power from the SOFC can be accurately controlled as well as the power from the GT. Furthermore, this concept does not use HE but mixers to control the SOFC and therefore does not rely on the response time of the HE which is favourable for the thermal inertia of the concept. The result is a score of 3 points for this concept.

## D.4 | Safety

Safety is of paramount concern for the RNLN, so the concepts are also graded on this parameter with the highest weighting factor. Since the handling of the Hydrogen, anode gas flow mixture and AOG is an unknown factor, because of the reactive nature of these gases, the safety cannot be guaranteed in this study. Therefore, the concepts will be graded according to the amount of fuel in the combustion chamber and the temperature in the system in equal power supply. The less fuel is combusted at once and the lower the temperature in the system the higher the score.

Due to the reheating of concept 'Multistage' the amount of fuel in one combustion chamber is smaller and therefore, in case something goes wrong, the risk of damage is smaller. For that reason, also the temperature after the first combustion chamber will be lower compared to the other concepts. Taken these arguments together a score of 3 point is given to this concept.
In concepts 'Regeneration' and 'Rankine' all fuel required will be combusted in one combustion chamber. The risk of damage is greater when something goes wrong and the temperature of the gases after the combustion chamber is higher, making these concepts less safe. For those reasons, the concepts score both 2 points.

## D.5 | Starting Time

The starting time is also a parameter that needs to be considered since the naval vessel has to start as quickly as possible. All concepts will score the same on this subject when considering the availability of power since all concepts have the GT, batteries and SC. Therefore, the starting time of the SOFC is considered with a focus on heating up the SOFC. Due to the reuse of waste heat from the SOFC and GT the concept will be rated to the amount of heat flowing back to the SOFC, which can be used to heat the SOFC, and the thermal inertia. So, the higher the amount of heat flowing back to the SOFC and the lower the thermal inertia, the higher the rating.

The starting time of concept 'Regeneration' will be longer due to the thermal inertia of the HE. Therefore, it takes more time to pre-heat the inflow gases which will result in more time to heat the SOFC. The score for this parameter is 2 points.
Concept 'Rankine' scores just 1 point since the starting of the ORC will take a lot of time using only waste heat. Furthermore, the thermal inertia of the HE also increases the starting time of ORC in this

concept system.
Concept 'Multistage' does not have these problems since the hot gases leaving the SOFC are directly used again in the mixers for pre-heating the gases for the inflow. The SOFC will then also be heated faster and therefore produce the required power faster. The result is a score of 3 points for this concept.

## D.6 | Overall Efficiency

This parameter is important since a higher efficiency results in a lower fuel utilization and therefore a small fuel storage, which will save weight and volume. Furthermore, a higher efficiency will also result in a lower amount of emission produced by the power unit. The useful work potential of a given amount of energy in the gases also needs to be used as efficient as possible and is therefore also considered in this parameter. The more exergy is used in the GT and the more waste heat is used elsewhere, the higher the concepts are rated.

Concepts 'Regeneration' and 'Rankine' will use as much waste heat as possible during pre-heating the flows in the system increasing the efficiency. Concept 'Rankine' also produces power in the Rankine cycle using waste heat from the GT increasing the efficiency even more. However, this concept also uses exergy rich gases from the SOFC for pre-heating the inflow gases. So, in this concept a certain amount of exergy will be destroyed, while concept 'Regeneration' only uses exergy low waste heat for pre-heating the flows in the system. Everything taken together both concepts will score 3 points.
In concept 'Multistage' less waste heat will be used since only two flows will be pre-heated. Furthermore, in this concept also exergy rich gases from the SOFC are used for pre-heating the inflow gases. So, in this concept also a certain amount of exergy will be destroyed. Everything taken together this concept will score 2 points.

## D.7 | Weight/Size/Cost

The available amount of space onboard is limited, so the size of the power unit needs to be considered as well as the weight of the of the power unit. The practicality and complexity are also of importance for implementation onboard of naval vessel since they influence the cost of the concepts. This parameter will be judged paying attention to the number and size of components and flows in the system. The less components and gas flows and the smaller the components the higher the score of the concept.

Concept 'Regeneration' is the simplest configuration of the three, a regular Brayton cycle connected in parallel to the SOFC, and therefore will be the smallest, lightest, and least complex. Since it is the simplest concept, it will also have the least number of expensive components and therefore will be the least expensive. For those reasons, this concept will score 3 points.
Concept 'Multistage' consists of two compressors and turbines, which will be more expensive, larger, and heavier than a system with one larger compressor and GT. However, the compressors and turbines will be smaller and lighter but will still increase the complexity of the flows and the connection between components. Furthermore, also the control of the flows to the mixers makes the concept more complex. In total this concept will score 2 points because of the weight and size.
Concept 'Rankine' consists of an entire extra power cycle, including an extra HE, pump, and steam turbine, so this concept is the largest, heaviest, most complex, and most expensive of the three. Furthermore, the extra generator contributes to a more complex processing of the electrical power. So, for this concept the practicality is lower than for the other concepts, resulting in a score of just 1 point.

# E | Schematic Diagram

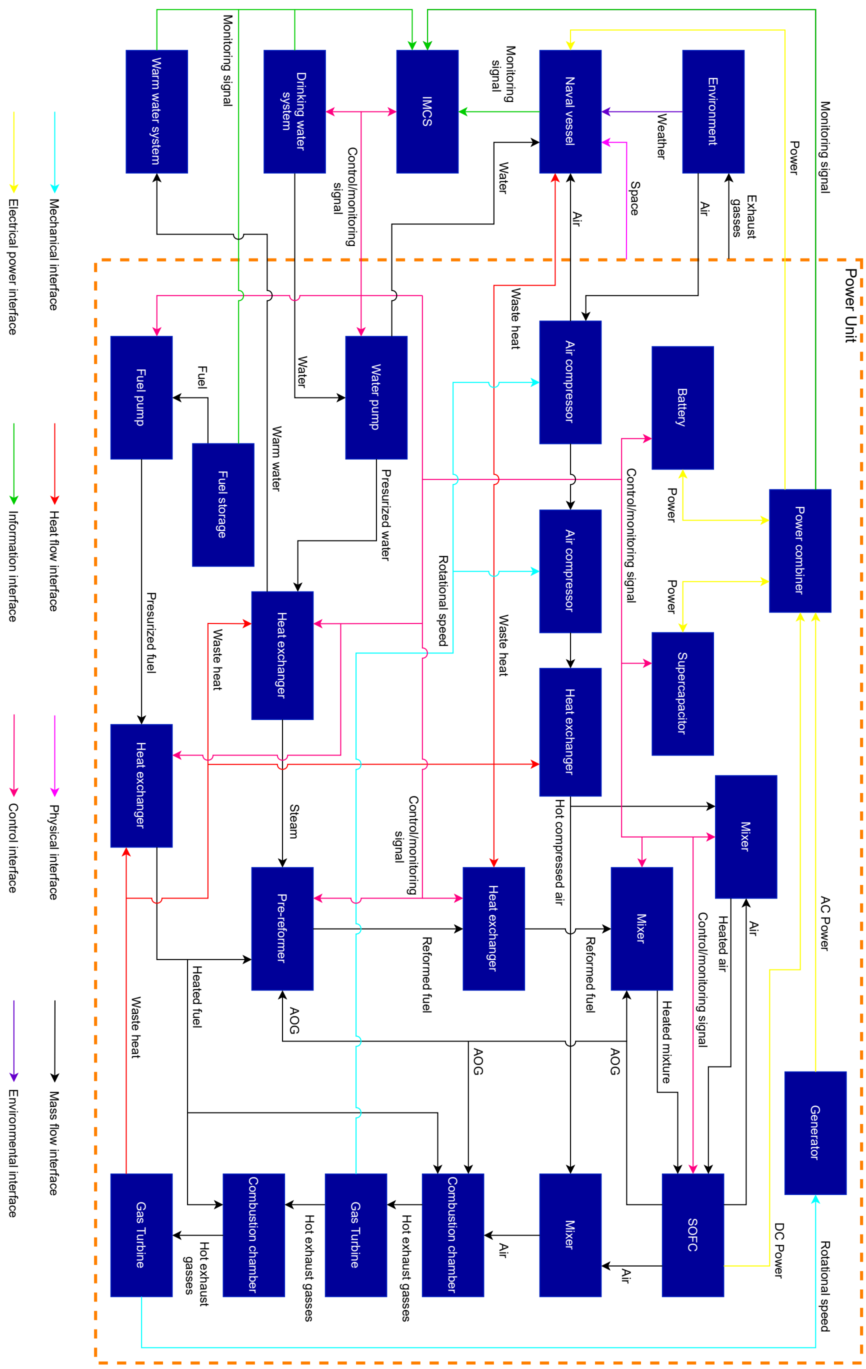


Figure E.1: The Schematic Block Diagram of the system showing the components and the interfaces.

# F | Additional Simulation Results

In this chapter the input parameters of the scenarios and additional important simulation results are displayed and discussed. Since the scenarios are so similar the results are also very similar and there is a possibility that many things will be described more than once in this chapter. However, for the investigation it is important that the performance of the hybrid power unit in the operational profile, described in table 3.1, is shown and discussed. For that reason, scenario I is described more extensive than the other scenarios. In scenario II and scenario III the relevant general information and differences between the scenarios are addressed.

## F.1 | Input Parameters

In this section of the report the input parameters for the scenarios are presented. This concerns graphs of the methanol and Oxygen molar flows into the first combustion chambers, the current density of the SOFC and the bypass ratios of the PHE. The inflow temperature of the anode and cathode flow is 900 K during stationary operation and increases to 1000 K for scenario I and scenario II and to 950 K for scenario III during the power step. This is necessary because the temperatures from the PHE for the anode and cathode are higher than 900 K. The molar flow of methanol into the second combustion chamber is 0 during stationary operation. During the load step the molar flow methanol into the second combustion chamber is regulated in such a way that 50% of the remaining oxygen is used for complete combustion of the methanol.
In figure F.1 the molar flows of methanol and Oxygen into the GT system are displayed. The values of the parameters are controlled manually.

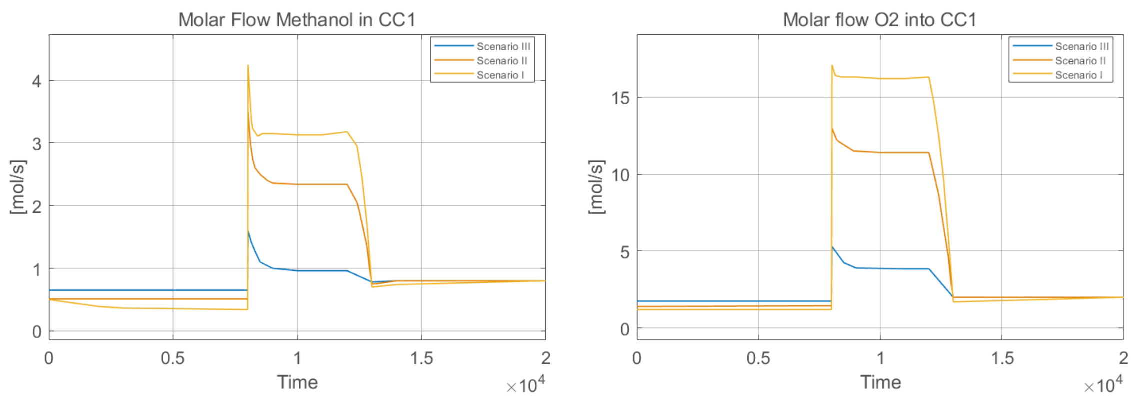


Figure F.1: The input parameters for the molar flow of methanol and Oxygen.

The current density for the SOFC and the bypass ratios for scenario I can be found in figure F.2. The bypass ratios of scenario II and scenario III can be found in figure F.3.
The bypass ratios of the PHE are used to control the temperatures of the methanol, water, and anode gases. The ratio of the exhaust gases flowing through the HE is depending on the amount of energy in the exhaust gases. Since the energy in the exhaust gases is larger during the power step of the GT the flow through the PHE will be smaller to control the temperature. The increase of exhaust gases through the PHE for methanol just after 8,000 seconds is to compensate for the increase of fuel supply and prevents the temperature of the methanol from decreasing to below saturated vapour temperature.

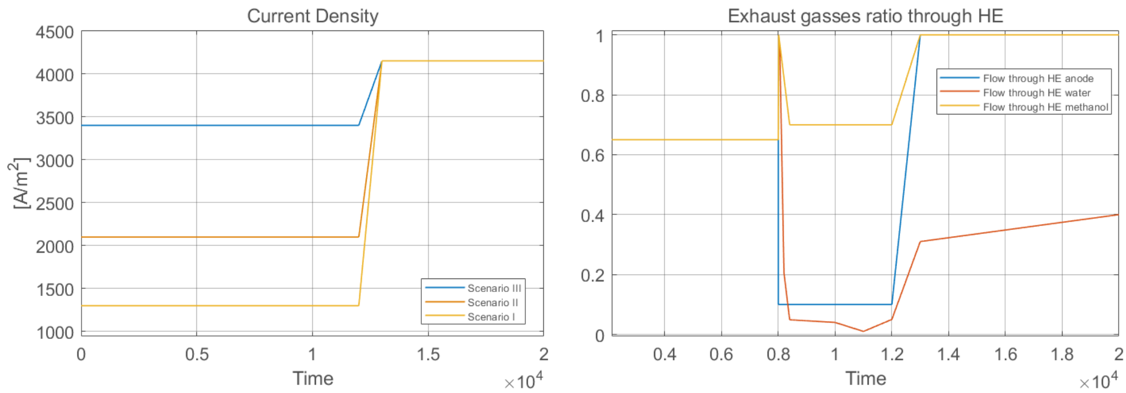


Figure F.2: The current density for all scenarios and bypass ratios for scenario I.

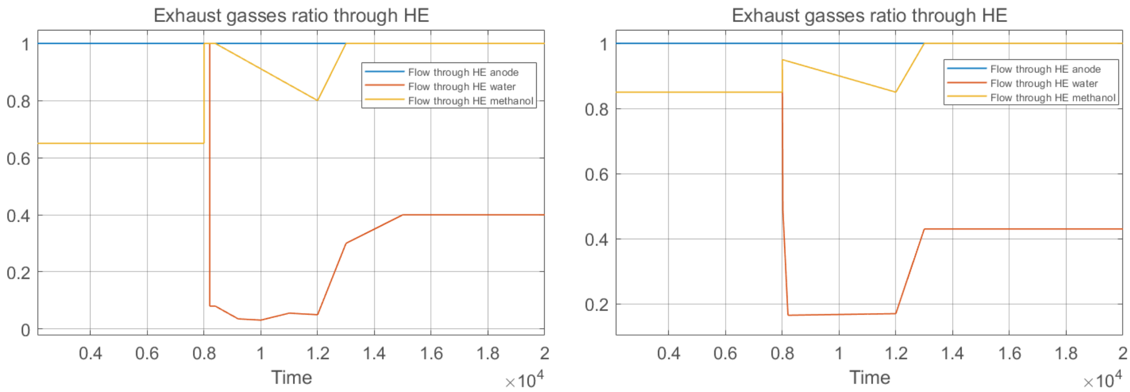


Figure F.3: The input parameters of the bypass ratios for scenario II (left) and scenario III (right).

## F.2 | Scenario I: Power Step from 'Low Speed and Station Keeping'

In this section of the report the additional simulation results of scenario I are presented and explained. These results will provide a more extensive overview of the system characteristics and behaviour.

The left-hand side of figure F.4 zooms in on the power consumption of the water pump, earlier shown in figure 6.6, which shows an increase during the power step of the SOFC after 12,000 seconds. Since the water consumption is depending on the methanol inflow in the pre-reformer, which is depending on the temperature of the methanol, the power consumption shows some fluctuations. The right-hand side of this figure zooms in on the region where the battery provides extra power during the air supply to the low-pressure air system, also earlier shown in figure 6.6.

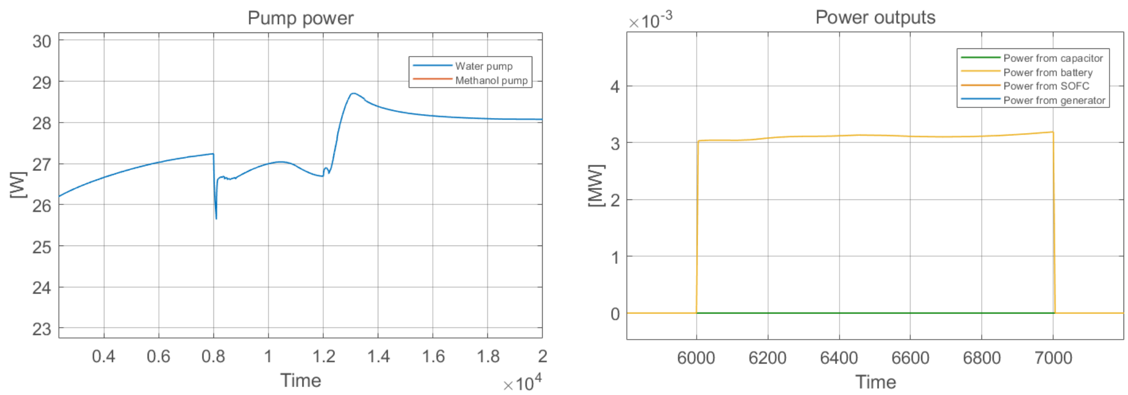


Figure F.4: The power consumption of the water pump and the power supplied by the battery.

In figure F.5 the power consumed by the compressors, the power produced by the first turbine and the difference between those powers is shown. The left-hand side shows an increase in power consumed by the compressors during the power step and increase of power delivered by the GT. On the right-hand side of this figure is zoomed in on the region where the low-pressure air system is used. There it is visible that the power consumed by the second compressor decreases a little as well as the power produced by the first turbine. This is caused by the lower air flow into the GT system after the first turbine where the air is drained for the low-pressure air system. There air flow through the first compressor is kept constant and therefore, the power does not decrease.

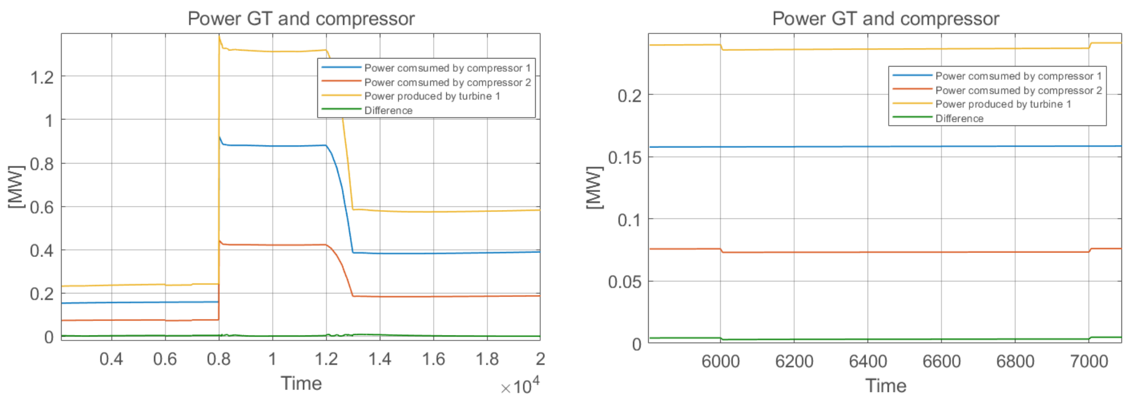


Figure F.5: The power produced by the first GT and consumed by both compressors.

The figures F.6 and F.7 show the temperatures of the flow in and out of the PHE. The small increases of the temperature of the gases during the use of the low-pressure air system are caused by the lower mass flow at equal fuel combustion. However, these differences are compensated by the mixing ratios in the mixing chambers to keep the temperature flowing in the SOFC as constant as possible. Although the timescale is large, 20,000 seconds, it is clearly visible that the thermal inertia of the PHE affects the temperature of the outflow substances, making the temperature difficult to control manually, especially for the methanol and water flow.
With the PHE for the air and anode flow is tried to obtain an outflow temperature that is a high as possible, not exceeding the inflow temperature of the SOFC. A higher air temperature will result in a lower fuel consumption to obtain the required power for both turbines. This also holds for scenario II and scenario III

It has to be noted that the temperature leaving the anode PHE does not match the inlet temperature of the methanol PHE although they are placed after each other. The reason for this is that the bypass flow and flow through the anode PHE are combined in a mixing chamber before entering the methanol PHE. Since the temperature of the gases in the bypass flow is always higher than the temperature of the gases leaving the PHE the temperature always increases between both PHE, unless the bypass flow is zero. In that situation the outlet temperature of the anode PHE is the same as the inlet temperature of the methanol PHE.

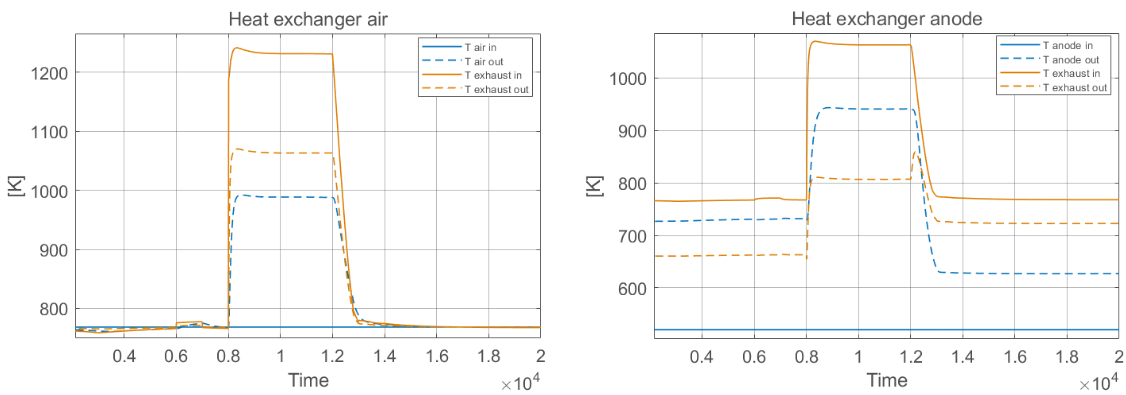


Figure F.6: The temperatures in the PHE for air and anode gases.

In figure F.7 can be seen that the temperature of the methanol during 'Low speed and station keeping' is larger than the 445 K of superheated methanol. This is to prevent the temperature of the methanol from decreasing to below the saturated vapour temperature during the increase of the fuel flow for the power step of the GT. To prevent excessive temperature in the pre-reformer this is compensated with a water temperature which is just below the 485 K of superheated water. The combined energy of the water and methanol is kept nearly constant as can be seen in the left-hand side of figure F.8.

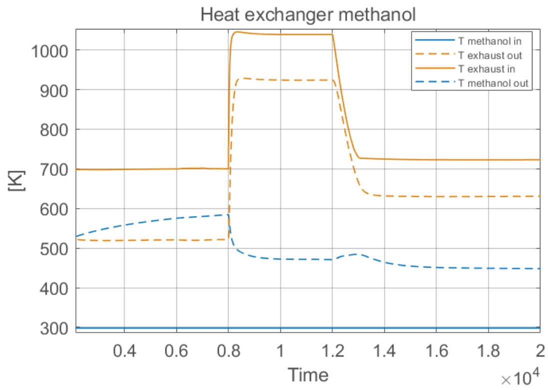


Figure F.7: The temperatures in the PHE for methanol and water.

On the right-hand side of figure F.8 the temperature of the outflow gases of the anode and cathode is displayed as well as the temperature of the PEN of the SOFC and the interconnect. From this figure it is clearly visible that the temperature of the SOFC influences the temperature of the outflow gases.

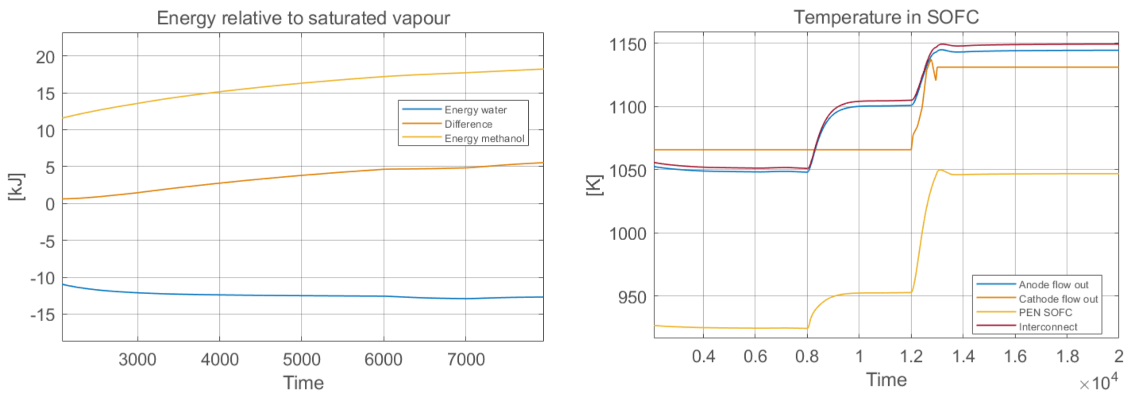


Figure F.8: The energies of the methanol and water flow and the temperatures of the SOFC.

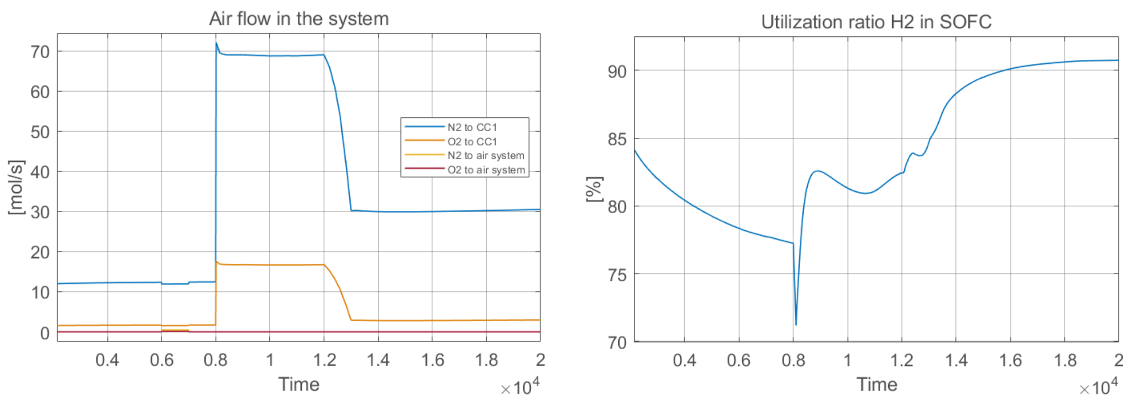


Figure F.9: The air supply to the first combustion chamber and the utilization ratio in the SOFC.

In figure F.9 the air flow into the first combustion chamber and the utilization ratio of the Hydrogen in the SOFC is shown. The left-hand side is zoomed out from the right-hand side of figure 6.9. The peak in the fuel supply for both combustion chamber is required to be able to make the power step within the 15 seconds. The right-hand side shows how much of the Hydrogen flowing through the SOFC is used. The fluctuations in the utilization ratio are caused by the fuel consumption of the pre-reformer, which is influenced by the temperature of the methanol, and the operation of the SOFC. When the temperature of the methanol increases, the pre-reformer responds with adding more methanol to correct for the pressure differences.

The $CO_2$ emissions and the fuel consumption during the operation of the power unit is displayed in figure F.10 at the left- and right-hand side, respectively. It shows an increase in both fuel consumption and emissions during the power step.

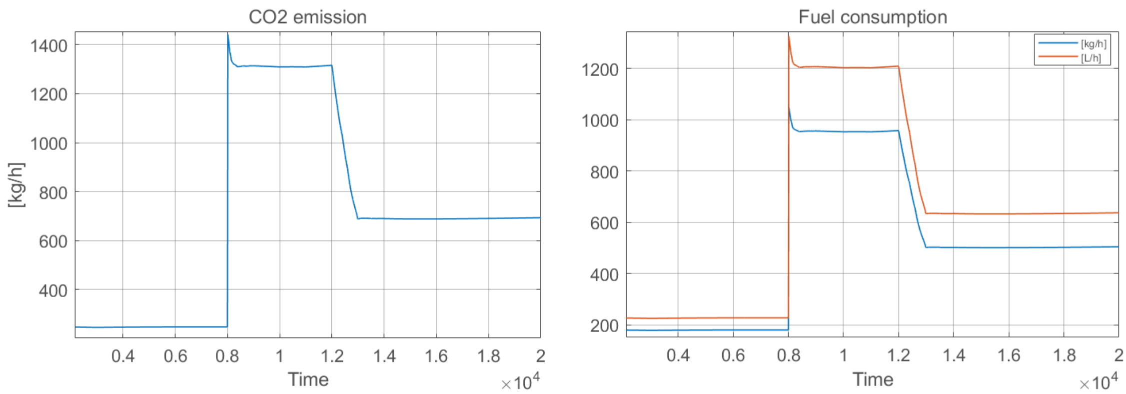


Figure F.10: The $CO_2$ emission and fuel consumption of the power unit.

In figure F.11 the available water flow for the central heating is shown. On the left-hand side can be seen that during the power step of the GT the water available for the central heating is larger because of the larger temperatures and mass flows of exhaust gases through the system. On the right-hand side is zoomed in on the region where the low-pressure air system is used. There the mass flow of exhaust gases is smaller due to a smaller air flow into the GT system, so less energy is available for the central heating.

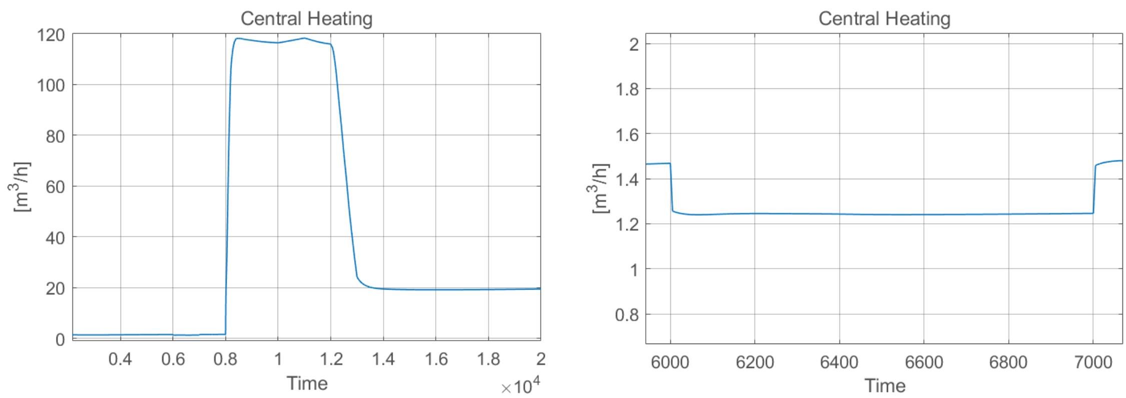


Figure F.11: The available water flow for the central heating.

In the figure below, figure F.12, the composition of the fuel in the anode gases and the fuel supply into the first combustion chamber is displayed. The left-hand side gives a complete overview while the right-hand side zooms in on the substances that are barely present in the anode flow. The amount of a certain substance is influenced by the operation of the pre-reformer and the SOFC. For example, a lower utilization ratio will result in a larger Hydrogen fraction in the anode flow leaving the SOFC.

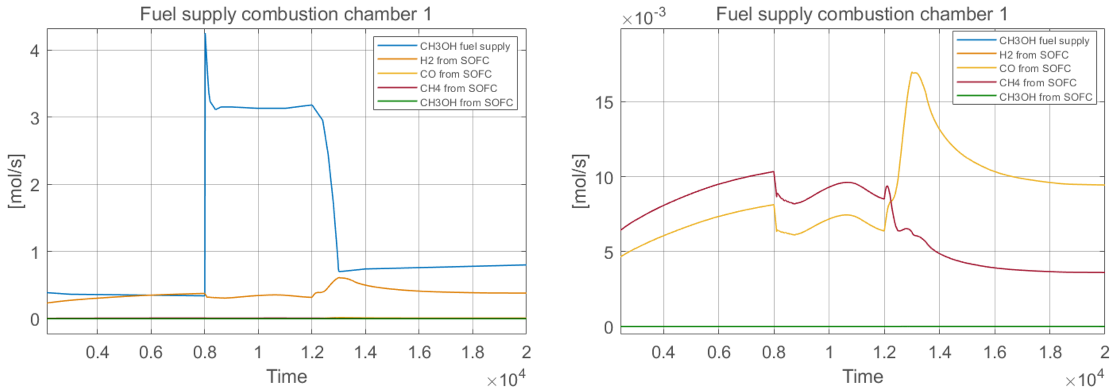


Figure F.12: The composition of the anode gases and fuel into the first combustion chamber.

The figure F.13 shows on the the mixing ratios of the mixers for the anode and cathode as well as the AOGRC flowing into the pre-reformer to control the temperature. The amount of mixing ratio is depending on the temperature of the gases leaving the PHE and the inflow temperature of the SOFC. Because the temperature of the gases leaving the PHE are larger during the power step of the GT the mixing ratio is smaller, although the inlet temperature of the SOFC is larger.

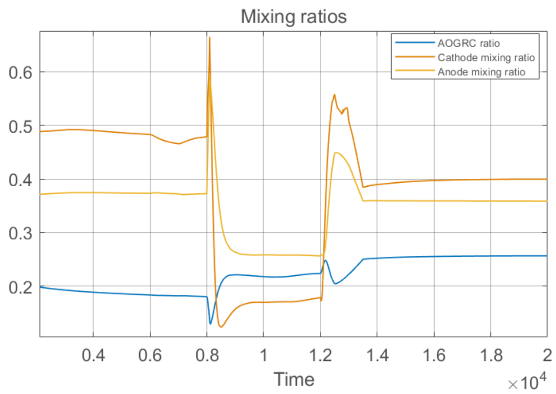


Figure F.13: The mixing ratios for the anode, cathode and pre-reformer.

## F.3 | Scenario II: Power Step from 'Operations/Economic Transit'

In this section of the report the additional simulation results of scenario II are presented and explained. These results will provide a more extensive overview of the system characteristics and behaviour.

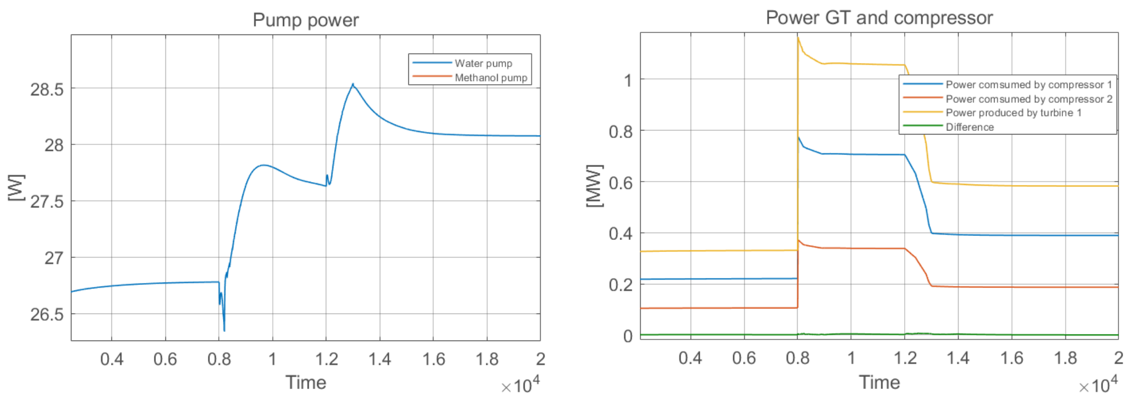


Figure F.14: The power consumption and production of different components.

The left-hand side of figure F.14 zooms in on the power consumption of the water pump earlier shown in figure 6.12. The fluctuations in the water supply, and therefore also the power consumption of the pump, have the same cause as in scenario I. The right-hand side of figure F.14 shows the power consumed by the compressors, the power produced by the first turbine and the difference between those powers.

The figures F.15 and F.16 show the temperatures of the flow in and out of the PHE. Also in this scenario it is clearly visible that the thermal inertia of the PHE affects the temperature of the outflow substances, making the temperature difficult to control manually, especially for the methanol and water flow. For that reason, the temperature of the methanol and water leaving the PHE show some fluctuations.

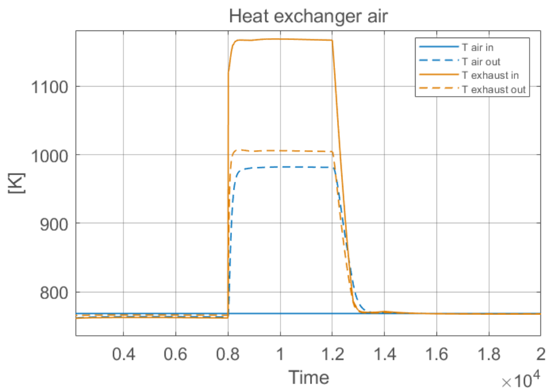


Figure F.15: The temperatures in the PHE for air and anode gases.

In figure F.16 can be seen that the temperature of the methanol during 'Operations/Economic Transit' is larger than the 445 K of superheated methanol. This is for the same reason as described in scenario I. To prevent excessive temperature in the pre-reformer this is compensated with a water temperature which is just below the 485 K of superheated water, also the same as in scenario I. The combined energy of the water and methanol is kept nearly constant as can be seen in the left-hand side of figure F.17.

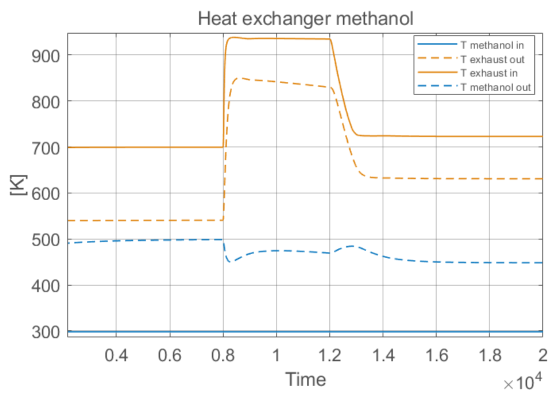


Figure F.16: The temperatures in the PHE for methanol and water.

On the right-hand side of figure F.17 the temperature of the outflow gases of the anode and cathode is displayed as well as the temperature of the PEN of the SOFC and the interconnect. From this figure it is clearly visible that the temperature of the SOFC influences the temperature of the outflow gases. What stands out is that the outlet temperature of the cathode flow only increases when the power supply of the SOFC, by means of an increasing current density, is increased. The outflow temperature of the anode flow already increases when the inlet temperature of the anode flow increases.

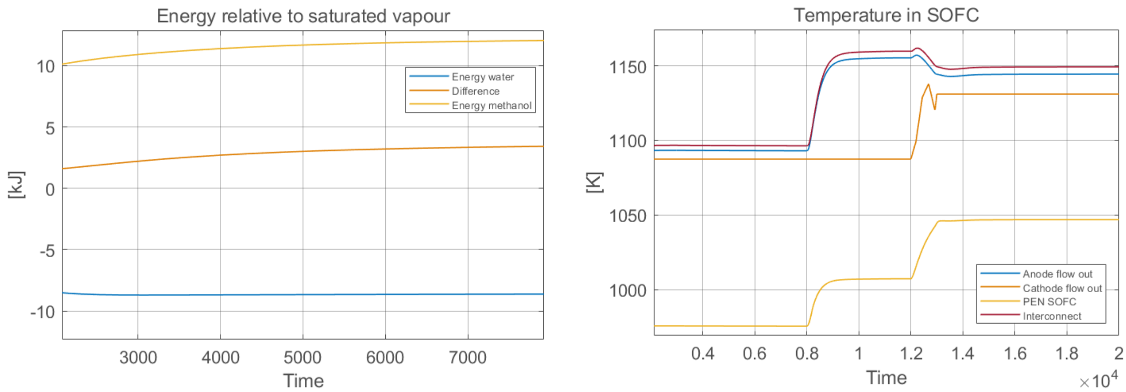


Figure F.17: The energies of the methanol and water flow and the temperatures of the SOFC.

In the figure below, figure F.18, the composition of the fuel in the anode gases and the fuel supply into the first combustion chamber is displayed. The left-hand side gives a complete overview while the right-hand side zooms in on the substances that are barely present in the anode flow. The amount of a certain substance is influenced by the operation of the pre-reformer and the SOFC.

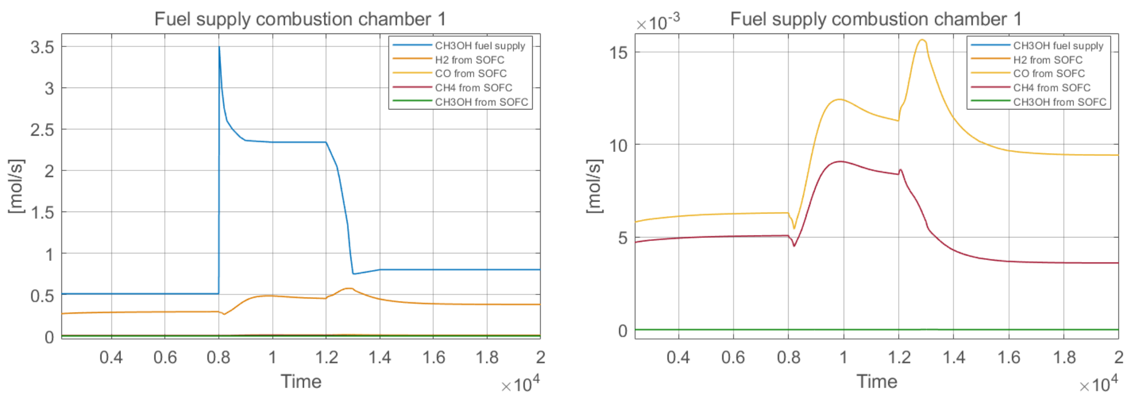


Figure F.18: The composition of the anode gases and fuel into the first combustion chamber.

In figure F.19 the available water flow for the central heating and the utilization ratio of the Hydrogen in the SOFC are shown. On the left-hand side can be seen that during the power step of the GT the water available for the central heating is larger, which is the same as in scenario I. The right-hand side shows how much of the Hydrogen flowing through the SOFC is used. The fluctuations in the utilization ratio are caused by the fuel consumption of the pre-reformer, caused by the temperature of the methanol, and the operation of the SOFC.

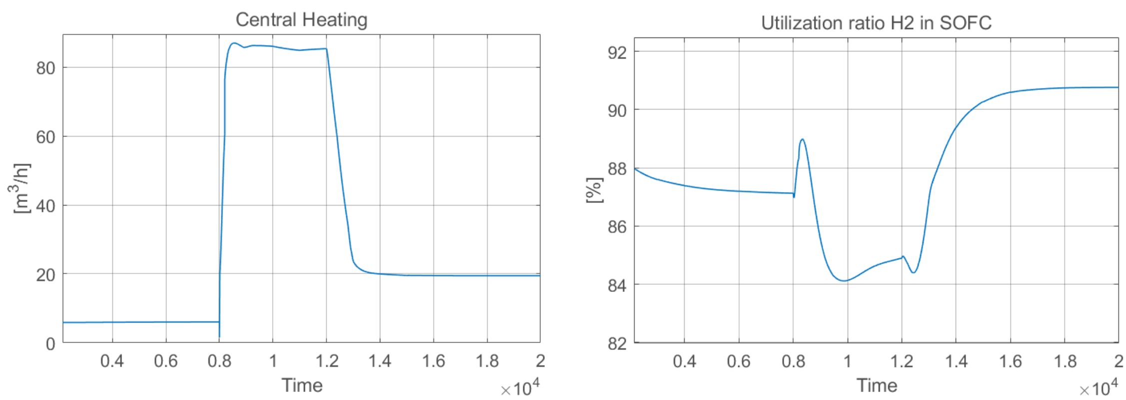


Figure F.19: The available water flow for the central heating and the utilization ratio in the SOFC.

The $CO_2$ emissions and the fuel consumption during the operation of the power unit is displayed in figure F.20 at the left- and right-hand side, respectively. It shows an increase in both fuel consumption and emissions during the power step.

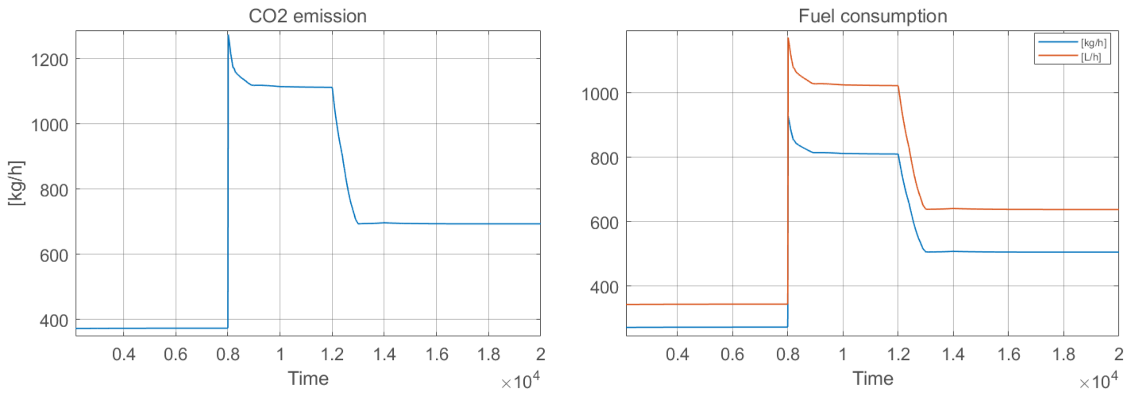


Figure F.20: The $CO_2$ emission and fuel consumption of the power unit.

The figure F.21 shows the mixing ratios of the mixers for the anode and cathode as well as the AOGRC flowing into the pre-reformer to control the temperature. The amount of mixing ratio is depending on the temperature of the gases leaving the PHE and the inflow temperature of the SOFC.

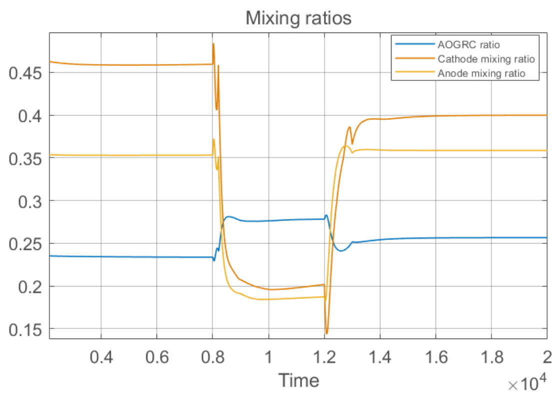


Figure F.21: The mixing ratios for the anode, cathode and pre-reformer.

## F.4 | Scenario III: Power Step from 'High Speed Transit'

In this section of the report the additional simulation results of scenario III are presented and explained. These results will provide a more extensive overview of the system characteristics and behaviour.

The left-hand side of figure F.22 zooms in on the power consumption of the water pump, earlier shown in figure 6.16, and shows that it is more constant, which is caused by a more constant methanol temperature than in scenario I and therefore also a more constant water consumption. The increase between 8,000 and 13,000 seconds is caused by the increase of the methanol temperature and the automatic correction of the pressure by adding more methanol. Since the water supply is coupled to the methanol supply the water supply also increases. In the right-hand side of figure F.22 the power consumed by the compressors, the power produced by the first turbine and the difference between those powers is shown. Also, here the same profile as in other scenarios is visible.

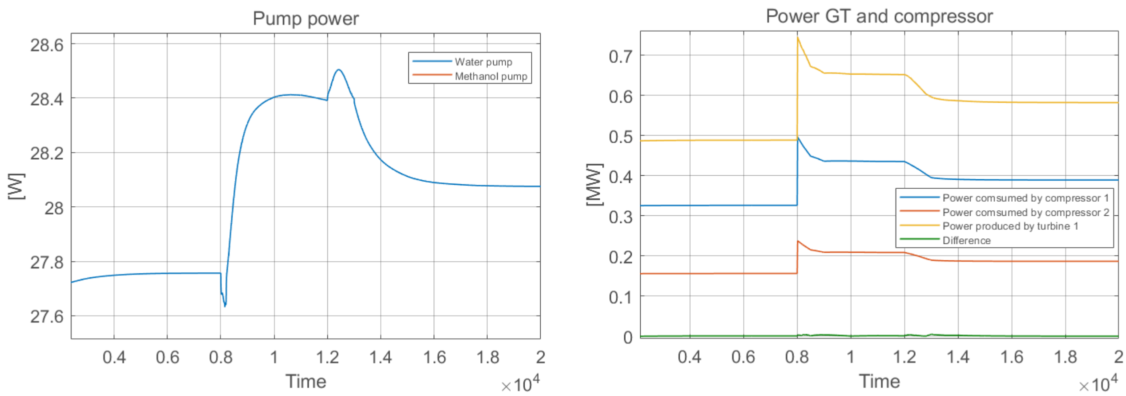


Figure F.22: The power consumption and production of different components.

On the left-hand side of figure F.23 the temperature of the outflow gases of the anode and cathode is displayed as well as the temperature of the PEN of the SOFC and the interconnect. Furthermore, the utilization ratio of the Hydrogen in the SOFC is shown on the right-hand side. Compared to the other scenarios there are less fluctuations, which is caused by are more constant temperature of the methanol leaving the PHE and therefore also a more constant fuel supply to the pre-reformer.

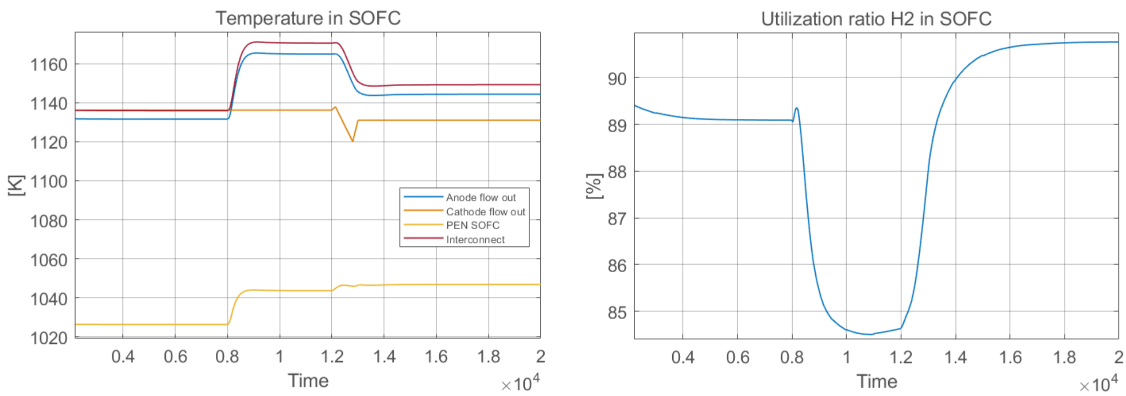


Figure F.23: The temperatures of the SOFC and the utilization ratio in the SOFC.

The temperature profiles of the PHE in the power unit can be found in figures F.24 and F.25. In the other scenarios this made the temperatures of the gases difficult to control manually, especially for the methanol and water flow. However, in this scenario the differences are smaller making the temperatures of the gases easier to control manually. In figure F.25 can be seen that the temperature of the methanol and water is always above 445 K and 485 K, respectively. Furthermore, there are no large temperature fluctuations.

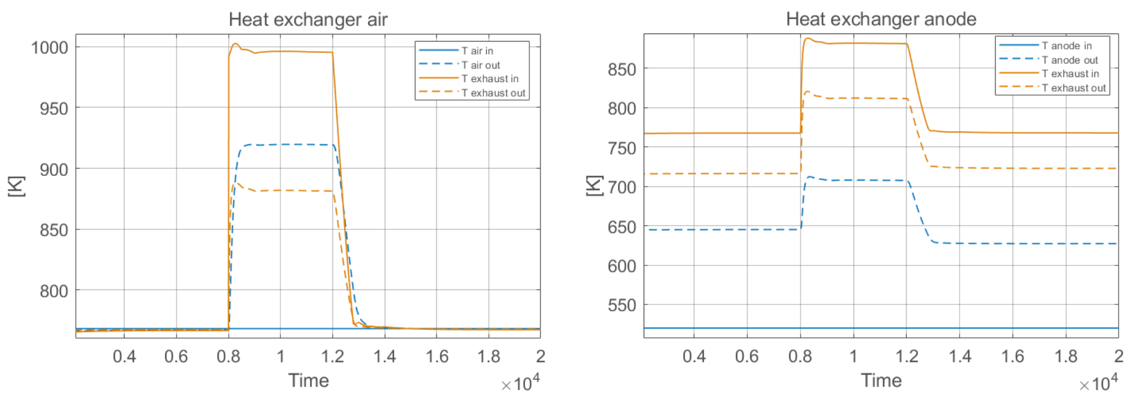


Figure F.24: The temperatures in the PHE for air and anode gases.

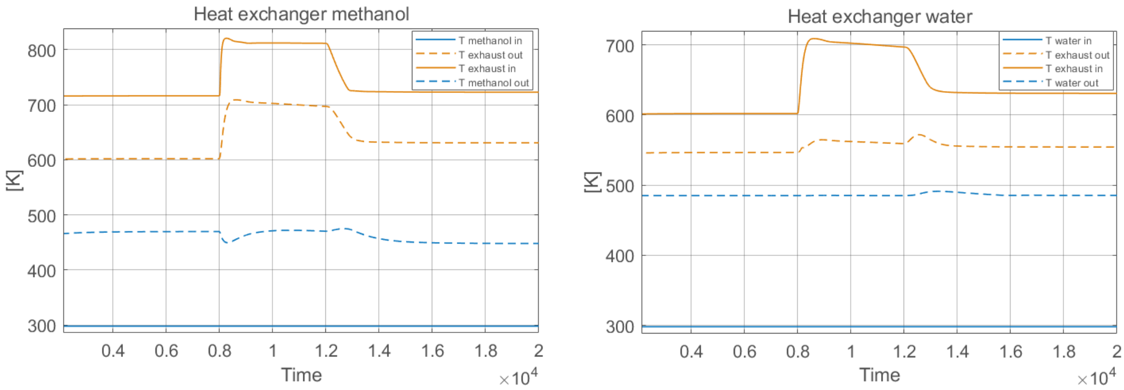


Figure F.25: The temperatures in the PHE for methanol and water.

The $CO_2$ emissions and the fuel consumption during the operation of the power unit is displayed in figure F.26 at the left- and right-hand side, respectively. It shows an increase in both fuel consumption and emissions during the power step. The profile does not differ from the results of scenario I and scenario II.

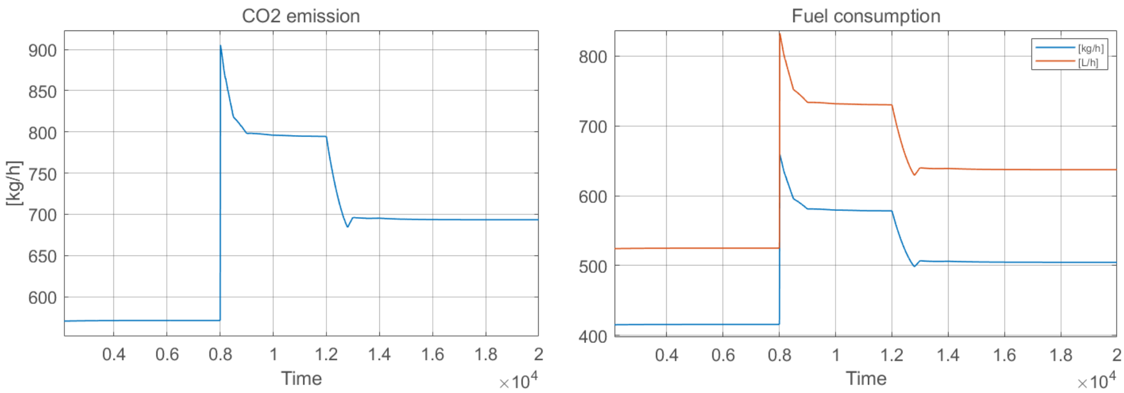


Figure F.26: The $CO_2$ emission and fuel consumption of the power unit.

In the figure below, figure F.27, the composition of the fuel in the anode gases and the fuel supply into the first combustion chamber is displayed. The left-hand side gives a complete overview while the right-hand side zooms in on the substances that are barely present in the anode flow. The amount of a certain substance is influenced by the operation of the pre-reformer and the SOFC. Also, these results show the same behaviour as in the other scenarios.

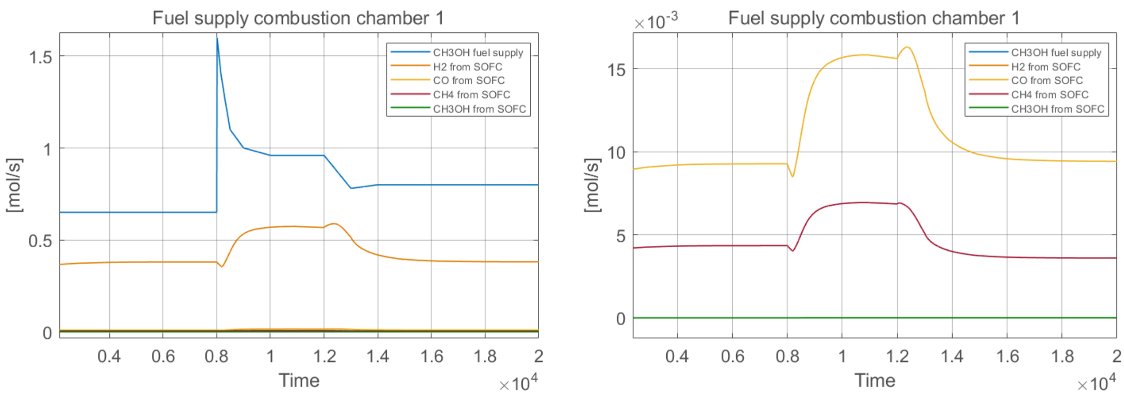


Figure F.27: The composition of the anode gases and fuel into the first combustion chamber.

In figure F.28 the available water flow for the central heating is shown on the left-hand side. Also here there is no difference compared to profile of the available water of the other scenarios. During the power step of the GT more water is available for the central heating. Furthermore, figure F.28 shows on the right-hand side the mixing ratios of the mixers for the anode and cathode as well as the AOGRC flowing into the pre-reformer to control the temperature. Since the methanol temperature was more constant in this scenario the AOGRC was also more constant. Furthermore, the mixing ratio for the anode is larger because the outlet temperature of the anode PHE is lower due to a lower temperature of the exhaust gases.

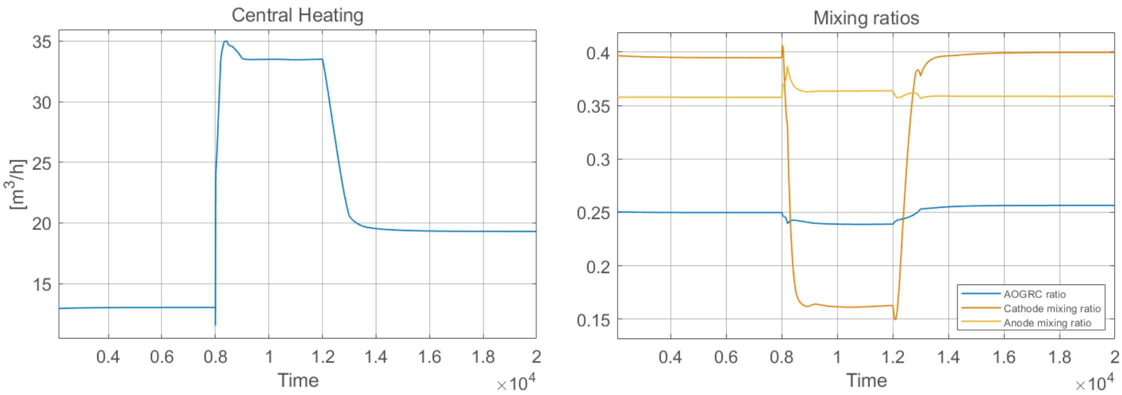


Figure F.28: The available water flow for the central heating and the mixing ratios.

# G | Decision Database

In this chapter of the report all the decisions made during the investigation are noted.

| ID | Description of the decision and argumentation | Consequences |
|---|---|---|
| 1. | A GT will be used for increasing the dynamic behaviour and using the residual fuel since the reliability, gravimetric and volumetric power density of GT are higher than those of the ICE. Furthermore, the gases from the SOFC have to be cooled, at the expense of efficiency, before they can be used in the ICE [14, 75]. | Operation of the GT in the configuration needs to be considered. |
| 2. | The SOFC will be operated **as** constant **as possible** since this increases durability, reliability, and maintenance. | 1. The GT has to respond to the load changes of the system and cannot be placed in series with the SOFC.<br>~~2. Constant fuel, steam, and air supply to the SOFC while varying fuel supply to the GT.~~<br>3. AC power from the GT has to be combined with the DC power from the SOFC |
| 3. | An external reformer will be used to prevent temperature gradients in the SOFC caused by the endothermic nature of methanol reforming. | Operation of the pre-reformer in the configuration needs to be considered. |
| 4. | For the steam and fuel supply pumps will be used instead of compressors since pumps require less energy as they work with incompressible fluids. | Operation of the pumps in the configuration needs to be considered. The methanol and water will enter the system at liquid phase and need to be vaporized. |
| 5. | The air and fuel inflow will be pre-heated, **using waste heat**, before entering the combustion chamber to reduce the fuel consumption and increase efficiency. | More HE, resulting in more weight and space taken by the power unit. |
| 6. | Batteries and SC will be used for peak shaving, energy storage and as power assistants. | Even faster response to load change, faster start-up time and better efficiency. |
| 7. | After leaving the pre-reformer the gases will be heated, **using waste heat**, to prevent thermal stresses in the SOFC | Extra HE ~~or addition of external heating,~~ resulting in more weight and space taken by the power unit. |
| 8. | The water and methanol will be pre-heated, **using waste heat**, before entering the pre-reformer using waste heat to increase efficiency. | 1. Less AOGRC required to maintain the pre-reformer temperature.<br>2. More HE, resulting in more weight and space taken by the power unit. |

| ID | Description of the decision and argumentation | Consequences |
|---|---|---|
| 9. | One pump will be used for fuel supply to both SOFC-system and GT-system. | Less space and weight taken by the power unit. |
| 10. | One compressor will be used for air supply to both SOFC-system and GT-system. | Less space and weight taken by the power unit. |
| 11. | The compressor and turbine will be directly coupled using a shaft and therefore reducing the losses due to efficiencies. | 1. The efficiency and operation of the shaft needs to be considered.<br>2. The rotational speed of the turbine en compressor will be the same. The same holds for the power production of the turbine and the power consumption of the compressor. |
| 12. | Waste heat from the GT will be used for preheating the flows in the system. | 1. The efficiency will increase since external heating can be left out.<br>2. Decision 5. and 8. are adapted. |
| 13. | Combustion **of the fuels in the anode gases** in the **first** combustion chamber will occur at four times the amount of air required for complete combustion to avoid excessive temperatures. | Larger air flow and the influence to the temperature in the mixing chamber needs to be considered. |
| 14. | The requirements will be very variable during the study because the development of the new naval vessel is still in full swing. | The requirements can still change during and after the investigation. |
| 15. | The compressor for the power unit will be shared with the low-pressure air system of the naval vessel. | 1. Saving space and weight of one compressor.<br>~~2. Increase of air flow through the first stage compressor.~~<br>~~3. Due to the variable flow the first stage compressor cannot be coupled to the turbine by a shaft.~~<br>4. The pressure ratios will be 10 for the first compressor and 2 for the second compressor. |
| 16. | The water pump for the power unit will be shared with the drinking water system and warm water system of the naval vessel. | 1. Saving space and weight of two pumps.<br>2. Increase of water flow through the pump.<br>3. Drinking water has to be used in the SOFC. |
| 17. | The waste heat leaving the power unit will be used for heating the water in the warm water system and central heating of the naval vessel. | Saving the energy of three 15 kW electrical boilers and external heaters and therefore increasing the efficiency. |
| 18. | Intercooling will not be applied in the configuration since the heat obtained by compression is required in the SOFC. | One less HE reducing space and weight. |
| 19. | The first stage turbine will be used to drive the second stage compressor. | 1. Air supply for both SOFC and GT can be kept constant without influencing the power output.<br>2. Fuel and air supply to the first turbine has to be adjusted to the required power.<br>3. Second turbine will drive the generator. |

| ID | Description of the decision and argumentation | Consequences |
|---|---|---|
| 20. | Both compressors will be coupled to the GT using a shaft since the required power of the first stage compressor exceeds the maximum power. | 1. Consequence 3. of decision 15. is deleted. 2. No separate air flow for the air system, but tapping the air flow to the second stage compressor. So, consequence 2. of decision 15. is also deleted. |
| 21. | Use waste heat from the GT to pre-heat the anode flow, reach higher temperatures and prevent excessive temperature gradients in the SOFC. | 1. One more HE, resulting in more weight and space taken by the power unit. 2. Decision 7. is adapted |
| 22. | The air in the second combustion chamber will be at least 2 times the air required for complete combustion of the fuel to prevent excessive temperatures in the second turbine. | 1. Air supply to the GT system influences the output power of the second turbine. 2. Decision 13. is adapted. |
| 23. | To control the temperature of the methanol, water and anode flow via the PHE bypasses will be used. Via these bypasses the amount of energy flowing into the PHE can be controlled. | 1. Consider the bypass ratios in the simulation model and design. 2. Extra mixing chambers. |
| 24. | During the 'Low speed and station keeping' operation of the naval vessel the temperature of the methanol leaving the PHE will be larger than just above superheated temperature to prevent the methanol temperature from decreasing to below the saturated vapour temperature when increasing the fuel supply during load step of the GT. | 1. The temperature of the water needs to compensate for the amount of energy of the methanol, so the temperature will be lower than saturated vapour temperature. By this way the energy flowing into the pre-reformer will be kept nearly constant. 2. The PHE for methanol and water can have a combined bypass. |
| 25. | Decision 24. also holds for 'Operations/ Economic transit' operation | See decision 24.. |
| 26. | The two turbines will have the same expansion ratio to maximize the work output [61]. | The expansion ratios will be 4.5 for the first turbine and 4.4 for the second turbine. |
| 27. | To save space and weight the air flow for the GT system and the cathode will share a PHE. | The inflow temperature of the cathode flow will increase during larger power step of the GT. |
| 28. | The order of the PHE for the water and methanol will be switched in the design. Since the methanol flow is larger than the water flow it requires more heat to reach the required temperature. | Consider this change in the simulation model and the design. |
| 29. | To increase efficiency after load steps, the SOFC power production can also be varied. | Decision 2. is adapted. |

Table G.1: The decision database containing the decisions, argumentation and consequences.

# H | SE Process Evaluation

The implementation of the SE process in combination with a thermodynamical investigation was part of a pilot to investigate whether these two disciplines can be applied together properly. In this chapter the evaluation of the pilot will be presented and discussed in two phases. In the first section the design process using SE will be discussed while in the second section the simulation process is considered. These two processes are chosen since these were the two main parts of the investigation.

## H.1 | Design Process

During the design of the power unit the application of the SE process turned out to be very useful. By using the processes and documents prescribed in the SE process, it became possible to systematically create a design of the power unit. In addition, the use of these processes required a lot of contact with the client, which made it even clearer on paper what he expected from the power unit. This made it even better to try to meet the requirements of the client. In other words, much better targeted research could be done.

Also, by using documents such as the FFBD, RAS and the SBD, the choices made during the process and the structure of the design could be better argued and described. This resulted in more support among the client and he also participated more actively in the research, which then benefited the research.

However, due to the phase in which the project is located, the SE process could not be applied correctly. For example, the possibilities for integration could not be converted into requirements as should be the case within the process. In thermodynamic studies, it will often be the case that not all possibilities are converted into requirements. This will mean that in such studies the SE process cannot be applied correctly. However, if SE allows this, this does not affect the applicability within thermodynamic studies.

All in all, it can therefore be said that the use of the SE process and is a very valuable addition in the design process of a thermodynamic system.

## H.2 | Simulation Process

SE played a much smaller role in the process of simulating the system than in the design process. In principle, it can be said that simulating is part of the verification process of the system, but in fact a lot is changed about the design during the simulation. It is not the case that only small things need to be adjusted to verify the system, but there are also quite large changes being made. This means that the SE process cannot be applied correctly in such a study and is therefore not a valuable addition. After all, verifying the system is already applied automatically during simulating.

As for the choices made during simulating, the SE process offers a valuable addition. By using the decision database, it is much better to trace which decisions were made and what influence they had. This in turn ensures that these decisions can be well discussed with the client.

# Hybrid Power Units in Naval Support Vessels

The Ministry of Defence (MoD) has to be able to fulfil its constitutional duties, and therefore has to be as agile and reliable as possible. The dependency on fossil fuels, of which the availability and affordability is expected to come under pressure in the coming years, is a threat to the execution of these tasks. Furthermore, the use of fossil fuels is harmful to the environment.

The technology of methanol fuelled Solid Oxide Fuel Cells (SOFC) is a promising tool to efficiently power naval vessels with alternative fuels and without producing pollutants. However, a standalone SOFC power unit lacks the ability to provide either adequate efficiency or load-following capabilities. Therefore, the configuration of the SOFC system needed to be enhanced to make this power unit suitable for naval applicability.

The early Systems Engineering (SE)-based decision to use a Gas Turbine (GT) has been confirmed by the literature, which concluded that the GT has the most potential. Therefore, the SOFC-based power system became a hybrid system consisting of a SOFC and a GT.

What exactly the configuration of the methanol fuelled SOFC-GT hybrid power unit should look like to achieve naval applicability was the objective of this study. During this improvement process also subjects, like compactness, durability, usability, emissions, maintenance, and reliability, were considered.

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