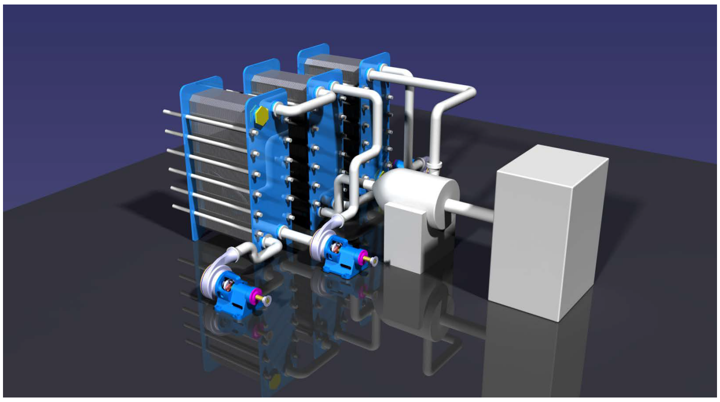

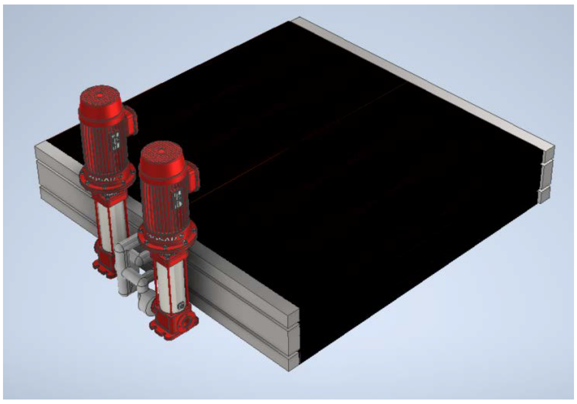

Waste Heat Recovery for Fuel Cells

Global Capstone Project with Volvo Group

Bachelor's thesis 2021:03

HUNTER DIDOMIZIO, CHINMAY GUPTA, SHREYA MANJO, ROSELLEN MARTIN, DEEKSHA SHARMA, JESPER LIDQVIST, JUSTUS LINDQVIST, ROBERT SUGUMARAN, FREDRIK ÖZARAS

DEPARTMENT OF MECHANICS AND MARITIME SCIENCES

CHALMERS UNIVERSITY OF TECHNOLOGY Gothenburg, Sweden 2021
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HUNTER DIDOMIZIO
CHINMAY GUPTA
JESPER LIDQVIST
JUSTUS LINDQVIST
SHREYA MANJO
ROSELLEN MARTIN
DEEKSHA SHARMA
ROBERT SUGUMARAN
FREDRIK ÖZARAS

Department of Mechanics and Maritime sciences
Chalmers University of Technology
Gothenburg, Sweden 2021
Department of Mechanical Engineering
Pennsylvania State University
State College, Pennsylvania, The United States of America 2021

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HUNTER DIDOMIZIO, CHINMAY GUPTA, SHREYA MANJO, ROSELLEN MARTIN
DEEKSHA SHARMA, JESPER LIDQVIST, JUSTUS LINDQVIST
ROBERT SUGUMARAN, FREDRIK ÖZARAS

Supervisor: Sven Andersson, Department of Mechanics and Maritime Sciences, Chalmers
Supervisor: Erik Hulthén, Department of Industrial and Materials Science, Chalmers
Supervisor: Alf Magnusson, Department of Mechanics and Maritime Sciences, Chalmers
Examiner: Mikael Enelund, Department of Mechanics and Maritime Sciences, Chalmers

Bachelor's thesis 2021:03
Department of Mechanics and Maritime sciences
Chalmers University of Technology
SE-412 96 Göteborg, Sweden
Telephone +46 31 772 1000

Cover: CAD model of the final concepts designed in CATIA (2021) and Autodesk Inventor (2021) by Robert Sugumaran and Deeksha Sharma.
Gothenburg, Sweden 2021

Abstract

Fuel cells are one of the cleanest ways of generating electricity, and as they the gain in popularity, the waste heat recovery (WHR) of these systems becomes increasingly more important. This is because it's possible to reuse this waste heat that the system produces for the purpose of reaching a higher overall efficiency for the entire system. Certain fuel cells, such as a proton-exchange membrane fuel cells (PEMFC), can operate at low temperatures with an efficiency close to 60%, making them well suited for non-stationary applications such as vessels or vehicles. The approximated energy loss, of 40%, for these fuel cells are in the form of dissipated heat at a low temperature of 75 °C. The aim of this project was to develop a WHR system for the low temperature waste heat dissipated from a PEMFC. For this project the waste heat of a 300kW PEMFC is used. The report documents the concept selection process, design and simulation of the selected concepts. To analyze, eliminate and select solution concepts, thorough research of the scientific literature on low temperature WHR systems was conducted and the three final concepts were compared with a Pugh matrix. The concepts were evaluated on efficiency, production cost, ambient conditions, maturity and physical dimensions. The two concepts that were deemed the most viable and practical solutions concepts were the Organic Rankine Cycle (ORC) and the Thermoelectric generator (TEG). The concepts were further developed and evaluated with the help of running simulations of the WHR systems in MATLAB Simscape and COMSOL Multiphysics, as well as designing 3D models of the systems in CATIA V5 and Autodesk Inventor. From the simulations of the selected concepts, the ORC proved to be more efficient at recovering heat with an overall system efficiency gain of 5 percentage point and an electrical output of 25kW. TEG has a comparatively low power output for its size as well as a high installation cost and requirement of low thermal fluid pressure. However, as the ORC entail more moving parts, as well as a working fluid, its operating process is more costly than the TEG's. The project concluded that the ORC is the most efficient and viable solution concept for WHR, however, the TEG concept holds the potential of achieving a much better efficiency rating with potential development in the semiconductor area and further optimization.

Sammandrag

Bränsleceller är en av de mest miljövänliga metoderna att producera elektricitet. Detta gör att de blir mer och mer populära, samt att problematiken kring bränsleceller blir viktigare att hantera. Problematiken grundas i dess verkningsgrad, samt den låga temperaturen som den producerade värmen har, vilket gör den svårare återvinna för att således öka systems effektivitet. De *proton-exchange membrane* (PEM) bränsleceller som användas idag har en verkningsgrad på ungefär 60%. Detta, tillsammans med att de fungerar vid låga temperaturer, gör att de lämpar sig specifikt för icke-stationära applikationer, så som fartyg och/eller fordon. De resterande 40% av verkningsgraden går förlorad, i huvudsakligen av spillvärme med låga temperaturer (runt 75 °C). Målet med detta projekt är därför att utveckla ett koncept, vars syfte är kunna ta vara på och återvinna spillvärmen, och på så sätt öka den allmänna verkningsgraden av systemet.

Projektet utgår från en PEM bränslecell med en effekt på 300kW. Med denna som utgångspunkt genomfördes en sållningsprocess av olika lösningskoncept, de som verkade mest lovande blev även designade och simulerade. Sållningen grundades först i litteraturstudier inom relevanta ämnen, vilket eliminerade ett större antal av de genererade lösningskoncepten. För att sedan få fram det mest lovande konceptet av de koncepten används en Pugh-matris. I matrisen utvärderades verkningsgrad, produktionskostnad, installations förhållanden, mognadsgrad och fysiska dimensioner. Efter denna jämförelse bedömdes det att det var den Termoelektriska generatorn (TEG) och den Organiska rankinecykeln (ORC) som var bäst kvalificerade för att återvinna restvärme med låga temperaturer. Med hjälp av simuleringar i MATLAB Simscape och COMSOL Multiphysics, samt med 3D modeller i CATIA V5 och Autodesk Inventor, kunde de två koncepten utvecklas vidare och utvärderas. Simuleringarna visade att ORCn hade högst verkningsgrad för restvärmeåtervinning, med en ökad verkningsgrad av hela systemet med 5 procentenheter, och en elektrisk nettoproduktion på 15kW. TEGn hade i stället en lägre produktion av elektricitet, vilket resulterade i en betydligt lägre ökning av systemets verkningsgrad. Detta, tillsammans med de högre installationskostnaderna, gjorde att det slutligen blev ORCn som ansågs vara den bästa lösningen idag. Dock, även om ORCn är bättre idag har den även fler rörliga delar och en arbetsväska vilket bidrar till högre driftkostnad än TEGn, vilket gör att TEG har potentialen att få en avsevärd högre verkningsgrad i samband med fortsatt forskning och utveckling inom halvledare.

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Without the guidance and support from several individuals and teams, the completion of this project would not have been achieved. We would sincerely like to thank all of those involved in helping. Thank you to our professors, Paris Vonlockette at Penn State University and Mikael Enelund at Chalmers University of Technology. Additionally, we would like to thank the other faculty members at Chalmers University, Sven Andersson, Erik Hulthén, and Alf Magnusson, for providing weekly feedback and guidance during our progress. And thank you to our friend, Karin Lidqvist, for proof-reading a draft of this thesis and the great feedback that it entailed.

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Hunter DiDomizio
Chinmay Gupta
Jesper Lidqvist
Justus Lindqvist
Shreya Manoj
Rosellen Martin
Deeksha Sharma
Robert Sugumaran
Fredrik Özaras

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University Park, May 2021

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1 Introduction

With a rise of population, the demand of energy is constantly increasing. At the same time, the knowledge and concern regarding the greenhouse effect and climate change is described as the challenge of our generation. Therefore, the interest in clean, sustainable energy has increased significantly during the last couple of decades. However, most sustainable energy systems have their own drawbacks. Due to their dependency on weather conditions, solar power and wind turbines have significant electrical ramping constraints and are unreliable compared to fossil fuels.[1] Hydro-power, for instance, is more reliable in terms of generated power, but is highly restricted by geographic location.[2] Hydrogen fuel cells on the other hand, do not have geographic limitations or ramping constraints. Additionally, fuel cells are reliable in efficiency and power output, and can be used in a variety of applications. More recently, fuel cells have grown in popularity as they prove to be a more sustainable way to power vehicles including, but not limited to, marine vessels, automobiles, and trains. While fuel cells have promising potential, there are still significant inefficiencies as roughly 50 - 40% of the energy produced is dissipated as heat.[2] For this reason, waste heat recovery systems are being heavily researched as they offer an opportunity for waste heat to be captured and re-utilized, thereby increasing the overall efficiency of the fuel cell.

This project is sponsored by Volvo Penta and aims to design and simulate a waste heat recovery system in order to enhance the overall performance of a fuel cell in the context of a marine vessel. While there are a broad range of concepts for recovering waste heat, the team focused on two specific ones. The more prevalent approach being a Organic Rankine Cycle (ORC) system, it acted as a baseline comparison for the second more novel approach for waste heat recovery by means of a thermometric generator. The team consists of four students from Chalmers University of Technology, studying mechanical engineering and chemical engineering with engineering physics, in addition to five other members from Pennsylvania State University, with four students in the energy engineering program and another in mechanical engineering.

This work investigated the possibility of designing a system for waste heat recovery around a 300kW fuel cell on board a marine vessel. The main findings were that while research suggests other candidates could become viable in the future, the ORC system was the superior choice for efficiency.

1.1 Background

The most common fuel cell for vehicles and vessels is the proton exchange membrane fuel cell (PEMFC). The fundamentals of the PEMFC are shown below in Figure 1:

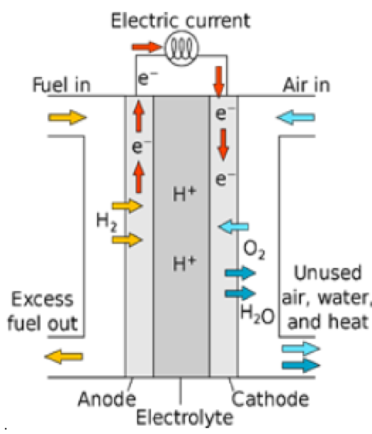


Figure 1: *Diagram of a PEMFC[3]*

The fuel cell consists of two sides, an anode and a cathode. On the anode side the fuel (di-hydrogen) is pumped in. When the fuel comes in contact with the membrane, the electrons get separated from the molecule, resulting in the creation of free electrons and hydrogen ions. The electrolyte helps the ions to pass through the cell. At the same time the free electrons are being led around the membrane, which create an electric current that can be used for power output. On the cathode side, the hydrogen ions and electrons react with the incoming oxygen that is in the air, and water is the result. Since the cathode reaction is exothermic, there will be some generation of heat. The anode and cathode reaction are shown in the two equations below:

$$2H_2 \longrightarrow 2H^+ + 2e^- \tag{1}$$

$$2H^+ + 2e^- + \frac{1}{2}O_2 \longrightarrow H_2O + \text{heat[W]} \tag{2}$$

As stated earlier, the primary disadvantage of the PEMFC is its low efficiency, because so much of the potential energy lies in the heat created by the reaction. Furthermore, the rejected heat from the fuel cell is typically a low temperature, thus, making it more difficult to recover find an implementation for in the system.

1.2 Problem Statement

Energy generation devices that release heat have the potential to become more efficient with the development of waste heat recovery (WHR) systems. While there are many applications that would benefit from a WHR system, this project in particular focuses on fuel cell applications. Apart from water created from the chemical reactions in a fuel cell, the cooling system must handle 100% of the rejected heat. The PEMFCs rejected heat is typically 75-80°C. A WHR system will process that waste heat and regenerate it into another form of energy for reuse, thus increasing the overall efficiency of a fuel cell. The fuel cell in this case is used to power a marine vessel. However, designing a WHR system that can scale to smaller or larger applications is ideal.

All production processes and machine operations experience wasted heat. This energy is released from each process in different ways, such as radiation, exhaust gas, or cooling fluid. Roughly 50-60% of the energy in a fuel cell is lost as heat and is transferred to the cooling system. The challenge behind this project is developing a system that is suitable for processing low temperature waste heat and fluids and in turn, produce more energy to be used on, or to power, the vessel. Using current technologies, the team of students will study existing WHR systems to determine potential candidate processes to adapt for the given situation. The common goal of the project is to design the best WHR system for a marine vessel powered by a fuel cell, all while learning to work as a global product development team.

1.3 Limitations

Due to the limited knowledge and practical applications regarding the subject, as it stands this project has certain limitations. For instance, although this project will focus on all viable options for recovering waste heat from a fuel cell, the goal is to not be limited by the existing solutions. This will require us to not anchor only on conventional solutions similar to Organic Rankine Cycle even if it is regarded as the current industry standard for low temperature WHR.[2] Additionally, the project will consider both a full system solution and a combination of two or more subsystems to achieve maximum efficiency. Furthermore, if a scaled down prototype is feasible, it would be manufactured in order to test the theoretical solution. However, a full-scale model will not be prepared given the difficulty to realize practical application, and any prototype limited to the waste heat recovery portion of the system.

1.4 Ethical and environmental aspects

Designing a WHR system for a fuel cell has full potential to be designed, manufactured, and operated ethically throughout its life cycle. There are several functions of the fuel cell and WHR system to consider during its operation. Since the main purpose of the WHR system is to increase the efficiency of the fuel cell itself, there are no significant negative implications. However, given the nature of the fuel cell being used to power a vessel or generator, manufacturing, operation, and maintenance should consider the potential environmental harm to marine and land ecology; as well as passengers or operators of the powered vehicle. Potential harm could ensue with the nature of the fuel cell operating to generate electricity in close proximity to water. The design of the WHR system should consider ethical standards across all its potential applications.

Another consideration is the source of hydrogen. Presently, most of the hydrogen for fuel cells is derived from fossil fuels, typically natural gas. Burning fossil fuels emits harmful greenhouse gases into the atmosphere. Combining the processes to retrieve hydrogen from reformed hydrocarbon molecules with carbon capture will help reduce carbon dioxide emissions. In the future, solar energy and biomass can be used to directly generate cleaner hydrogen more ethically.

Disposal and decommissioning of any and all liquids or waste materials used in the design and production of the proposed WHR system should follow local governmental and energy regulations. Manufacturing or construction of the comprehensive system should be produced to abide by labor and environmental laws.

The environmental aspect of this project is decidedly positive. The WHR system that will be developed/theorized, would increase the efficiency of the fuel cell while minimizing wasted energy. This will promote the use of fuel cells in many more applications, which entails a greener, possibly conventional method of energy generation. The success of this project would eventually increase the use of fuel cell powered vessels, trucks, cars, generators etc. This would in turn surely aid the advancement of clean energy and help the world move towards the eco-friendly practices, which would be in line with The Sustainable Development Agenda[4] produced by the UN.

A successful endeavor in increasing the efficiency of of a PEMFC application would surely be a helpful step in achieving the high goals set by The Sustainable Development Agenda[4]. Mainly in reference to goal #7 Clean energy where clean energy produced by fuel cells are a good step, but also #11 Sustainable cities and #12 Responsible consumption. The team also wished to believe that the cooperation done here between Chalmers, Penn State and Volvo Penta is in line with goal #17, Partnership for the goals.

2 Method

In order to generate well developed and functional systems that could provide a solution to the task supplied by Volvo Penta, a system for how the team was to proceed was needed. To start making headway with the work ahead, ample amounts of research on the subject had to be made. These, in combination with studying the customer needs and specifying the system boundaries in a black box diagram, were the first parts of the work to be done. Following these first steps a detailed plan on how the project should continue was formed, Figure 2 below illustrates this plan.

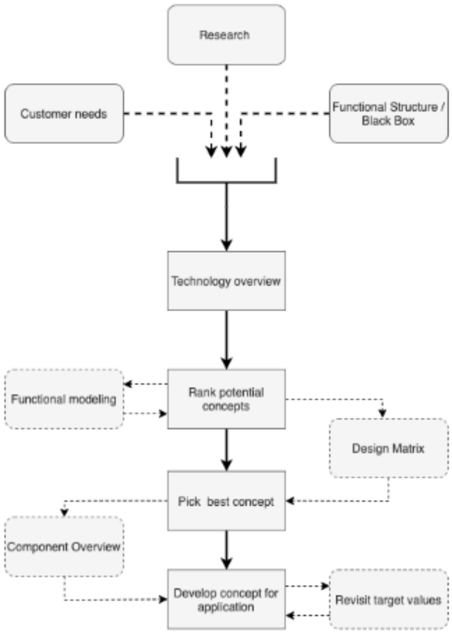


Figure 2: *Guiding flowchart for project work*

2.1 Research

To gather information about what concepts are currently available, research about WHR and PEMFC was conducted throughout. Possible solutions were evaluated; advantages and disadvantages weighed against each other, and different characteristics were studied and measured. In doing so, the team was able to compare them to each other and make an educated assumption as to what would best serve our purpose. Early on in the project, the entire team was assigned to the same preliminary research. As viable design ideas were derived, the team designated specific tasks and/or topics to team members as required. Specialization of tasks allowed for ownership of work in order to meet certain tasks and assign deadlines for the customer.

2.2 Customer Needs

Next followed the specifications of costumer needs, as it is part of the product development process. This project, being sponsored by Volvo Penta, customer needs were based upon their specifications and wishes, as well as end consumer satisfaction. Based on the information given to the team, this project was given the focus of marine shipboard application. Additionally, as meetings kept occurring throughout the timeline of the project, the customer needs were updated to better suit the customer. Determination of customer needs did not only consist of what Volvo Penta requires, but was also based upon external research from literature review.

In doing so, the following needs were derived when designing a WHR system for the 300kW on board a marine vessel:

- While the system must recover heat, it cannot have an overall loss of efficiency At any operational stage. Therefore, the proposed solution should aim for a 5% increase in overall efficiency.
- The proposed system should not be too costly to maintain, to the point where it outweighs power recovered. Similarly, the system should not be overly expensive to manufacture.
- The system should be durable enough to compare to a common diesel engine.
- Similar to automobiles produced to scale, the WHR system should also be designed with the intention of mass production.
- Larger sized systems could potentially generate more electricity, but that possibility has to be balanced with vessel constraints.
- The WHR system should be versatile enough to be used in marine applications of varying size.
- A complex WHR system equates to higher production and maintenance costs; lower numbers of subsystems is more cost-effective over a longer period if time.
- The proposed solution should not be louder than the fuel cells it is working with.
- Ideally, the WHR system should work in any number of ambient conditions, even if it is running in extreme heat or in a snowstorm.

In order to balance contradicting needs, a quantitative method was used to compare different requirements. Every specification was assigned an importance value ranging from one to five, with one being the least important and five being the most. Along with its graded importance, every specification was also given a threshold value and an objective value, to show the range every concept should aim for. This information is demonstrated in Table 1 for comparison. The specifications were ranked based on what the sponsor, Volvo Penta, required from this project as outlined in the teams initial meeting with them. For example, the sponsor has asserted that determining a novel method of producing electricity should be the main focus of this project. Thus, the electricity output metric has the highest importance value of 5. Additionally, the efficiency of the system affects the output of electricity so it would also have a higher importance value than another specification, such as ease of mass production. Because ease of mass production is an area that requires further research and development, it may fall out of the scope of what this team can control and thus will not be highly valued in terms of the final product. It is important to note that the specification of electricity output also encompasses any other possibilities such as heat recycled for preheating the fuel cell.

Table 1: *Customer Needs*

Spec. No.	Specification	Importance	Threshold Value	Objective Value	Units
1	Efficiency	5	3	5	%
2	Electricity Output	5	20	>30	kW
3	Maintenance Cost	1	600	>400	$
4	Durability	3	800	>1000	Newtons
5	Temperature Homogeneity	3	$\Delta 30$	$> \Delta 30$	°C
6	Ease of Mass Production	2	40	>50	Units/year
7	Size	3	8	<5	m^3
8	Versatility	1	1	2	Vessels
9	Weight	3	500	380	kg
10	Production Cost	2	300	134	$10^3$$
11	Complexity	4	6	5	Subsystems
12	Time to Market	2	24	12	Months
13	Noise	1	80	60	dB

2.3 Black Box

To conceptualize the problem in a non-solution-based manner, a black box of the system is produced, see Figure 3. The important inputs are the hot circuit from the fuel cell and the cooling water from the sea or cooler from a generator set (genset). The team also decided to include a power supply, input information, and some eventual utilities for the processes in the system. The main output of the black box was energy that is readily available for a particular application.

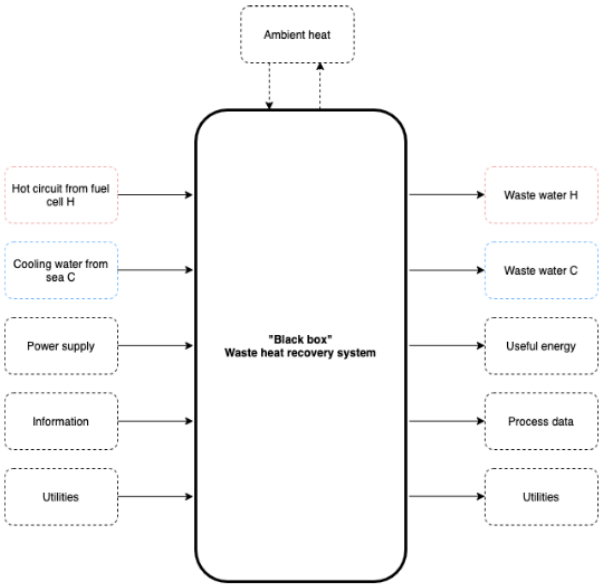


Figure 3: *Black box diagram for WHR system*

2.4 Functional Structure

A preliminary functional structure was created to visually conceptualize the sub-functions in the system. The main function of the system was to recover waste heat produced by the PEMFC; this function is divided into the sub-functions shown in Figure 4 along with how they interact with each other. The team worked with the functional structure to generate concepts for solving each sub-function. The diagram was kept as general as possible as to not prematurely imply a solution. The system boundary was estimated from the mission statement. The inputs and outputs were established from the black box. The representations of the different lines are clarified below the diagram.

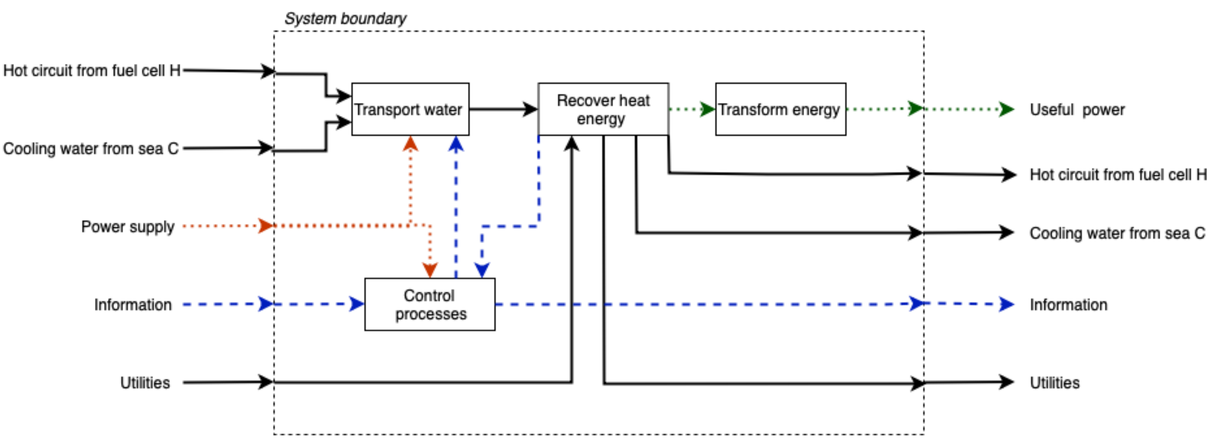


Figure 4: *Proposed functional structure for WHR*

2.5 Technology

This section is an overview of the concepts studied and identified in existing research. The focus was on the sub-systems outlined in the functional structure, mainly transport of water, recovering heat energy, transforming energy (to electricity) and control of the process. The overview contains the cycles/processes applicable, deselecting non-applicable thermodynamic cycles, such as internal combustion that does not fit into the work intended by the functional structure. The work produced a literature review, providing summary, description, and critical evaluation of a particular process and its inherent properties. Thus, the review highlighted the research relevant to our specific areas. The research was summarized in a literature review document for reference in the technological overview part of the final report.

2.6 Concept Generation

Below is a preliminary list of concepts from the initial concept generation and brainstorming sessions:

- Utilization of steam to pre-heat the fuel cell for greater efficiencies
- Steam reformation and/or water gas reactions to increase hydrogen feed rate
- Improving upon the existing ORC systems
- Use of alternative cycles such as Stirling-cycle
- Utilizing electricity from the fuel cell to super heat the steam (so as to increase the delta, therefor facilitating heat recovered through steam turbines, or TEG)
- Production of static electricity from heat
- Thermoacoustic: heat exchangers with rectifier induce acoustic waves producing electricity by a linear alternator or bi-directional turbine.
- Thermoelectric: Using materials with Thermoelectric properties (semiconductors) to produce an electric potential, recovering energy from the waste heat.
- Utilizing a thermosyphon, for thermal integration between a chemisorption system and the fuel cell.

2.7 Evaluation Potential Concepts

The ranking of potential solutions for the problem was arranged so the maximum costumer value could be achieved. According to The value model[5], the costumer value can be defined as:

$$\text{Customer Value} = \frac{\text{Satisfaction of needs}}{\text{Use of resources}} \tag{3}$$

According to the definition, costumer value can increase by two different approaches. Either by increasing the satisfaction, which is made by increasing the numbers of costumer needs that have been solved, or solving the needs with a better quality. Another approach is to focus on the denominator, making it as small as possible. This is achieved by decreasing the time, money or/and effort that the costumer must put into the product.

The first step of the ranking is there to eliminate the potential solutions that do not satisfy all the customer needs. This was done with the use of a screening-matrix. However, it should also be stated that the different concepts and solutions can be modified in this state so that they fulfill every costumer need. The concepts that passed through the screening-matrix were put into a different Pugh-matrix. At this state, the different concepts were compared in regard to how well they fulfill the different costumer needs. By having one of the concepts as a reference it was clear if the rest is better or worse at fulfilling the customer needs. By changing the reference, and comparing the different scores, the risk of being biased was minimized. Also, when necessary, this process was iterated with different improvements to the concepts to ensure that the best possible concept was not overlooked.

2.8 Develop Concept

Once the qualitative optimization comparison was complete and the best possible concept was selected, a detailed mathematical analysis was conducted to provide energy production, efficiency, and design specifications. This was achieved after continued research of the applicable parameters and variables that pertained to the chosen system. With this, a comprehensive explanation of how the WHR system and its sub-components operate was developed.

In addition to the detailed written and mathematical computation of the selected WHR design, a CAD drawing of the engineered device and a simulated heat flow map was developed as a visual. The written explanation was cross referenced with the rendered design of the system. It was agreed that these figures be produced internally by the team using CATIA or a similar software, but if needed could be outsourced by a design company or other students that can assist with making the product come to life, meeting the customer and consumer needs.

2.9 Risk Plan

In an effort to identify, evaluate, and plan for potential issues during the progression of the project, a risk plan was produced as a guiding document. Part of the process was identifying and planning for potential risks. The risk plan focused on a few subjects, such as management and organizing external risks. In addition to the risk plan, a team contract has been signed by all team members, stating the planned meetings and communication regime, how files are handled and stored, along with planned workload distribution in an effort to align the teams work and avoid potential issues in these areas. The process started with defining the impact levels to a numerical basis used in the later evaluation. The risk is quantified on a level of 1-5, increasing number, increasing impact. The plan was defined for performance (Result), schedule and team/individual workload in Table 2.

Table 2: *Risk Plan Weighting*

Level	Performance impact	Schedule Impact	Workload Impact
1	No impact	No impact	No Impact
2	Minor impact	No effect on milestones	Less than 3 hours of additional work for the team
3	Moderate impact	Still able to meet milestones, revised time plan	less than 9 hours of additional work for the team
4	Significant	Major revision of planning, risk of missed deadline	Less than 20 hours of additional work for the team
5	Severe	Schedule is delayed. Not able to deliver according to the deadline	More than 20 hours of additional work for the team

With this definition, a 2nd matrix was formed. It calculated the qualitative risk level by the combination of impact against probability and assigning a high, moderate or low qualitative risk level. Probabilities ranged from low to high [Prob. Of occurrence: a 10%, b 30%, c 50%, d 70%, e 90%].

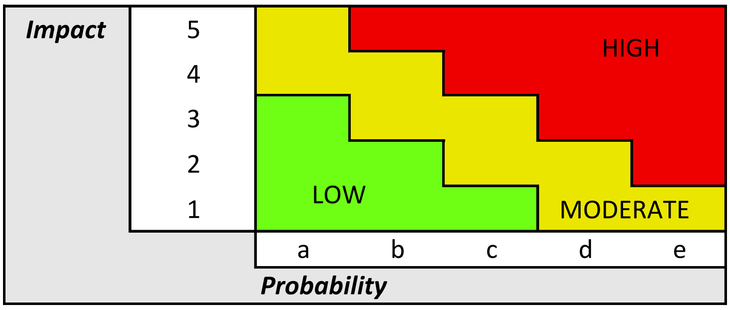


Figure 5: *Risk Matrix*

This risk level was inserted in the risk matrix Table 2, assigned risk levels to identify potential issues, and established risk reduction and corrective measures to each risk. The risk plan can be found in Appendix.

2.10 Project Management

The team worked together for most of the project and the workload was split evenly among the members. When work was distributed into sub-groups they were mainly divided between Pennsylvania State University or Chalmers University of Technology. This was to mitigate the difficulties of different time- zones. The coordinators of Penn State and Chalmers are listed in appendix A. The progress made by individuals or sub-groups were informed to the whole team, ensuring that every member was up to date. All work was registered in the time and work log which was accessible to all students, examiners and sponsors.

Each member of the team had responsibility over some part of the project. The preliminary areas of responsibilities are listed in the appendix. This did, however change as the project progressed, and various areas required more attention. The person responsible for a particular area was in charge of the work on that topic.

3 Technology Overview

This section will present the system candidates more in depth, starting with the Organic Rankine Cycle and then the Thermoelectric generator and lastly the Thermoacoustics.

3.1 Organic Rankine Cycle

An Organic Rankine Cycle (ORC) system refers to when a liquid refrigerant is circulated to an evaporator where heat is introduced to the refrigerant to convert it to vapor. The vapor is then passed through a turbine, with the resulting cooled vapor then passed through a condenser for condensing the vapor to a liquid. The ORC is a typical choice in WHR technologies because this cycle can operate with low, medium, and high-temperature heat sources. Therefore, this cycle presents high flexibility and compatibility with waste heat. This makes ORC a promising, and well used, option for WHR from a fuel cell. This method of WHR would increase the efficiency of a fuel cell considerably.

History

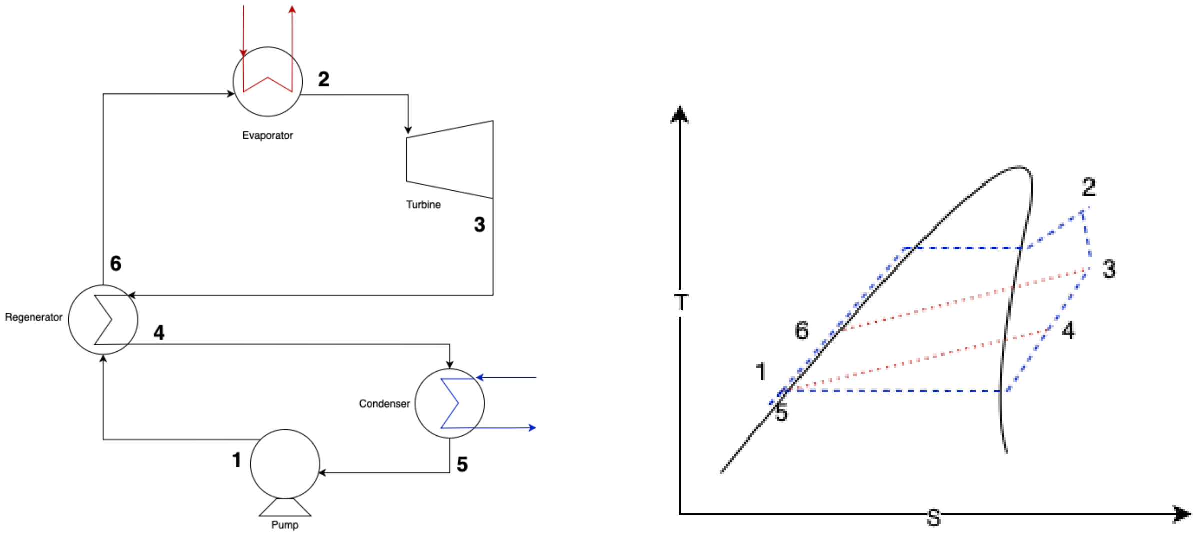
Organic Rankine Cycle development started in the 1850s following the development of steam engines. In spite of Nicolas Léonard Sadi Carnot's foresight of using other fluids than water.[6] It took until the middle of the 20th century to benefit from this thermodynamics analysis, such as taking advantage of the inherent flexibility of the ORC to optimize the use of low-quality heat sources. Work on ORC was mainly done by small university teams and small companies since the larger companies avoided the more niche markets. Only a few small "pure-play" companies were persistent enough to turn the ORC niche into a commercial success.

Theory

In the ORC, the working fluid goes through cycles of evaporation, expansion and condensation. As the fluid expands inside the turbine, thermal power is converted into a rotational power. By adding a rotational electromagnetic converter to the cycle the ORC can produce an electric power output.

The ORC is an attractive system for heat recovery when the thermal power of the energy source is limited. ORC utilizes an organic, high molecular mass working fluid which has a lower evaporation temperature than water.

There are different configurations of ORC, but at its simplest form the ORC consists of a pump, evaporator, turbine and condenser. For low temperature WHR it is common to add a regenerator to the cycle, which is an internal heat exchanger, preheating the working fluid before it enters the evaporator. A typical ORC with a regenerator is presented in Figure 6a.



(a) (b)

Figure 6: *(a) ORC with a regenerator, (b) T-S diagram ORC with a regenerator*

- (5-1) Pump:
  The working fluid pressure is increased from condensation pressure to evaporation pressure.
- (1-6) Regenerator:
  The working fluid is preheated in the internal heat exchanger by the super-heated vapor exiting the expander.
- (6-2) Evaporator:
  The working fluid is heated with the thermal energy from the heat source and changes phase to a super-heated saturated vapor.
- (2-3) Turbine:
  The super-heated vapor expands in the turbine, transforming thermal energy into rotational mechanical energy. The fluid exits the turbine at a super-heated state.
- (3-4) Regenerator:
  Heat is transferred between the high temperature super-heated vapor and the low temperature fluid exiting the pump. The working fluid exits the regenerator, slightly cooled.
- (4-5) Condenser:
  The working fluid is cooled by exchanging heat with the cool side fluid.

Organic Rankine Cycle (ORC) coupled with a dry working fluid typically requires very little, to no super-heating. This makes it easy to implement the a regenerator in the cycle as the fluid exits the turbine at a super-heated state. A regenerator typically increases the thermal efficiency of the ORC, thereby increasing the power output of the cycle.[7] However, if the condenser does not have a limit to the load in which it can handle, the implementation of a regenerator will not increase the power output significantly.[8] The T-S diagram for the ORC is presented in Figure 6b. As fluid expands isobarically in the turbine it exits at a much higher temperature than that of condensation, seen in Figure 6b at point 3.

Efficiency calculation and estimate

Thermal efficiency, and more importantly, net power gained, is highly dependent on the heat exchangers and working fluid chosen for the ORC system.

The processes stated in section 3.1 are described by the following equations.

Pump

The pump work absorption is calculated by the enthalpy change of the working fluid through the pump.

$$W_{5-1} = \dot{m}(h_1 - h_5), \tag{4}$$

where W_{5-1} is the work absorbed by the pump, $\dot{m}$ is the working fluid mass flow, h_5 is the enthalpy of the fluid before the pump and h_1 is the enthalpy of the fluid after the pump.

Regenerator

In the regenerator heat is transferred between the heated fluid leaving the turbine and the cold fluid leaving the pump.

$$Q_{\mathrm{IHE}} = \dot{m}_{\mathrm{hot}}(h_6 - h_1) = \dot{m}_{\mathrm{cold}}(h_3 - h_4) = \{\text{assuming } \dot{m}_{\mathrm{hot}} = \dot{m}_{\mathrm{cold}}\} = (h_6 - h_1) = (h_3 - h_4), \tag{5}$$

The effectiveness of the regenerator needs to be taken into account as well. This can be described as the ratio between the energy received by the fluid, and maximum energy input.[9]

$$\epsilon_{\mathrm{reg}} = \frac{h_3 - h_4}{h_1 - h_6}, \tag{6}$$

where Q_{IHE} is the Heat transfer in the internal heat exchanger, $\dot{m}_{\mathrm{hot}}$ is the working fluid mass flow exiting the turbine and $\dot{m}_{\mathrm{cold}}$ is the working fluid mass flow exiting the pump.

Evaporator

Heat is added to the working fluid at constant pressure, and can be calculated by the following equation.

$$Q_{\mathrm{HHEX}} = \dot{m}(h_6 - h_2), \tag{7}$$

with Q_{HHEX} being the heat transfer in the hot side heat exchanger.

Turbine

As the fluid expands, work is produced by rotating a shaft connected to the turbine.

$$W_{2-3} = \dot{m}(h_2 - h_3) \tag{8}$$

W_{2-3} = Work produced in the turbine.

Condenser

The condenser exchanges heat with the cold sides fluid.

$$Q_{\text{CHEX}} = \dot{m}(h_4 - h_5) \tag{9}$$

Here, Q_{CHEX} = is the heat transfer in the cold side heat exchanger.

Application

Utilizing the ORC as a means for WHR has broad applications which has led the ORC to be extended past the use for fuel cells, to also include a multitude of other industrial WHR and primary power generating systems. Historically, the ORC was developed following steam engines, and has since been studied and optimized for broader applications. Various ORC power plants have been built, mainly for WHR and combined heat and power applications. Beyond fuel cells, ORC WHR designs have been utilized in internal combustion engines, as well as in gas and steam power cycle exhaust. The goal is to achieve a versatile, more efficient design that can be further applied to both traditional and innovative energy generation sources.

3.2 Thermoelectrics

The thermoelectric (TE) generator has the ability to convert a temperature difference into electrical energy. By using semiconductor technology, a TE generator (TEG) is heavily reliant on the material science of module. With no moving parts, this device takes up less space and less upkeep than other alternatives such as the Rankine cycle or sterling engine. The advantages that the TEG provides make it a practical choice for WHR.

History

In the years 1821-1823, scientist Thomas Johann Seebeck discovered that two dissimilar metals with junctions at different temperatures could deflect a compass magnet. Seebeck quickly realized that a thermometric force was inducing an electric current, which by Ampere's law was deflecting the magnet. To be more specific, the temperature difference produced an electric potential which drove an electric current in a closed circuit, appropriately referred to today as the Seebeck effect, and connected Seebeck coefficient. This mechanism is the driving force behind operation of the TEG.

Theory

Thermoelectric generators work by utilizing the heat flux from a high temperature heat source, contrasted against a low temperature reservoir. A flow chart depicting this process can be seen in Figure 7.

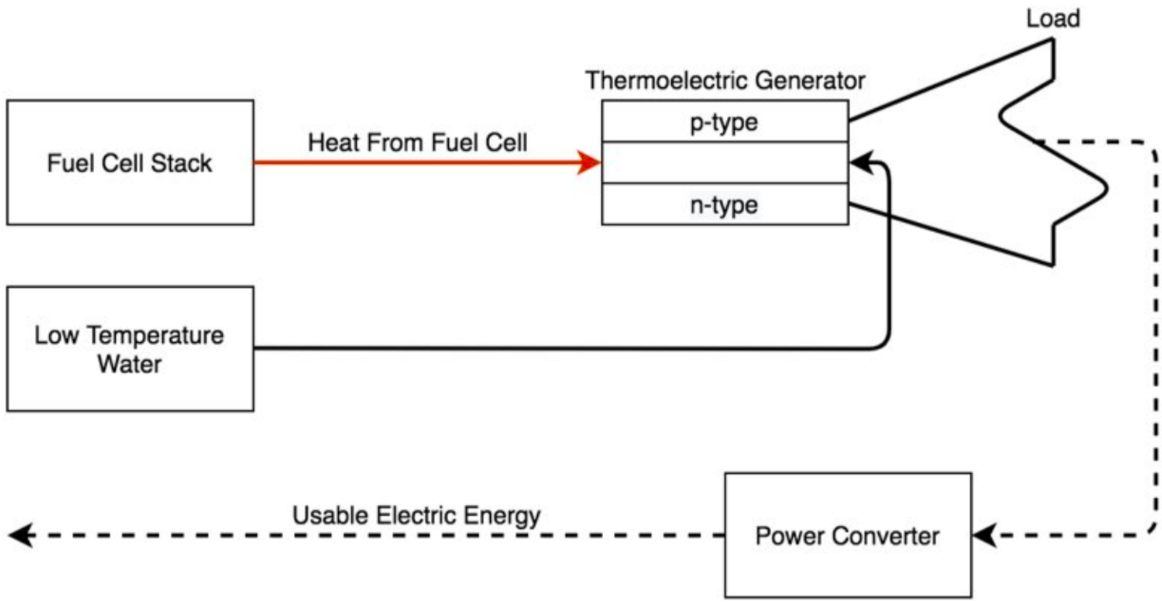


Figure 7: *TEG Conversion process*

A TE module is a device that converts thermal energy directly into electrical current via a temperature difference. The flow of energy can go from thermal to electrical or vise versa, depending on the TE module. The focus of this project involves one out of two types of TE modules. There are TEGs that operate based on the Seebeck effect and TE coolers (TEC) based on the Peltier effect. A TEG will provide electrical generation when heat applied to the system causes a temperature gradient across the TEG. In this scenario, the electrical power output is proportional to the temperature difference between TEG junctions. A TE circuit composed of materials of different Seebeck coefficients (p-doped and n-doped semiconductors), comprise a TEG. TEGs produce clean energy and serve as a potential candidate for transforming low temperature waste heat into electrical power.

Application

Typical applications for current TEGs, more often involve low power applications for locations that are hard to reach and difficult to maintain. For example, they are commonly used as off-grid generators in uninhabited locations, able to operate in all climates. Because of their low maintenance, TEGs have also been used in deep-sea applications and in space, a prominent example being the Mars Curiosity Rover. [10].

Efficiency Calculation and Estimate

Preliminary research indicates that a handful of equations are required to estimate the efficiency[3]:

$$q_{\mathrm{h}} = \alpha I T_{\mathrm{h}} + K_{\mathrm{TEG}} \left(T_{\mathrm{h}} - T_{\mathrm{c}}\right) - 0.5 R_{\mathrm{TEG}} I^2 \tag{10}$$

$$q_{\mathrm{c}} = \alpha I T_{\mathrm{c}} + K_{\mathrm{TEG}} \left(T_{\mathrm{h}} - T_{\mathrm{c}}\right) - 0.5 R_{\mathrm{TEG}} I^2 \tag{11}$$

where q_{h} is the heat applied to the hot side of TEG, q_{c} is the heat applied to the cold side of TEG, T_{h} is the temperature from the hot side, T_{c} is the emperature from the cold side, K_{TEG} is the thermal Conductivity, α is the Seebeck Coefficient, I is the output current generated by TEG, R_{TEG} is the electrical resistivity of the TE module.

The main driving force of power generation in a TEG is the temperature difference and the Seebeck coefficient. Additionally, the thermal conductivity is used as a multiplier to the temperature difference, its value, which comes from properties of the material itself, plays a significant role in maximizing the power generated.

$$P_{\mathrm{TEG}} = \left(q_{\mathrm{h}} - q_{\mathrm{c}}\right) = \alpha \left(T_{\mathrm{h}} - T_{\mathrm{c}}\right) I - R_{\mathrm{TEG}} I^2 \tag{12}$$

$$\eta_{\mathrm{c}} = \frac{P_{\mathrm{TEG}}}{q_{\mathrm{h}}} \tag{13}$$

where P_{TEG} is the power generated by TEG and η_{c} is the conversion efficiency of TEG.

3.2.1 Maturity of Technology

Historically, the use of TEGs has been fairly limited to space probe applications. Extreme reliability was the justification for their low efficiencies. TEGs are rarely seen in applications today, as their low efficiency and high production costs have been a barrier in their development. However, the advantages of TEGs are numerous. These include, but are not limited to, noiseless operation, no moving parts and, no working fluids. As a result there is little to no maintenance or extra costs, and direct energy conversation through semiconductors. Thus, the advancement of more efficient TEGs appears promising as researchers and industry are working to increase the operating range of materials to work in higher temperature differences and search for low-cost materials to justify lower efficiencies. If efficiencies are increased or costs are cut, they can be more desirable for a broad range of applications in the future.

3.3 Thermoacoustics

Thermoacoustics (TA) is the merging of the fields of acoustics and thermodynamics. Thermoacoustic devices utilize the oscillating pressure and flow along a temperature gradient to create engines or refrigerators. The temperature gradient in a thermoacoustic engine (TAE) creates a standing wave which is in turn can be converted into electrical power. The TAE working fluid undergoes a Stirling cycle. Unlike a traditional Stirling device, however, this oscillation of gas is achieved without any moving parts[11]. The lack of moving components grants the TAE a high level of reliability and simplicity, with a very low onset temperature due to the absences of mechanical friction. Similar to traditional Stirling engines, the TAE is flexible in its heat source, making the utilization of waste heat easy. Thermoacoustics have for these reasons been of interest in the field of sustainable energy.

History

The history of thermoacoustics theory starts with basic acoustics were Laplace in 1860 adjusted Newton's mach number for air with regard to compression and expansion of sound waves [12]. Acoustic theory was expanded by Rayleigh in the late 1800's [13] and [14]. However, before both Laplace and Rayleigh, Higgins identified the TA phenomena in 1777 with his "singing flame" experiment [15]. Moving forward to the 1950's were the first patents were filled for the first TA generators by Bell Telephone Laboratories [16]. In 1998 the first traveling wave TAE was tested [17].

Theory

Thermoacoustic systems can work in two distinct directions. First, there is the heat to electricity process. Here, heat is given to the TA system and electricity is produced making thermoacoustics is the prime mover. The other application is when the system works in reverse, and electricity is supplied and heat/cold is produced via a thermoacoustic heat pump. This project focuses on the first direction of having thermoacoustics as a prime mover, as illustrated in Figure 8.

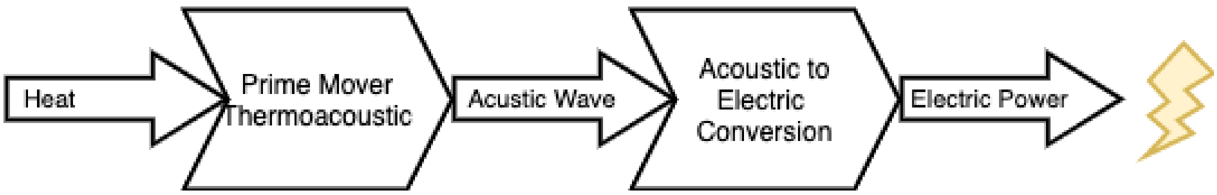


Figure 8: *Prime Mover - TA Conversion process*

MaGaughy, Mitchell[16], in his Master's thesis, manages a good reference for the basic calculations that go into the design and analysis of TA engines. The theory can be split into two main parts, the basic acoustic power calculations, and more specific design parameters of the TA system which can be used for further design studies.

Prime Mover

Using TA as a prime mover refers to the use of acoustic power being produced by a heat differential used to generate electrical power.

Acoustic to Electric Conversion

Converting the acoustic power of the TA device to useful electricity is in its most basic form easy to understand. The goal is to convert the power contained in the acoustic wave traveling inside the acoustic tubes and convert this motion into another form of energy. TA devises are separated into different categories depending on the characteristics of the acoustic wave, either standing or traveling wave.

A standing wave can be viewed as a wave propagating through a closed tube were the constructive interference creates a series of nodes that appears to be "standing", or, not moving. In contrast a traveling wave can be viewed as a wave in an infinite/open ended tube were the nodes appears to be "moving" along the length of the tube. Noting that any real TA devices will operate with a mix of standing and traveling waves. The standing/traveling notation of the TA type comes from what the device is optimized for, and what type of waves are most prominent in the design. A **pure** is often added in front, to reiterate that the devise is solely optimized for one type of wave.

The methods used for converting the power do not fundamentally change with a moving or standing wave device, only the geometry of the installation changes. Timmer *et al.*[18] goes into this subject in their paper making a to date "what is a comprehensive summary of the mechanics used for the purpose of converting the acoustic power into electricity." They split up the conversion equipment into four main types:

- Electromagnetic devices
- Piezoelectric devices
- Magnetohydrodynamic devices
- Bidirectional turbines

Starting with the electromagnetic variant, this can be from the simpler side of the scale a of the shelf loudspeaker. Simply a loudspeaker working in reverse, where the acoustic wave induces movement in the speaker element, resulting in a current output. The loudspeaker is a surprisingly apt conversion devise being a low inertia, linear alternator designed to work in a large range of amplitudes and frequencies. A loudspeaker permits use in a large range of operating pressures, as there are no enclosures in the design. The pressure difference the element needs to handle is that of the pressure difference in the acoustic wave.

Other linear alternators can and have been used in TA devises, but have the problem of a comparatively high prize per unit; with high material and manufacturing costs. Both piezoelectric devises and Magneto-hydrodynamic devises are limited by there range of motion, with the intent of high output for our systems, they fall short in the higher amplitude range.

Bidirectional turbines are by many seen as the most promising development in the field. These turbines are configured with a geometry that enables them to rotate in the same direction, independent of the fluid's flow direction. This means that they can rotate a generator by utilizing the oscillating air column of the thermoacoustic system. Comparatively, they are cheap to mass produce thanks to the low ΔP over the turbine. The material can, for example, be made of 3D printed plastics [18].

Application

While the technology is well used within the field of cryocooling, it has seen limited success outside of that field. There have been tests with TA generators in the fields of very remote, low power output applications, such as running sensors on natural gas pipelines. Current applications are highly robust but have a low power output given the size of the unit[16].

Efficiency calculation and estimate

Thermoacuostic power scales with $p_{\mathrm{m}}aA$ where p_{m} is mean pressure, a is the speed of sound and A is the cross sectional area of the tubes[16]. Inspecting the corresponding units for the above equation are $[Pa][\frac{m}{s}][m^2]$, from this we can deduce that p_{m}, mean pressure, will have a large impact on the efficiency of the WHR system, compared to changing the cross sectional area A.

System output from the TA generator can be calculated in several ways, either by looking at previous research and making assumptions based on there designs, giving an indication of the power output of a new system, or by creating a new system and calculating from the ground up, to get a more accurate result. The main issue is the complex nature of the acoustic wave, and their interactions with the walls and geometry of the unit, as well as interactions with other waves. Essential work was preformed in this area by the Los Alamos National Laboratory with their DeltaEC software, used for TA calculations by several researchers in the field[16][18][19][20].

Maturity of technology

Kees De Blok and his team at Aster Thermoacoustics shows a practical application in their work with waste heat recovery[21] for a land based process with flue gas heating media at 150 - 160 °C. A power output of around 10kW, comparatively low power output for the physical dimensions of this unit at around 3.8 x 1.4 x 1.3m^3 (width x height x length) shows a low power density. This process was successful in showing the inherent design qualities of a TA WHR system. It is that of high reliability and close to zero maintenance. In summary, although these technologies are at their core very mature, they require further research to fit into our specific field of study. What might be researched is the power coupling and operating pressures that effect power output to a high degree to increase the power density of a TA WHR.

3.4 Fuel Pre-Heating

The electrochemical reaction kinetics in a Polymer Electrolyte Membrane (PEM) fuel cell are highly influenced by the reactants supplying pressures and electrode temperatures. For an open cathode PEM fuel cell stack, the power output is constrained due to the use of air acting as a reactant and coolant. Optimal stack operation temperatures are not achieved, especially at low to medium power outputs. Based on the ideal gas law, higher reactant temperatures would lead to higher pressures and subsequently improve the reaction kinetics. The hydrogen supply temperature and its pressure can be increased by preheating; thus, slightly offsetting the limitation of low operating stack temperatures. The exit air stream offers an internal source of waste heat for the hydrogen preheating purpose.[22]

Theory of Fuel Pre-Heating

A theoretical model for calculating a Fuel cell's potential effect is that of the Nernst Potential

$$E_{\text{Nernst}} = \frac{\Delta G^{\circ}}{nF} - \frac{\Delta S}{nF}(T_s - T^{\circ}) + \frac{R_u T_s}{nF}\left[(P_{H_2} + \frac{1}{2}(P_{O_2})\right] \tag{14}$$

where ΔG° is the free reaction enthalphy at 298K, n is the number of moles of electron transferred in the reaction, F is Faraday's constant, ΔS is the reaction entropy at 298K, T° is the reference temperature of air(298K), T_s is the fuel cell operating temperature and P is partial pressure.

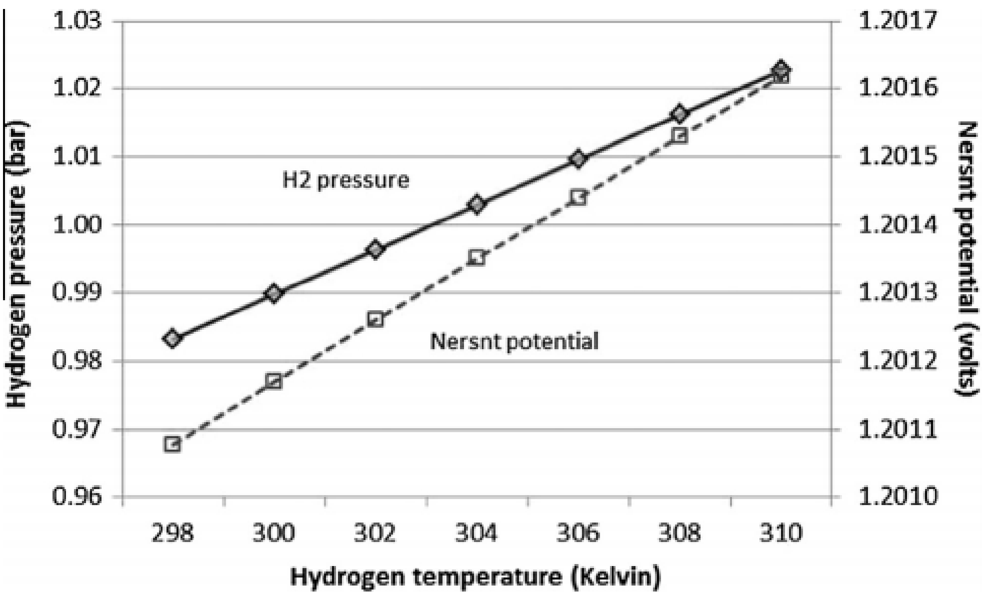


Figure 9: *A Fuel cells theoretical increase of electric potential when temperature increases*

This clearly shows a linearly increasing effect of the fuel cell potential with increased H_2 pressure, which is achieved by preheating according to the Ideal Gas Law.

Testing

According to Mohamed *et al.*[22], an experimental study in utilizing waste heat from an open cathode PEM fuel cell air stream was performed based on the ideal gas relationship of increasing the reactant temperature to increase the pressure. Two hydrogen preheating loops of fresh supply (open) and recirculation (closed) was developed. The base results were a maximum power range between 3.5W/cm^2 and 4.5W/cm^2. The results indicate that the waste heat recovery may have a positive effect on the maximum stack power output by 8–10%. However, the effect can be obtained only by balancing the sensitive operational requirements of the fuel cell's electrochemical mass balance, stack thermal management, heat exchanger operating conditions and the hydrogen supply humidity. In this case, the open loop hydrogen preheating is a promising method compared to the closed loop due to the recirculation of water into the stack that limits the positive power gain. The waste heat utilization was less than 10%, due to heat capacity limitations of the hydrogen flow[22]. The following sketch is a simplification of the system they used.

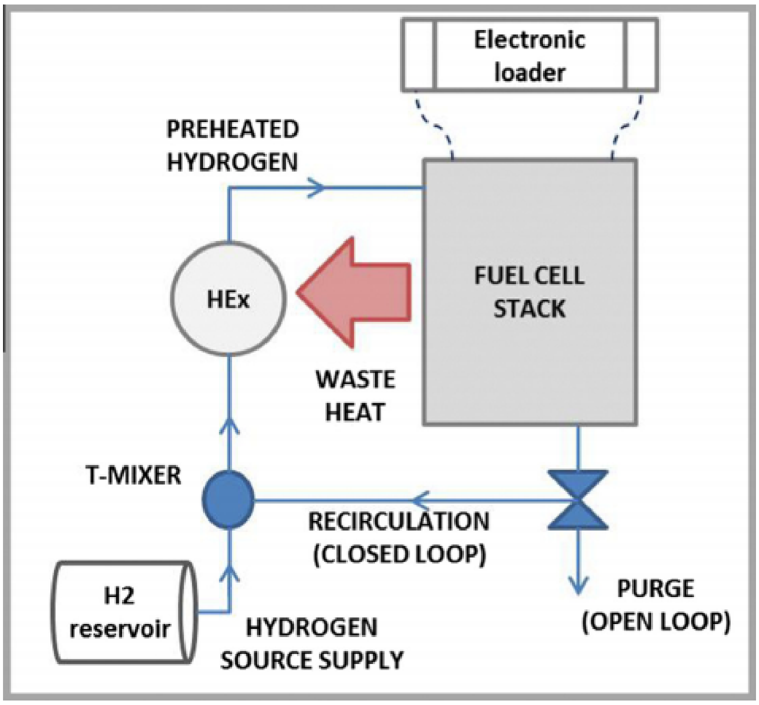


Figure 10: *Simplified Sketch of System for pre-heating Hydrogen with waste heat*

The following figures plot fuel cell voltage versus temperature, according to the experiments conducted by Giovanni *et al.* [23]

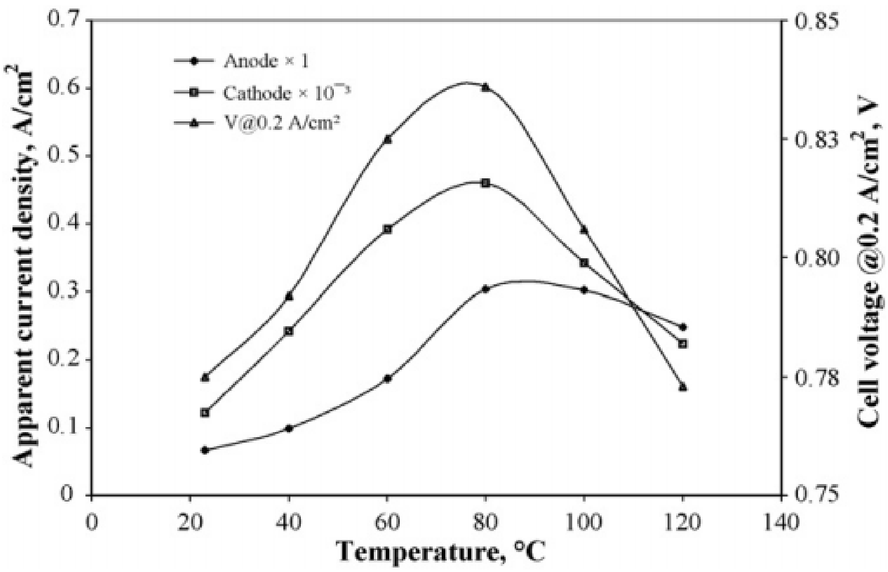


Figure 11: *Experimental Temperature Dependency for a PEM fuel cell[22]*

Proposed Specifications

The following system specifications in figure 12 were suggested by Mohammed *et al.*[22]

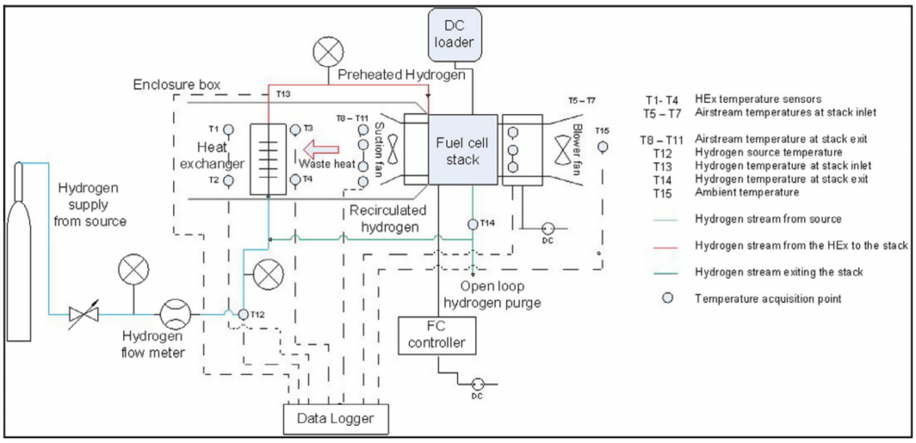


Figure 12: *Extensive Sketch of a WHR System for preheating hydrogen fuel*

Metrics

The following metrics have been found to be consistent throughout the research done on this subject and will be considered in its evaluation.

- 2-5% expected increase of effect.
- 10% maximum possible increased effect in an open cathode system.
- Preheating between 2-13°C experimentally tested once.
- System has not been tested in practice.
- The waste heat utilization was less than 10% due to heat capacity limitations of the hydrogen flow.

Viability

Wagner *et al.* [24] tests show that the optimal operating temperature for a PEM fuel cell is 80°C, but that the closer you get, the less effective it is to increase every °C. Considering that it can be expected for a fuel cell to operate at a temperature close to this, the system is unlikely to provide any valuable increase in effect.

4 Selection of Potential Concepts

Before continuing further with the ranking of the potential concepts, some of the concepts have been excluded based on the following arguments:

1. The solution was not applicable to this project, often due to the low temperature differential.
2. It was too expensive compared to its efficiency to be profitable at best case scenario.
3. It was not a concept for heat recovery.
4. The concept does not have sufficient evidence/testing/literature.

4.1 Candidate list

The following system ideas were considered candidates for the process:

- Utilization of steam to pre-heat the fuel cell for greater efficiencies.
- Steam reformation and/or water gas reactions to increase hydrogen feed rate.
- Improving upon the existing ORC systems.
- Use of alternative thermodynamical cycles such as Stirling-cycle.
- Utilizing electricity from the fuel cell to super-heat the steam (so as to increase the delta, therein facilitating increased heat recovery; through steam turbines or TEG).
- Production of static electricity from heat.
- Thermoacoustic: Heat exchangers with rectifier induce acoustic waves producing electricity by a linear alternator or bi-directional turbine.
- Thermoelectric: Using materials with Thermoelectric properties to produce an electric potential to recover energy from the waste heat.
- Utilization of working fluids/coolants like ammonia.
- Utilizing a thermosyphon for thermal integration between a chemisorption systems and the fuel cell.

4.2 Excluded Concepts

The following concepts have been excluded from the process as per the stated reason.

Preheating the hydrogen:

While utilization of steam to preheat the Hydrogen flow entering the fuel cell for greater efficiencies was a promising idea. It is not actually a concept for recovering said waste heat. As such it was not included in the following Pugh-matrix as per reason #3. While this could be an implementation of the heat once recovered, Volvo Penta's preferences are as stated earlier to transform the energy into electricity, our research also showed that preheating the hydrogen would not compete with this alternative in efficiency regardless.

Steam reformation and/or water gas reactions:

As per reason #3 this was also excluded because it is not a concept for recovering waste heat. It will not be kept for further research for application as the current research does not hold potential.

Stirling cycle:

With a Stirling cycle, the most important factor for its efficiency is the temperature gradient between the hot and cold side.[25] The larger the temperature difference between the hot and cold sections of a Stirling engine, the greater the engines efficiency by order of magnitude. While this is true for any thermodynamic process when used for WHR, a Stirling engine is multiple times more expensive than other options and with a low temperature gradient like presented in this case, it cannot be efficient enough to compensate for this fact.[25] For this reason it was excluded from this project as per reason #2.

Production of static electricity from heat:

This method for WHR is largely untested and has little to no applicable research or data behind it[26], it was therefor eliminated as per reason #4.

Utilization of working fluids/coolants like ammonia:

A system more commonly refereed to as the Kalina cycle, this is a modern adaptation of the commercial standard ORC.[27] It is a considered a rising alternative but is currently strictly worse for the low temperature of this case.[27] it has been excluded based on a combination of reason #1 and 4.

4.3 Included Concepts

The following concepts remained after the exclusion process. The concepts listed below where determined to be most suitable, out of the candidate list in section 4.1, for the waste heat recovery application that this project studies and where further screened in section 5.

- Organic Rankine Cycle
- Thermoaccoustic Generation
- Thermoelectric Generation

5 Ranking Potential Concepts

Customer needs, as received from our client/sponsor, were initially translated into comparable metrics and categories, as seen in the earlier part of this report. However, these categories were extremely differentiated, i.e., varied from one another only by a shade of context. For instance, in the initial list multiple types of efficiencies for the system had been taken into account; these categories, while important in their individual, distinct contexts, could thus be grouped under a larger umbrella category of **Efficiency**. This allowed for a more meaningful analysis when using the Pugh matrix. The categories discussed below represent the final, grouped criteria based on how each of the three technologies were evaluated. Figure 13 illustrates how these specific needs have been grouped for the purposes of the Pugh Matrix evaluation.

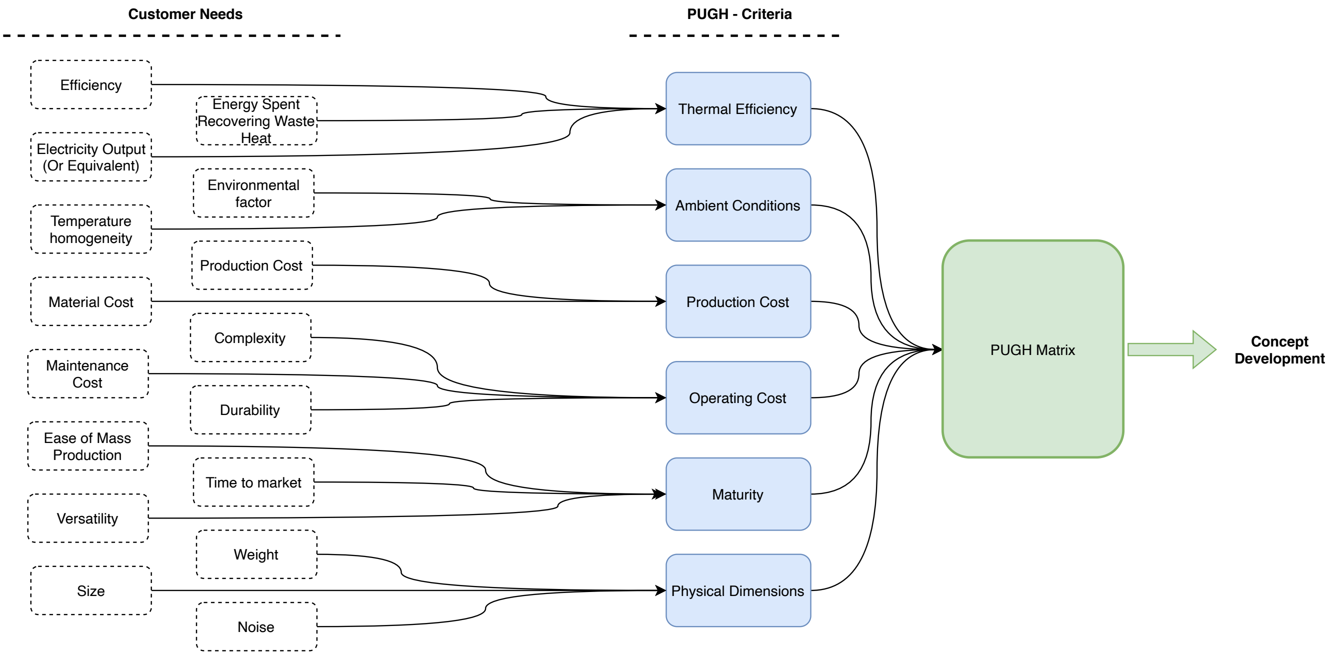


Figure 13: *Pugh Criteria Groupings*

5.1 Thermal Efficiency

The **Thermal Efficiency** metric evaluated for all concepts chosen for the Pugh-matrix can be extended to evaluate the efficiency gain of the power generating system. The power generating system is limited to the installed components in the vehicle or other application, and does not include, for example fuel production or handling prior to use from the systems fuel storage.

The Power generating system consists of fuel storage, a PEMFC of 300kW power output and a nominal efficiency of 60%, with 40% rejected as waste heat at 70°C via the cooling water circuit. This gives 200kW of waste heat to handle with the WHR system. The Pugh matrix in section 5.7 references thermal efficiency, being our main efficiency metric, the η_{thermal}, where a 1% η_{thermal} of the WHR system will correspond to approximately 0.667% efficiency increase of the power generating system, assuming no extra power load to run the heat recovery system, or if included in the thermal efficiency number. Considering the Customer needs specified in Section 2.2 the threshold value of power output at 20kW corresponds to a heat recovery system overall efficiency $\eta_{\text{thermal}} \approx 10\%$.

5.2 Production Costs

Production costs are a sum of the raw materials, direct labor, and factory overhead. Due to WHR systems being a novel technology, much of the production for each component is unknown. The production cost metric was used as a relative comparison, because no accurate cost estimations were obtainable.

5.3 Ambient Conditions

The metric of ambient conditions can be considered as the measure of suitable working temperatures for the WHR system. This metric was a highly important concept in the Pugh-matrix, due to the complexity of the system. The 300kW PEMFC, that was researched upon, dissipated heat at considerably low temperatures. This made choosing potential concepts difficult, since most conventional WHR systems work in temperature ranges upward of 200°C. In order to finalize a feasible solution, ambient temperatures of 60 to 70°C were considered. The potential concepts were eliminated or chosen on the basis of their working temperature and efficiency being as close as possible to 70°C.

5.4 Operating Costs

Operating costs is a combination of three different specifications: maintenance costs, durability, and complexity. Combining the importance rating of those three specifications from the customer needs table yielded an average importance rating of 2, thus it is not as important of a metric compared to the other metrics. The determination of each concept rank in comparison to the other techniques was fairly straightforward. TA and TEG both had equal complexity and maintenance costs, due to the low amount of moving parts required to sustain these concepts.[3][20] With that in mind, their durability was also deemed equivalent for the same reasons. However, the ORC has more moving parts and subsystems than both the TA and TEG.[8] As a result, the ORC was deemed to have higher operating costs than the other two concepts.

5.5 Maturity

Technological maturity is a concept retaining to a products life cycle, i.e. the establishment of conceptual framework, prototyping and lastly building to scale. The maturity of a product has important implications for research and development, or in a technology's strategic planning. For example, the potential of a concept could be fruitful if it is immature, having room for improvement even if it isn't the superior choice as of today. Although prototyping is often easy, mass producing a unstudied product to scale is often much harder. Mature technologies on the other hand, have been in use for a long time. Therefore, most of their problems have been addressed and issues resolved. Further developing mature technologies leaves little room for improvement the older they get and are often preferred for industrial use.

5.6 Physical Dimensions

When evaluating and comparing the physical dimensions of a particular design/technology, the main considerations include both the physical size and the number of subsystems within the design. Fundamentally, an increase in the number of subsystems would contribute to an increase in the number of moving parts Consequently this would also decide other design considerations such as shape, size, and how the system would fit into the technical design of the carrier/marine vessel. It would also affect other criteria such as production costs, and efficiency which have been separately evaluated. Thermoacoustic systems consist of the largest number of subsystems, and are also physically the largest of the three technologies evaluated here. Its function, however, remains dependent on geometry; any redesigns based on this criteria would have to take that into consideration. ORC systems fall next in terms of complexity - however, while these still have a high number of subsystems, it is important that these components can be arranged in many different ways, offering great design flexibility. Lastly, TEG has the smallest footprint of the three. These systems have close to zero moving parts, are fairly small and offer great design flexibility due to this reason. Because the individual elements are so small, they may be designed as per system, and design specifications with a greater degree of accuracy. TEGs can be adjusted as per the spatial design needs of the vessel.

5.7 Pugh Matrix

A Pugh matrix is used to compare the concepts performance with regards to the different criteria. To validate the results consistency and to minimize the human factor of the decision making process, the Pugh matrix process is repeated for each of the concepts as a solution-reference.

Table 3: *Pugh Matrix with ORC as a reference*

Criteria	**Concept Solution**			
	Importance Weighting	**ORC**	**TA**	**TEG**
Efficiency (Thermal)	5	REFERENCE	-1	-1
Production Costs	3		1	-1
Ambient conditions	4		1	1
Operating Costs	2		1	1
Maturity	2		-1	-1
Physical Dimensions	2		-1	1
Σ+			9	8
Σ0			0	0
Σ-			-9	-10
Net value			0	-2
Ranking		**1**	**1**	**2**

Table 4: *Pugh Matrix with TA as a reference*

Criteria	Concept Solution			
	Importance Weighting	ORC	TA	TEG
Efficiency (Thermal)	5	1	REFERENCE	0
Production Costs	3	-1		1
Ambient conditions	4	-1		0
Operating Costs	2	-1		0
Maturity	2	1		1
Physical Dimensions	2	1		1
Σ+		9		7
Σ0		0		11
Σ-		-9		0
Net value		0		7
Ranking		**2**	**2**	**1**

Table 5: *Pugh Matrix with TEG as a reference*

Criteria	Concept Solution			
	Importance Weighting	ORC	TA	TEG
Efficiency (Thermal)	5	1	0	REFERENCE
Production Costs	3	1	1	
Ambient conditions	4	-1	0	
Operating Costs	2	-1	0	
Maturity	2	1	-1	
Physical Dimensions	2	-1	-1	
Σ+		10	3	
Σ0		0	11	
Σ-		-8	-4	
Net value		2	-1	
Ranking		**1**	**3**	**2**

The scoring was based on the research done in the technology overview, Section 3. If one of the concepts was found to be of better performance than the reference, it would be assigned a positive valued point (1), if inferior a negative point (-1), and zero points (0) if it had similar performance. Furthermore, since some of the criteria were assigned greater importance than others, there is an **importance weighting** that is multiplied with the individual score for each of the criteria for the concepts to give the value a weighting.

For the first matrix, with the ORC as a reference, the reference and TA performed the best. For the second matrix, with TA as a reference, the TEG performed best, lastly with the TEG as the reference, the ORC performed the best. Since the ORC performed the best in two of three cases, it is the concept that would be considered to have the best potential performance. Therefore, it is one of the concepts that will be further developed. However, since the values that are being used for the comparison are only based from literature reviews, the second best will also proceed for further development and comparison. Thus, the ORC and TEG will proceeded for further development.

6 Development of Final Concepts

This section presents the development process of the two final concepts, ORC and TEG.

6.1 Software Selection

For the simulations, it was decided to use a variety of software for the different parts of the process.

MATLAB[28] simulations were performed with a variety of widely accepted MATLAB extensions along with the MATLAB work-space. The Simulink plugin was extensively used, along with the Simulink application Simscape. Simulink is a graphical programming environment, running the block based simulations. The plugin Simscape extended this functionality with an extensive library of both creator made and custom building blocks for modeling heat, mechanical power, and mass transfer within the system. This alleviated the need for extensive coding knowledge, as it both created and solved equations for the given system.

COMSOL Multiphysics®[29] is a finite element analysis and solving tool, it is able to analyze and solve systems of several physical domains. This software was used to develop well defined models for solving heat and mass transfer, being able to both give numerical results and visualize different parameters of the design to facilitate optimization.

CATIA[30] and **Autodesk Inventor**[31] were used to model the ORC, and the Thermoelectric generator respectively. These modeling software were chosen based on personal preference and for the sole purpose of creating a visual with dimensions of the selected concepts.

CoolProp[32] is an open source library containing thermophysical fluid properties. The library can be called to MATLAB via a python interpreter and used in modeling systems in Simscape. For this project CoolProp is used to generate the working fluid property tables for the ORC.

6.2 Thermoelectric Generator Subsystems

For the complete Thermoelectric generator, there are three main subsystems: cool side heat exchanger, hot side heat exchanger, and the Thermoelectric module. The hot side heat exchanger serves to conduct the heat from the fuel cells to the Thermoelectric module. The Thermoelectric module is comprised of semiconductors that uses materials with low thermal conductivity[3], where cool water is piped in to create a substantial enough temperature difference within the module so that power can be generated. Additional subsystems include pumps that are used to transport the heat from the fuel cell to the hot side heat exchanger and transport cooling water to the cold side heat exchanger.

Thermoelectric Generator Simulation

Thermoelectric systems are, at their core, a mix of complex material and fluid properties, and simple-to-understand mechanical layouts. The simpler system design gives the TEG simulations a head start compared to ORC simulations, as a good grasp of the initial design parameters are required. Ideas presented in previous work[3] and TE components available for purchase online gives a foundation to build on.

Our simulation process used two different software and several iterations. The first stage was to model the Thermoelectric elements to get an understanding of their power output depending on the junction temperatures inside the TEG-system.

Thermoelectric power output

This part was done at an early stage during the process of ranking potential concepts. The simulation is based on the Simulink software for MATLAB.

$$\text{Current} = \frac{SC \cdot \Delta T}{(1+m)R}, \tag{15}$$

where $m = 1$ if $RL = m$ (RL being Load resistance and R being internal resistance), SC is the Seebek Coefficient.

$$\text{Voltage} = -R \cdot SC - \frac{2\,Wm}{Vm}, \tag{16}$$

where Wm is the matched power and Vm is the matched voltage.

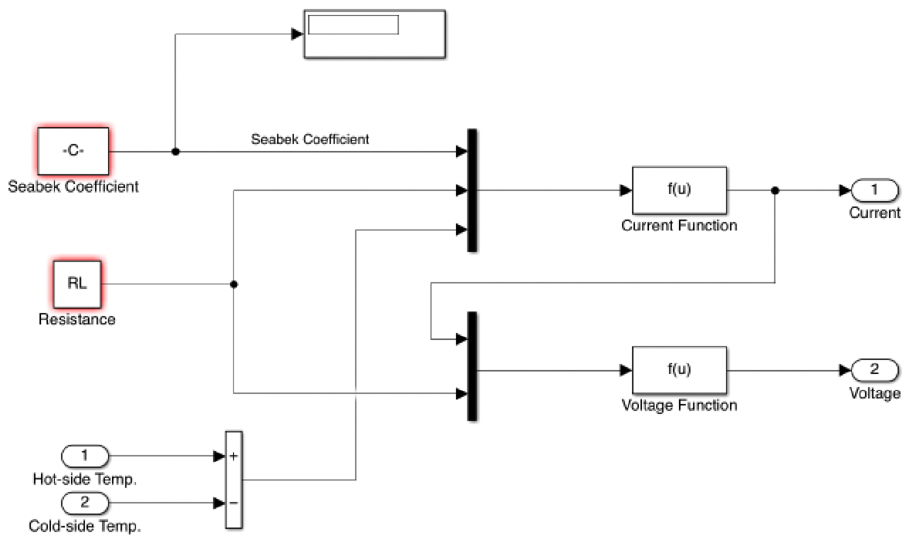


Figure 14: *TE Simulink model*

The model, shown in Figure 16, takes the hot-and-cold side of temperature input, along with a set resistance and Seebeck Coefficient, and other various parameters set in the work space. It output the voltage and current produced by the TE element(s). This is the core of the power generating part of the system, the rest of the simulations and calculations are the basis for the temperature inputs.

Thermo Electric System

Following this step a Simscape model was set up to simulate mass and heat transfer though the WHR system.

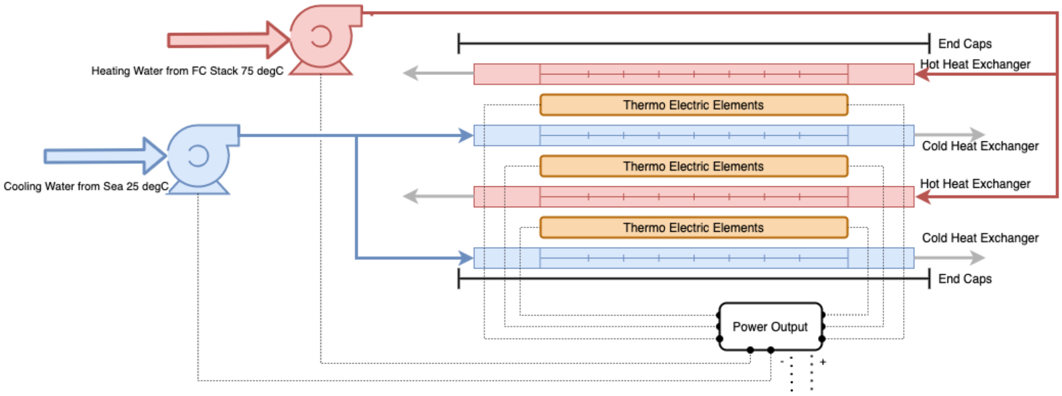


Figure 15: *Principal layout TEG*

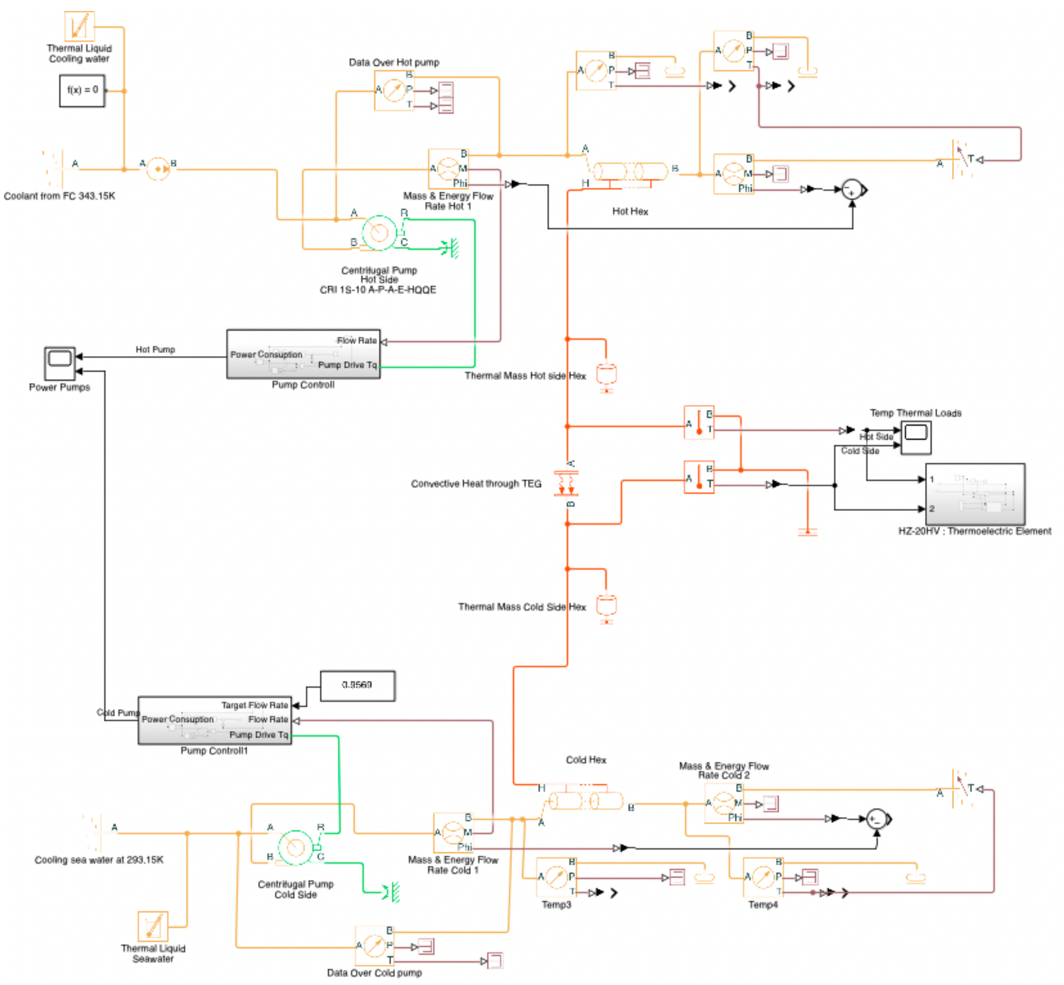


Figure 16: *Early iteration TEG Simscape model*

The basis of the model proceeded from Figure 14, was the concept of sandwiching TE elements between hot and cold heat exchangers, where they can be stacked intermittently as many times as needed to achieve the optimal mass flow rate and heat transfer. The fluid flow direction of the hot and cold heat exchangers were chosen as counter flowing, similar to a cross flow heat exchanger to achieve a similar heat profile across the TE junctions.

The goal and main problem for optimizing the system came from the inherent trade off between heat transfer rate, and pressure drop over the heat exchangers. Greater heat transfer required good contact between the fluid and the surrounding material, *i.e*, the heat exchangers. Greater contact gives the system a higher pressure drop, or head, increasing the pump work required to run the system.

The first model, represented in Figure 16, was produced to get an understanding of how the heat flowed from the hot fluid to the cold fluid over the TE element. The top of the model represented the hot side reservoir, pump, pump controller, and heat exchanger. The bottom of the model is a mirror of the same system for the cold side heat exchanger. In between the hot and cold side systems, the TE element is simulated with thermal masses connected to the TE Simulink model represented in Figure 14, with a convective heat transfer block simulating the heat transfer trough the TE element to the cold side.

Pump controllers were programmed with PI controllers to control torque feed to the pump blocks and modeled to represent a real centrifugal pump sized for the application of cooling water at the hot side flow, specified by Volvo Penta in Section 6.2.

Fluid & heat dynamics simulation

The simulation was set up to model the expected dynamics. The focus was shifted to implementing realistic values into the Simscape model by modeling the heat exchanging elements in the Comsol.

Comsol simulations required a geometry to simulate. This is where the detailed design process began. The basic model is inspired by a paper by Gao *et al.*[33] where they propose a sandwiched design where one layer of TE elements are placed on both sides of a heat exchanger to transfer the heat from the warm fluid to the TE elements. In their case the cold side of the elements were cooled by the aluminum housing of the generator. The new design was clearly inspired by their work as it lends itself well for expansion with a higher number of elements.

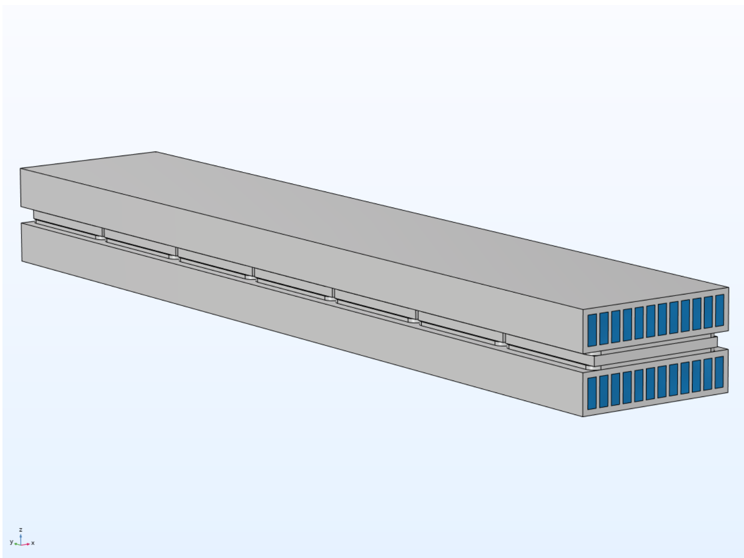


Figure 17: *Early iteration of the TEG Comsol model*

Figure 17 shows the basic layout that the simulations started with. The blue color shows the fluid channels, encased by the gray color; hot and cold heat exchangers. The middle shows 7 TE elements of HZ20HV[34] type.

The HZ20HV TE module consists of 160 thermocouples electrically connected in series and thermally connected in parallel. The thermocouples are a pair of dissimilar conductors, in this case Bismuth Telluride (Bi_2Te_3). Use of the HZ20HV for the model is a good representation of an available, industrial grade, modern TE element. The small size of 68 x 74.5mm^2 lends itself well for a very scalable TEG design.

This design was optimized for different fluid flows and pressures within the assumptions made, see section 6.2. Iterating simulations led to geometry changes of the heat exchangers from the results of different studies. The subjects studied were Heat Transfer in Solids and Fluids, Comsol type ht, and Laminar Flow, Comsol type spf.

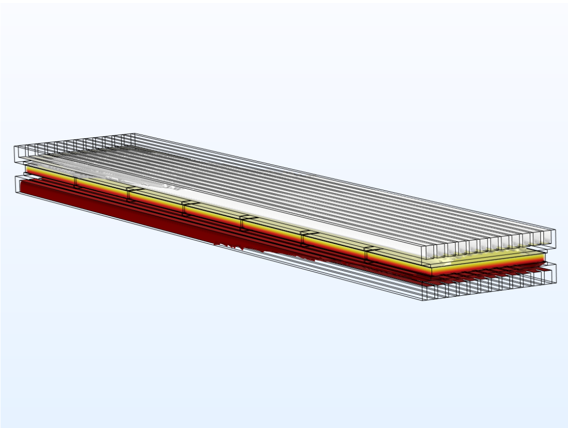


Figure 18: *Isothermal Contours shown in over the heat excgangers corossections and TE elements*

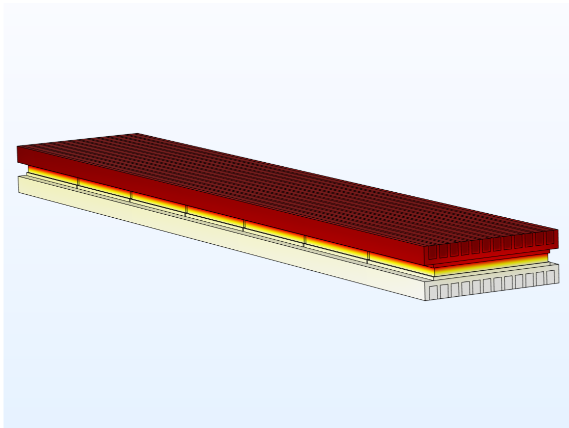


Figure 19: *Temperature shown in color, indicating a uniform heat flow over the length of the heat exchangers*

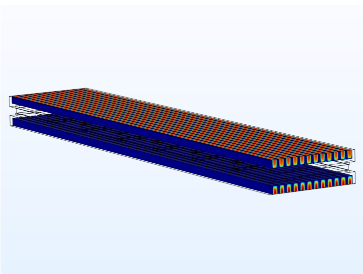


Figure 20: *Velocity of each individual heat exchanger channels*

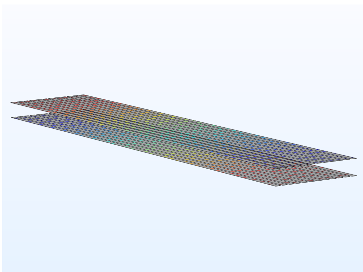


Figure 21: *Pressure of the heating/cooling media over the length of the heat exchangers*

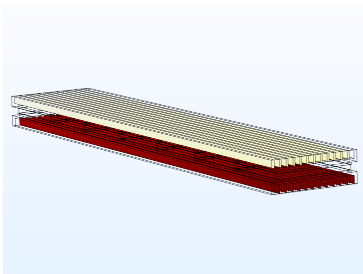


Figure 22: *Wall temperature of the heat exchanger channels*

The output files show the solids; temperature and Isothermal Contours and for the fluids; velocity, pressure and outlet temperatures. An example of the output file is presented in Figures 18-22.

After achieving a geometry that behaved in a reasonable manor, data was exported via probes placed on the mating surface of each TE element. In addition to in- and outlet pressures for the hot and cold sides heat exchangers to export a .txt file to import into MATLAB. The amount of of data from the Comsol simulations produced required changes to fit the Simulink model.

An altered model was produced to import different Comsol results/Data sets and built a matrix of the resulting values. Each data set included hot/cold side temperatures for all 7 TE junctions and in-/out pressures for both heat exchangers. Another corresponding matrix was produced to represent the change in input variables, namely the total number of heat exganger (HEX) elements. One HEX element is represented in the above geometries with two heat exchangers (hot and cold) and the 7 sandwiched elements. Iterating the model over a different amount of element assemblies changed the mass flow of heating/cooling media through the heat exchangers and effected all output variables.

After setting up the in- and output matrices in MATLAB, iterative calculations were preformed to produce presentable values to the team and the reader. The results were then plotted and interpreted. After changing how the Simulink ran the TE power output calculations were changed to a separate file which iterates over the 7 TE elements to calculate there individual power outputs. Pump power was set as function of pressure loss over the heat exchangers, and calculated similarly to equation 4. The resulting total power output could was calculated as

$$W_{\mathrm{Net}} = W_{\mathrm{TE}} - W_{\mathrm{pump}} \tag{17}$$

with W_{Net} as the net power output of the system, W_{TE} the total power output from the TE elements and W_{Pump} is required power to overcome the pressure drop over the heat exchangers. A cost matrix was produced to calculate how the total unit cost changed with the number of TEG modules, this calculation is represented below.

$$\mathrm{Cost} = 7 \cdot \mathrm{nTE} \cdot \mathrm{CostTE} \tag{18}$$

where nTE represents the number of HEX elements, CostTE is the unit cost for one Thermoelectric element and 7 being a multiplier, as there are 7 TE elements for every HEX element. The total power output was divided by the cost value to give a $ value to every watt of power produced by the unit. This value is not to be taken as a real value, just an indicator of the change in total unit cost with differing numbers of HEX modules. For every 7th multiple of TE elements there is a cost for the corresponding heat exchangers, but the price of them individually should scale with the number of TE elements. Pump costs are not evaluated in this calculation.

The team found reason to quantify the value of the temperature change, or ΔT over the TE junctions of one HEX element; as "Temperature homogeneity," constructed to show how much the temperature differs over the length of the heat exchanger. This is dependent on mass flow, i.e number of HEX elements is defined as follows.

$$T_{\mathrm{Homo}} = \left| \frac{T_{\mathrm{in}} - T_{\mathrm{out}}}{T_{\mathrm{in}}} \right|, \tag{19}$$

where T_{Homo} is the number compared for different configurations. T_{in} and T_{out} represents the mating surface temperature for the TE junctions at the first TE element, and the last element with regard to the flow direction, respectively. The absolute value of the fraction gave both hot and cold heat exchangers a positive value output to interpret.

Initial Data

In the model it is assumed that the heat exchangers are of stainless steel, and that the piping loss for the pumped fluid is close to zero. This is different than that of the heat exchanging cores, along with the data given by Volvo Penta. For the simulation, both of the fluid flows are of clean, fresh water quality, negating any scaling particles or mixes of any minerals.

The following data was provided by Volvo Penta:

- Outlet flow from Fuel Cell 245 - 280l/min
- Temperature of this outlet flow is 75°C
- Ambient temperature 20°C
- Pressure is load dependent, but around 2bar at max load

6.3 ORC Subsystems

The proposed Organic Rankine Cycle system consists of five subsystems: primary heat exchanger, turbine, regenerator, pump, and a water cooled condenser. The primary heat exchanger essentially transfers the dissipated low temperature heat from the fuel cell stack to the working fluid. This fast moving heated fluid then moves to the turbine which rotates, spinning a generator to produce electricity. The working fluid vapor at the low pressure is cooled to be a saturated liquid phase in the condenser by the air, which is then pumped back to the regenerator, completing the Rankine cycle. The regenerator, takes in the cold liquid, heating it up using the waste heat from the fluid used in the turbine for improved efficiency.

Heat exchangers

The simscape model uses the Number of Transfer Units (NTU) method to calculate the rate of heat transfer between the two liquids in all of its heat exchangers. The NTU method is very useful for all flow arrangements when doing numerical calculations and suits our situation well.[35] It introduces the variable heat exchanger effectiveness (ϵ), which is a dimensionless number ranging between 0 and 1.

$$\epsilon = \frac{q_{\mathrm{act}}}{q_{\mathrm{max}}}, \tag{20}$$

where q_{max} is the maximum possible heat transfer in the exchanger, which would be attained if one of the fluids was heated equally to the maximum temperature difference present in the exchanger, this would be the difference in entering temperatures for the hot and cold side, q_{act} is defined as:

$$q_{\mathrm{act}} = C_h(Th_i - Th_o) = C_c(Tc_o - Tc_i), \tag{21}$$

where C_c and C_h are the heat capacity rates ($i.e$, mass flow rate multiplied by specific heat) for the hot and cold fluids respectively. T_h and T_c denotes hot and cold fluid, subscript i and o denotes inflow and outflow. The method also introduces a values to NTU, which is indicative of the size of the heat exchanger

$$NTU = \frac{UA}{C_{\mathrm{min}}}, \tag{22}$$

where C_{min} being the smaller of the heat capacity rates and C_{max} being the larger, A being area and U the overall heat transfer coefficient. It can then be shown that for any heat exchanger that

$$\epsilon = f\big(NTU, \frac{C_{\mathrm{min}}}{C_{\mathrm{max}}}\big), \tag{23}$$

this equation takes the following form for our counter-flow exchanger

$$\epsilon = \frac{1 - \exp[-NTU(1 + C_r)]}{1 - C_r \exp[-NTU(1 - C_r)]} \tag{24}$$

with

$$C_r = \frac{C_{\mathrm{min}}}{C_{\mathrm{max}}} \tag{25}$$

being the heat capacity ratio of the system.

Turbine

In the turbine calculations of simscape, the pressure drop and flow rate are scaled from the specified nominal operating condition based on Stodola's ellipse relation. It has long been recognized,[36] that at any point in the expansion downstream of the throttle the pressure-flow relation may be approximated by

$$\text{Mass Flow Coefficient} = \frac{W_i}{\sqrt{\frac{P_i}{V_i}}} = \text{Constant}, \tag{26}$$

where W_i is flow to next stage, P_i is shell pressure and V_i is specific volume with the subscript i denoting any point in the expansion. Stodola's ellipse relation[37] then states that

$$\Phi_i \propto \sqrt{1 - \left(\frac{B_i}{P_i}\right)^2} \tag{27}$$

where Φ_i is the mass flow coefficient described earlier, P_i is inlet total pressure and B_i is exit static pressure.

6.4 ORC Simulation

While the ORC is already a well studied method, and the team does not expect the results from the simulations to differ from available numbers, regarding its efficiency. It was important that the team provides its own simulations to further strengthen the argument for its application here. Earlier research and applications suggested a 4-6% increase in efficiency, with temperatures below 100°C.[27] The performed simulations should have provided a similar number if the reference is to be trusted.

Design Specifications

The Rankine cycle has several variations but the one most suited for our system is the ORC, with a regenerator[38], using a working fluid that evaporates at a temperature much lower than the waste heat outflow from the PEMFC. As such, the team simulated this using values from the given situation.
The following Figure 23 was illustrated to be a visual model for our system, using this as a basis the team created a complex Simscape model with various subsystems to model the ORC.

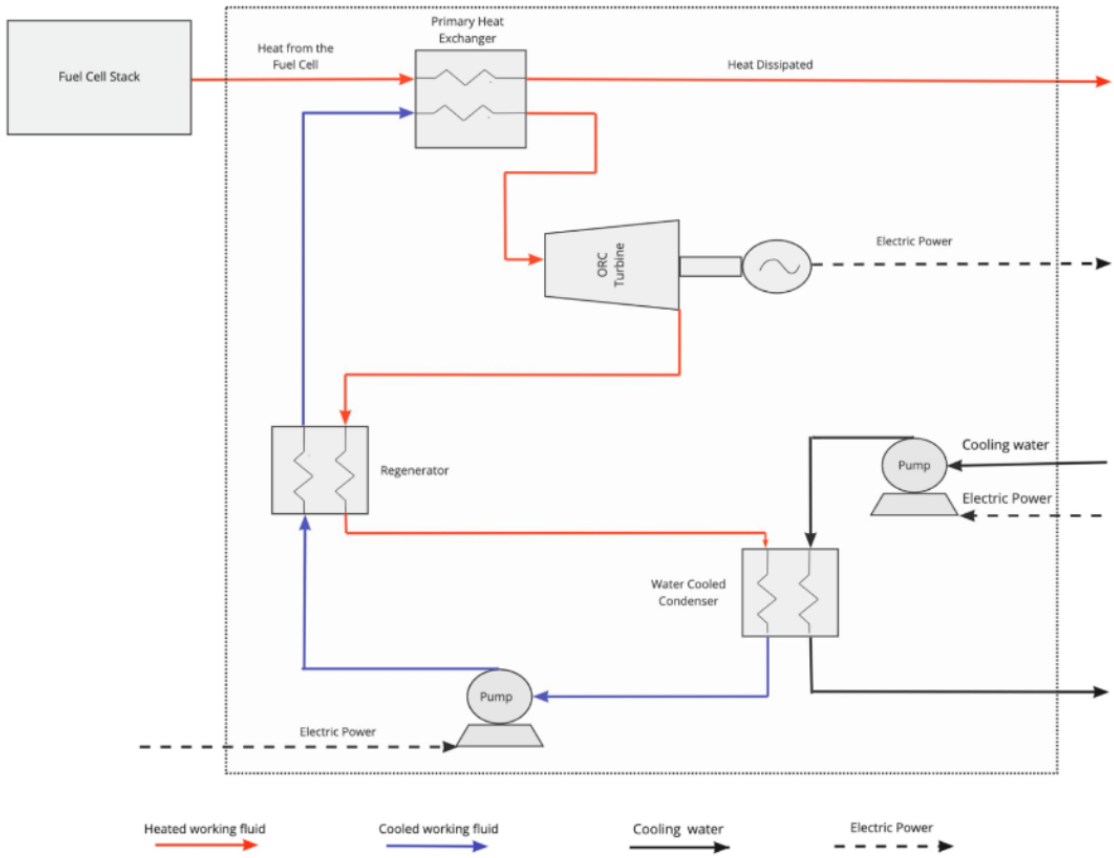


Figure 23: *An early sketch of the ORC system design*

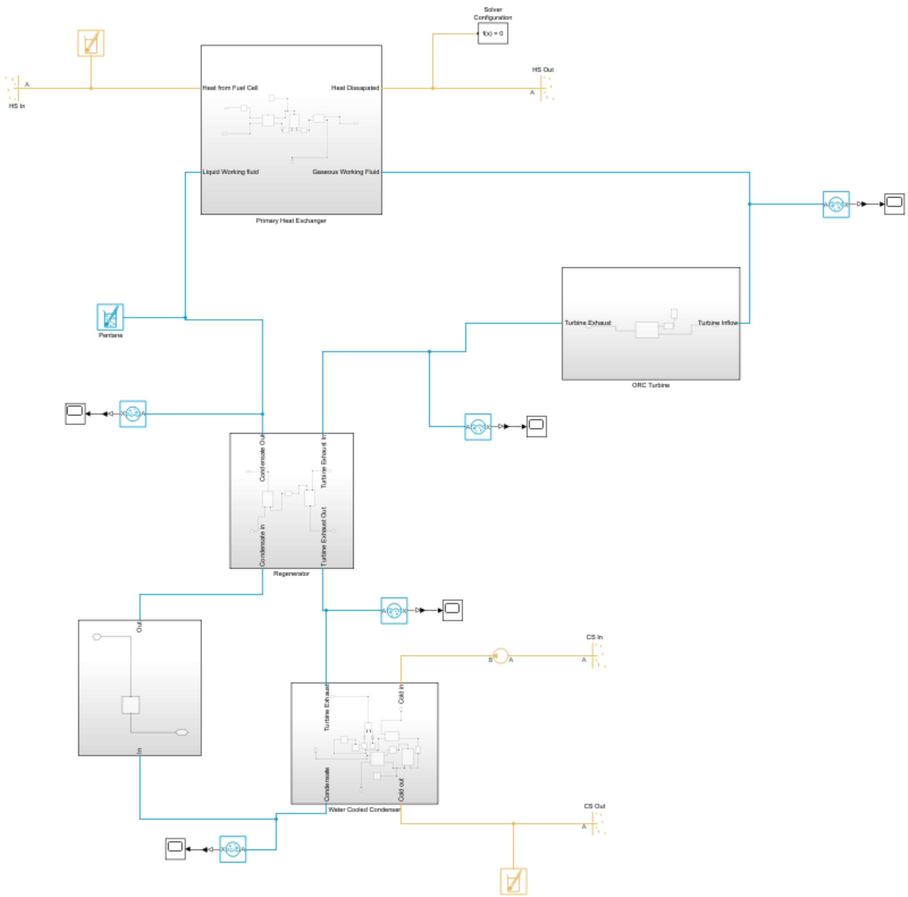


Figure 24: *Complete ORC simulation with the included subsystems*

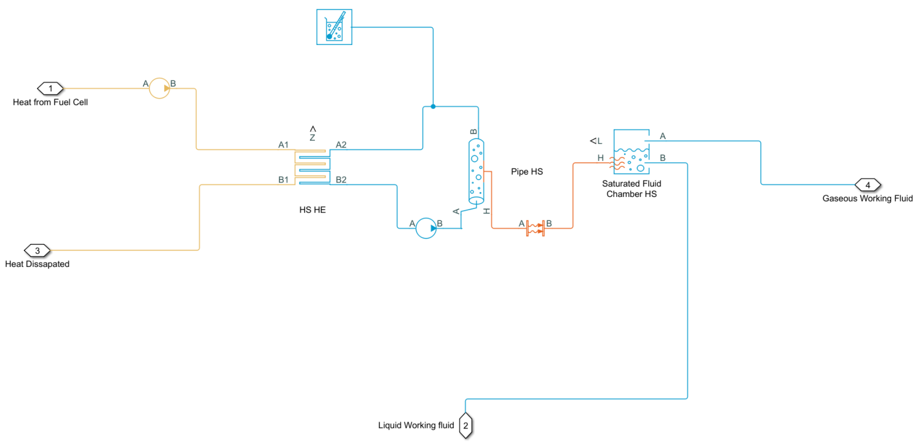


Figure 25: *Hot side Heat Exchanger as modelled in simcape for the ORC system*

Calculations

The main argument for choosing a simulation with Simscape was, as mentioned earlier that it simplified the calculations and coding part significantly. Since the fluid inside the system is under constant change of temperature, pressure, enthalpy, flow and phase, the fact that a trusted computer system did the mathematics was almost a requirement for the simulations and calculations to be trustworthy regarding the ORC.

Initial Data

The working fluid in the system was Pentane, as it provided the best values in the simulations. However, research suggested that R-123 might be the superior option.[7] While it is not expected that the outcome will be vastly superior, it is worth a mention and could be subject to further research.

The following data was provided by Volvo Penta and is used as boundary conditions for the system in the computer calculations for the differential equations.

- Outlet flow from Fuel Cell 245 - 280l/min
- Temperature of this outlet flow is 75°C
- Ambient Temperature 20°C
- Pressure is load dependent, but around 2bar at max load

7 Results and Illustrations

In this section the final designs and results of the chosen concepts are are presented.

7.1 Thermoelectric Generator

The Thermoelectric generator (TEG) is an interesting mix, with relatively simple-to-understand dynamics and physical layout. Given the limited amount of previous research existing on the topic, the simulation regime had to be created from the ground. The process of having to create this simulation regime presented an unexpected task not anticipated at the start of this project.

System Analysis

The simulation work comprised of two different routs at the end; a generic Simulink/Simscape solution showing the correct characteristics but hard to tune into real values, and a more specific simulation with the Comsol/MATLAB mix. Conclusions were drawn from both models, real, or close to real values from the second model, and the trends of the system dynamics were examined in the first model.

The software used showed huge potential and helped a great deal for the calculations. The programming interface gave us all the calculations ready to use. The only programming required was to create simple equations to draw understandable conclusions from the data. Below the data collocated from the second model is presented, which for this project produces the usable values.

Comsol/MATLAB model

The heat exchange model was first created in Comsol, and the results exported to MATLAB in matrix form. The export file included temperature and pressure data from the Comsol file. Results are all for low pressure application running from $\approx$ 500Pa down to $\approx$ 10Pa of ΔP over the heat exchangers.

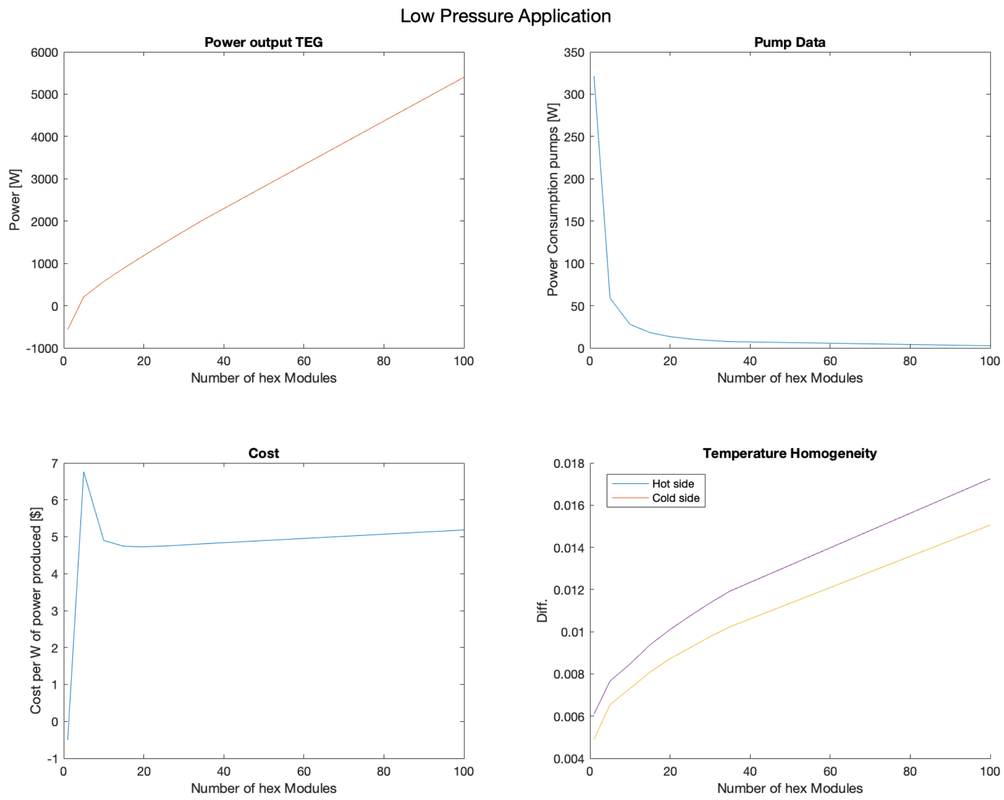


Figure 26: *Resulting plots TEG simulation, upper left shows resulting power output, upper right shows Power consumption of the pumps, lower left shows cost per watt of power output of TE elements and lower right shows temperature homogeneity, all of them showing number of HEX modules on the x-axis*

Top left of Figure 26 shows the main output data from the simulation, providing a maximum power output of 5400W of power output with one hundred heat exchanger (HEX) modules, with the power output being negative for < 5 HEX modules, due to the high back pressure to the power output, more pump power was required to force the fluid through the system than is produced by the system itself.

The pump data plot in Figure 26 shows the power consumption by the pumps in the system, decreasing fast as more HEX modules are added as the split fluid flow decreased the pump force required.

The cost plot is based on Equation 18 and indicates the efficiency of the Thermoelectric elements installed, the result was higher efficiency of the modules when there were less of them installed. The temperature homogeneity plot represents a number created to show the temperature change over the number of TE junctions for each module, with an increasing delta over the length of the module. As the number of modules were increased the mass flow decreased for each module.

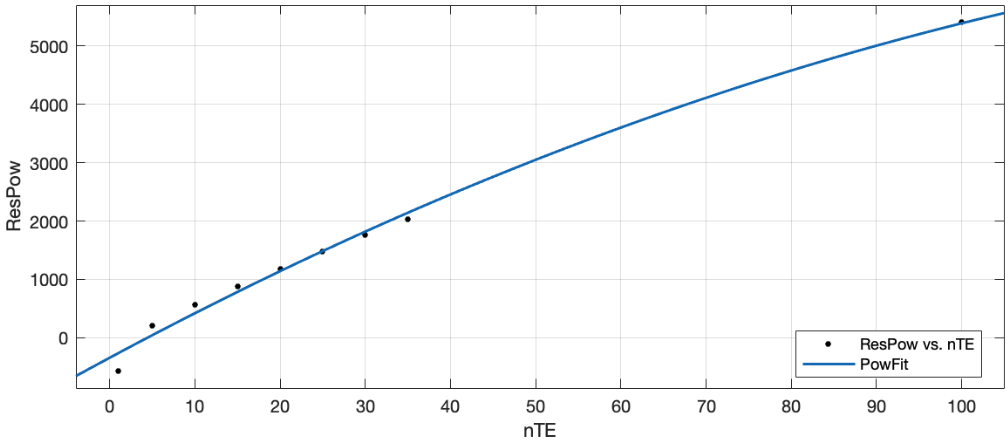


Figure 27: *Polynomial fit [2nd deg] Power Output to number of TE elements, x-axis representing number of HEX modules and y-axis representing the resulting power from the generator in W*

Figure 27 expands on the results shown in Figure 26, adding a polynomial fit function to the 9 data points of the top left Figure. It is clear there is a decreasing slope over the data points, indicating that there is a max value of HEX modules that can be added for the specified heat flow and flow regime with decreasing yield.

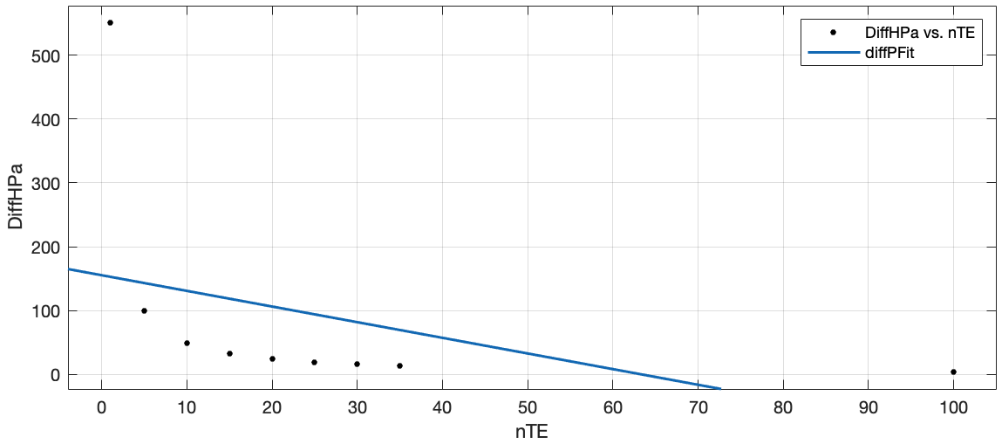


Figure 28: *Polynomial fit [1st deg] ΔP hot side to number of TE elements, x-axis representing number of HEX modules and y-axis representing the pressure loss over the hot side HEX in Pa.*

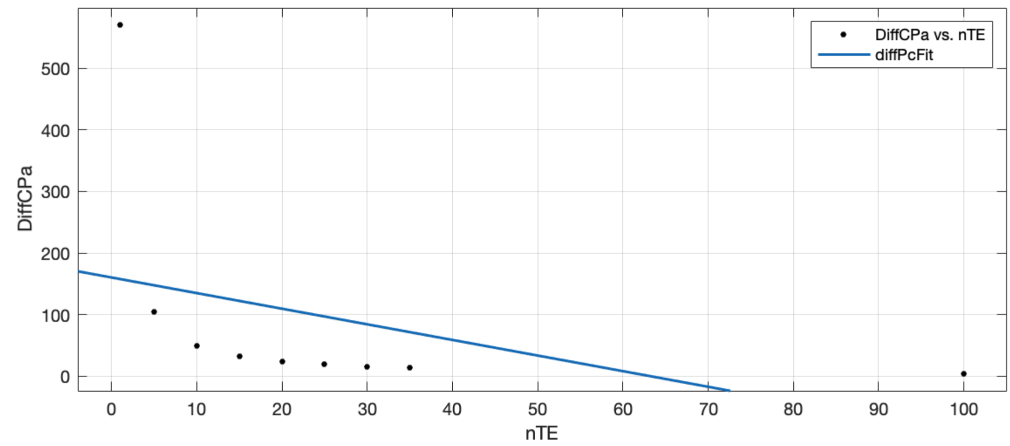


Figure 29: *Polynomial fit [1st deg] ΔP cold side to number of TE elements, x-axis representing number of HEX modules and y-axis representing the pressure loss over the cold side HEX in Pa.*

Figures 28 and 29 provided the data for the pressure loss over one HEX element, for either hot or cold sides. As evident from the Figure, there was a sharp decline in the back pressure as the number of elements increased. This has a direct relationship with the power consumption of the pumps, increasing the power output as pump work goes down and power output increased.

Additionally, it was evident that the pressure differential was so close to equal over the hot and cold sides that; in this case they can be seen as the same value. This came down to the use of a completely mirrored design of the heat exchangers and close to the same mass flow of the thermal liquids.

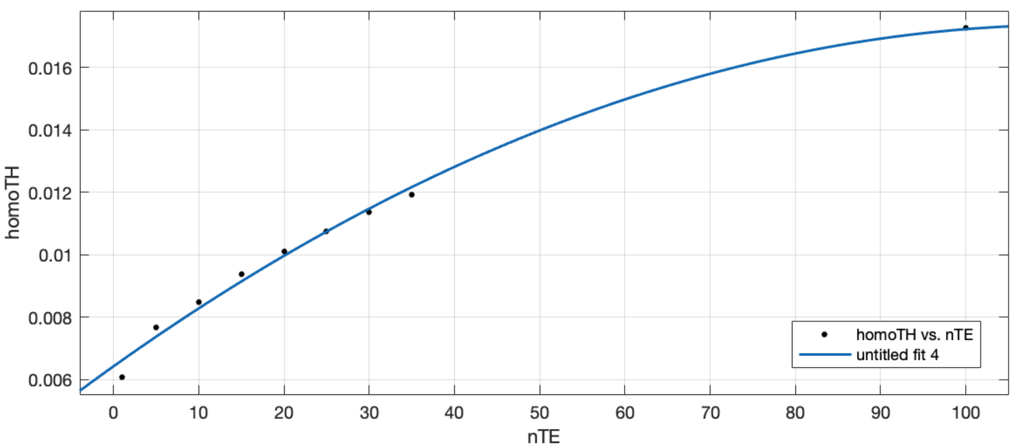


Figure 30: *Polynomial fit [2nd deg] hot side temperature homogeneity to number of TE elements, x-axis representing number of HEX modules and y-axis representing temperature homogeneity as a dimensionless number*

.

The temperature homogeneity value was constructed to give a numerical value to the temperature difference over the TE junctions mating surface of one HEX element, represented in equation 19. It was noted that the homogeneity was decreasing with a higher number, indicating that the difference is proportionally higher. However, the value was slowly converging with some significance, similar to the total systems output plot, in Figure 26.

Materials

Thermoelectric generators are constructed by four main components. There are systems that interface with the heat source called hot and cold heat exchangers. Thermoelectric materials, called semiconductors generate power directly from the temperature difference of its elements. These materials must have a high electrical conductivity and a low thermal conductivity. These parameters are necessary to ensure that when one side of the TEG is hot, the other will remain cold. Having a low thermal conductivity helps to generate a larger voltage within the temperature gradient. Several semiconductors have shown great potential for use in a TEG, such as bismuth telluride, lead telluride, and silicone germanium. However, some of the ideal semiconductors contain rare earth metals, which are particularly expensive.

CAD Drawings

Figure 31 is a concept visualization of the Thermoelectric generator. The visualization has three layers in total: hot heat exchangers and two layers of cold heat exchangers. As depicted, the hot side heat exchangers are twice in size compared to the cold side heat exchangers. This is to ensure that a hot heat exchanger each faces a cold heat exchanger, with TE semiconductors sandwiched in between. The pump on the right side is connected to plenums that connect to the cold heat exchangers while the pump on the left side is connected to plenums that connect to the hot heat exchangers.

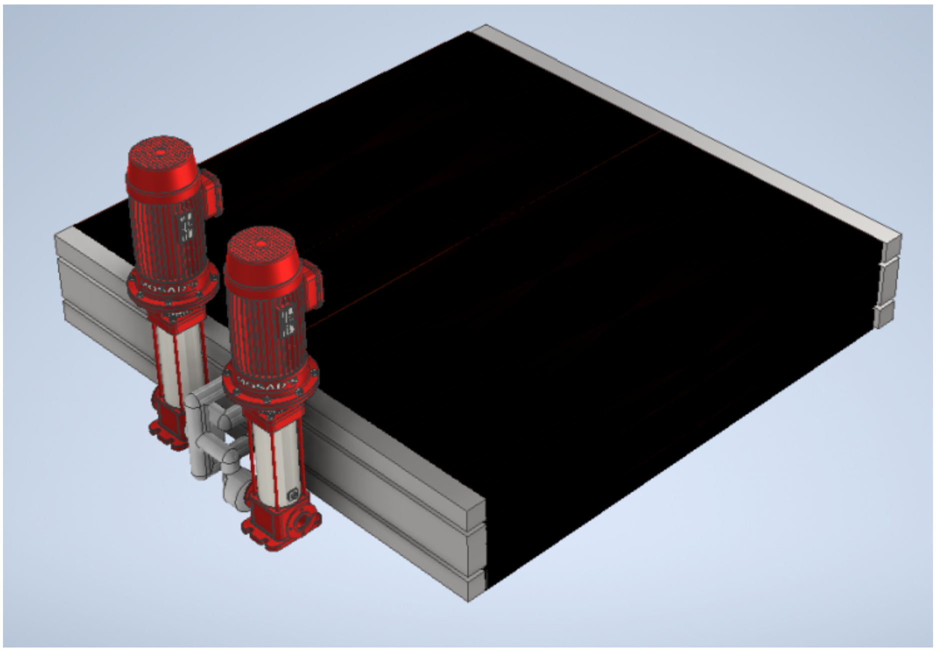


Figure 31: *CAD Render of Thermoelectric Generator*

Figure 32 shows the outline of a Thermoelectric generator with the plenums and pumps removed, for a better view of the cold and hot heat exchangers.

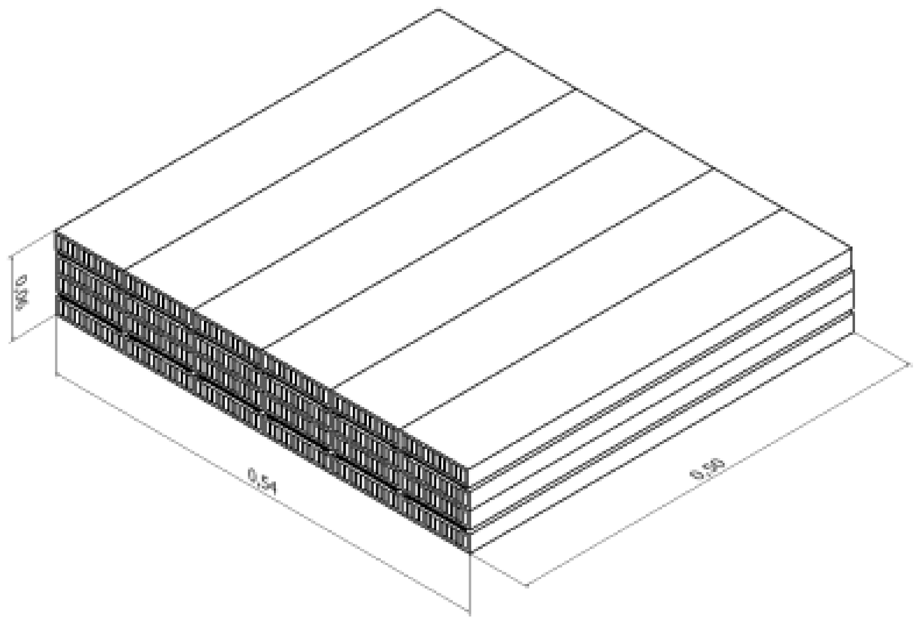


Figure 32: *TEG Dimensions in meters*

Figure 33 is a front facing view of one element, the bottom layer is the hot heat exchanger while the top layer is the cold heat exchanger.

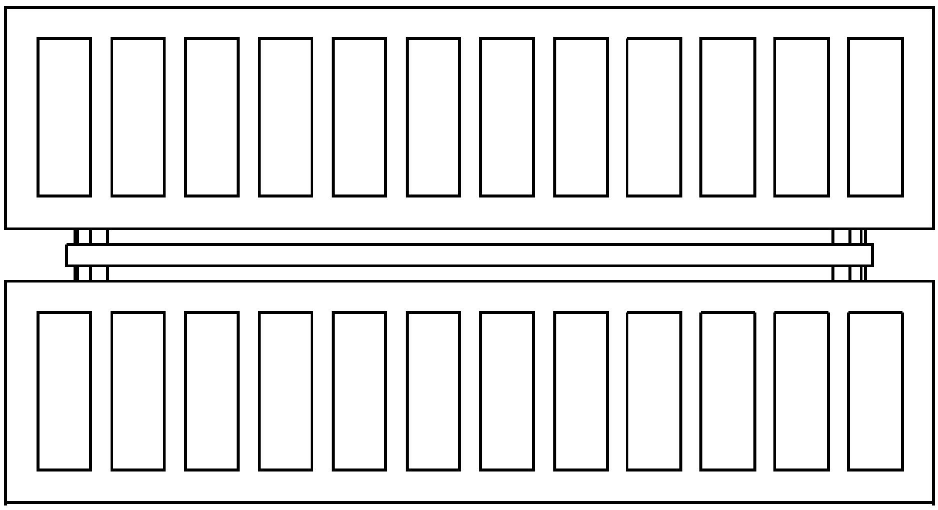


Figure 33: *TEG Single Element Front View*

Figure 34 is more similar to how the TEG will look as more layers of the Thermoelectric module, along with additional heat exchangers get added. With the single element drawing in mind, Figure 34 shows a front view of 18 elements stacked together, along with the sizing of each layer and whether each layer is a cold heat exchanger, hot heat exchanger, or a semiconductor.

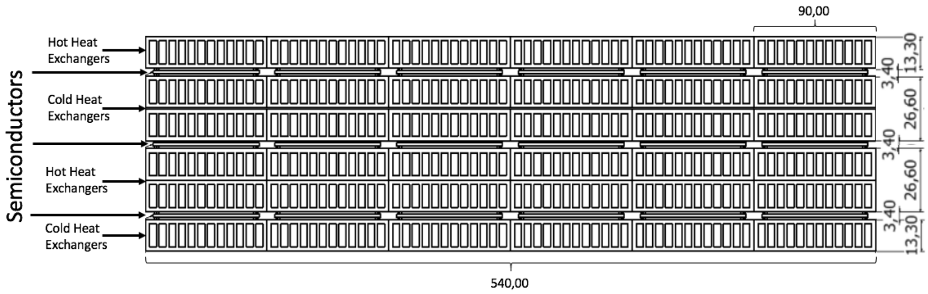


Figure 34: *Detailed Dimensions of Front Facing TEG (millimeters)*

Cost

The TEG produces electricity directly though semiconductors and has no moving parts that require additional maintenance. While little to no maintenance costs are an advantage, the design has substantial production costs that have created barriers for development in the past. In previous industrial applications, the only TE modules available were made of bismuth telluride (Bi_2Te_3), an expensive and toxic rare earth element. Each TE module can cost up to $100 per module. The toxicity and high costs implications from using bismuth telluride have make research and advancement in new TE elements attractive. For example, organic TE elements such as conductive polymers are effective in low temperature heat recovery applications.[39] These materials are easy to manufacture, and have potentially lower costs as printing technology can be scaled easily. The high costs of rare earth elements used in producing Thermoelectric elements has discounted the use of TEGs in many applications. However, with the development of cheaper and more efficient materials, TEGs are being looked at again for use in WHR applications.[39] Furthermore, as the system and each of its sub-components are still in development, it is impossible to produce an exact cost ($/kW) or total installation cost for the TEG.

Results

The net power output of the analyzed TEG concept system solution after taking potential pump head losses, and negligible heat loss to the surrounding into account is 1184W for 18 HEX elements represented in the CAD drawings in Section 7.1, and 5400W for the largest simulated system of 100 HEX elements. There are no moving parts which makes maintenance easy. However, the semi-conductors simulated have a high capital cost. The solution concepts can be improved over time with more research and development but the potentially high efficiency cannot be quantified at this moment.

These results amount to an overall efficiency increase of 0.39% for the 18 HEX elements and 1.8% for the most powerful design of a 100 HEX elements. The thermal efficiency is $\eta_{\text{thermal}} = 0.59\%$ for 18 HEX and $\eta_{\text{thermal}} = 2.7\%$ for the 100 HEX element configuration.

In these calculations the heat loss to surroundings has been neglected, and the system is assumed well insulated. In practical terms insulation should be efficient with the simple and compact dimensions of the design.

7.2 ORC

This section presents the ORC simulation results, materials, a CAD model of the system and the potential cost of manufacturing.

System Analysis

For the system, it is important to understand that since the only constant values are the heat flow into the hot side heat exchanger and the sea temperature (which for this situation is assumed constant), every equation related to the working fluid will be connected in a grand system of differential equations. As such, it is not practical to solve this without computer assistance.

The report will still continue to list the most important equations to understand the system. However, since the exact values for these equations vary over time as the system is running, graphs of the values from the simulations will also be included for further understanding.

The most important factor in generating power from the ORC system is the enthalpy of the working fluid, and while this varies slightly with just temperature it is much more about evaporating and condensation the fluid. It is for this reason a fluid (Pentane) that evaporates at a temperature much lower than the heat flow into the system, at 36°C[40] as compared to the inflow of water at 75°C, was selected.

For visualization purposes Figure 35 shows the vapor quality of the working fluid prior to and after the turbine. The system needs a couple seconds to reach steady state, which is why the first seconds of the plot seem to oscillate.

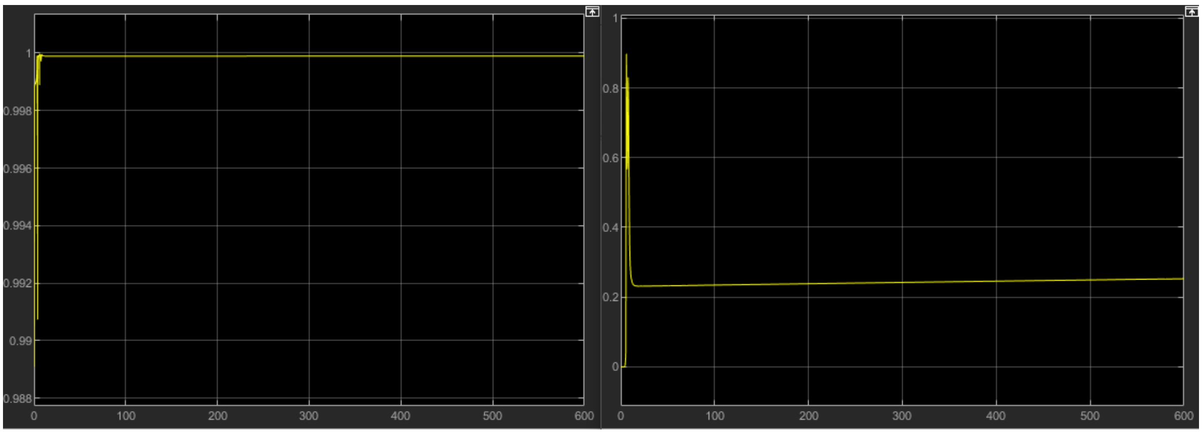


Figure 35: *Vapor fraction of the working fluid plotted against time, left is prior and right is post turbine.*

Figure 35 displays that prior to the turbine vapor quality is almost 1, meaning the fluid is almost 100% vapor, post turbine there is about 20% vapor left, meaning the enthalpy lost over the turbine has caused the fluid to partially condensate. This is excellent as the electric generation over turbine is calculated as

$$P_{\mathrm{el}} = \dot{m}(h_{\mathrm{a}} - h_{\mathrm{b}})\eta_{\mathrm{is}} \tag{28}$$

where h_a and h_b are the fluid enthalpy before and after the turbine, $\dot{m}$ is the mass flow of the fluid and η_{is} is the isentropic efficiency of the turbine. The working fluid then flows into the regenerator, where its residual heat is used to preheat the fluid prior to the hot side heat exchanger. In this regenerator a heat balance was created in the following manner, where the energy lost from the hot side must equal the heating effect onto the cold side.

$$Q_1 = \dot{m}_1(T_{H_{\text{in}}} - T_{H_{\text{out}}}) \tag{29}$$

$$Q_2 = \dot{m}_2(T_{C_{\text{out}}} - T_{C_{\text{in}}}) \tag{30}$$

$$Q_1 = Q_2 \tag{31}$$

where the subscript 1 and 2 reference the hot and cold fluid respectively, Q_1 is heat transferred from 1 to 2 and Q_2 from 2 to 1, but these values must also satisfy equations for the heat exchanger inside the regenerator

$$Q_1 = U_1 A_1 \Delta T_{1_{\text{lm}}} \tag{32}$$

$$Q_2 = U_2 A_2 \Delta T_{2_{\text{lm}}} \tag{33}$$

where ΔT_{lm} is defined the logarithmic mean temperature, U is overall heat transfer coefficient and A is the heat exchanger area. The same system of equations is also at place inside both of the heat exchangers. One must also take into account the pressure change that occurs during evaporation or condensation of the working fluid, as well as the pressure differential caused by the pumps and turbine. The fluid must always satisfy the following equation:

$$\left(\frac{P_2}{P_1}\right) = -\frac{\Delta H_{\text{vap}}}{R}\left(\frac{1}{T_2} - \frac{1}{T_1}\right) \tag{34}$$

where ΔH_{vap} is the enthalpy of vaporization, T_1 and T_2 is the temperature before and after respectively, likewise P_1 and P_2 is the pressure before and after respectively. One also needs to subtract the power lost to the pump before a net output can be achieved, it is theoretically calculated as:

$$W_{\text{p}} = \dot{m} \cdot (h_4 - h_3) \tag{35}$$

where W_p is the work done by the pump, h_3 and h_4 is the enthalpy before and after the pump respectively. However, this must also be compared to what is commercially available for the given pressure differential. The best option that was found was a larger pump for the condenser and then a smaller for the working fluid, together they consume 3kW worth of power, which along with the output resulted in 15kW net output of they system. This results in an overall efficiency increase of 5% and a thermal efficiency increase of $\eta_{\text{thermal}} = 12\%$, which is to be compared to the Carnot efficiency of the system:

$$\eta_{\text{carnot}} = 1 - \frac{\text{T}_{\text{Cold}}}{\text{T}_{\text{Hot}}} = 0.158 = 15.8\% \tag{36}$$

where T_{Cold} and T_{Hot} are the hot inflow and the sea temperature used for condensing, respectively. A loss factor of 0.95 has been taken into account when calculating the overall efficiency, to simulate losses of energy through ambient heating of the surroundings.

Components and materials

The ORC is composed of a generator, turbine, regenerator, cold and hot side plate heat exchanges (PHX), as well as cold and hot side centrifugal pumps. Additional to these static parts, there an organic working fluid, Pentane, evaporating and condensing as it moves through the system. This working fluid will need to be replaced periodically throughout the systems operation.

CAD Drawings

Figure 36 presents a conceptual visualization of the ORC system. The figure shows an evaporator, a regenerator, a condenser, a turbine, pumps and a generator. The heat exchangers in the figure are all plate heat exchangers and the pumps are centrifugal pumps. The hot water outlet from the fuel cell is pumped into the hot side PHX and evaporates the working fluid in the cycle. The cold side PHX is connected to the sea-water pump to condense the working fluid.

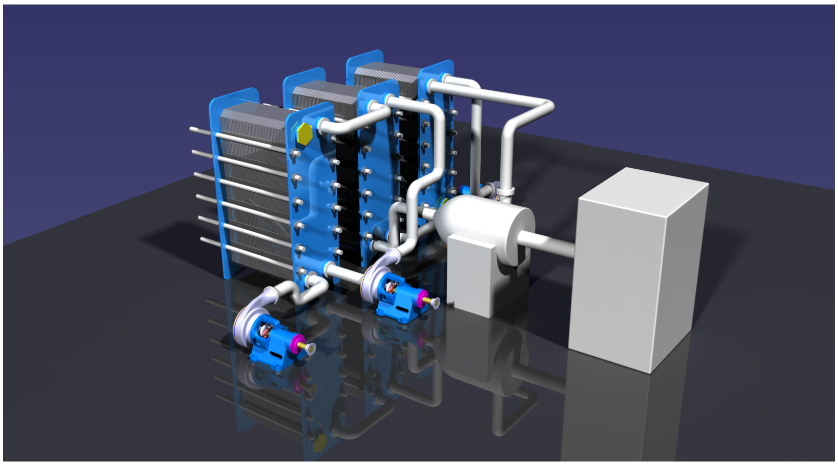


Figure 36: *CAD render of ORC*

For the dimensioning of the PHX, the total heat transfer area of the heat exchangers are acquired from the Simscape modelling of the system described in section 9.2.1.

$$A_{\mathrm{HT}} \approx 4m^2$$

Using GG003 PHX from ONDA Advanced Heat Exchangers Cathalog[41] as standard dimensions for width and height of HEX plates, the number of plates are given

$$w = 180\mathrm{mm}$$

$$h = 480\mathrm{mm}$$

$$A_{\mathrm{PHE}} = w \cdot h = 0.0864\mathrm{m}^2$$

$$\frac{A_{\mathrm{HT}}}{A_{\mathrm{PHE}}} \approx 47 \text{ plates}$$

The length of the heat exchangers are acquired from ONDA for 25-50 plates, giving a length of 330 mm.

Cost

Majority of the production costs for the ORC is a sum of each component; the evaporator, regenerator, condenser, turbine, centrifugal pumps and a generator. Additional to this, maintenance costs incur from the working fluid needed in the system during operation. The operation and maintenance costs are highly dependent on the choice of working fluid. In the ORC system design, Pentane was selected as the working fluid as it is a good candidate for moderate to low temperature WHR.[42] Generally, Pentane is more costly than traditional refrigerants such as R123 and R245fa, but cheaper when compared to benzene.[42] It is the case that Pentane is also more efficient which justifies the higher maintenance costs.

Results

The resulting net output from our system when taking pumps and losses into account is around 15kW, which varies slightly depending on what assumptions are made for the turbulence of the pipe flow. These results from the simulations are in line with researched data and earlier applications, with a 300kW fuel cell a net output of 15kW is an efficiency increase of 5%, which is in line with what was expected from the aforementioned research[27],[40],[9],[42] and [38].

7.3 System Interfaces

Both the ORC and TEG systems need to interface and work in conjunction with the fuel cell and other surrounding systems, as well as with the operators, both in terms of control of the system and to provide information about the systems performance.

Pumps

In total the ORC requires between two or three pumps and the TEG requires one or two pumps. The range of pumps for both the systems depends on the head loss over the hot side heat exchanger of the systems. If the back pressure is < 2 bar the output pressure from the fuel cell can be sufficient to uphold the thermal flow, otherwise a boosting pump needs to be installed to overcome the back-pressure. The back-pressure is calculated in the simulations for the heat exchanger but naturally the total back-pressure may vary to a large extent depending on the installation and pipe routing of interconnecting piping.

Both the ORC and TEG require one pump for the cooling water flow. In both simulations this is set to a similar flow as the heating flow, around 280 lpm in accordance with the initial conditions in Section 6.2 and 6.4.

The pump requires several considerations when choosing type and size, similar to the pump for the heating flow. Pump efficiency is heavily dependent on running conditions, and there appropriate sizing for the actual pressure and flow regime. Some initial calculations for pump power was preformed for a vertically oriented, multistage centrifugal pump with a 5cm in- and outlet port. This type of pump is used to a large extent on marine vessels for similar purposes for heating and cooling systems. The multistage design reduces the slip of the pump impeller and facilitates higher efficiency, while increasing the sensitivity to varying running conditions, furthermore emphasizing the proper design considerations before installation. With a properly designed system the running conditions should be close to constant over the whole range of operations of the system, gaining an efficiency of close to $\eta = 50\%$ for this type of pump [43].

The ORC requires one pump more than the TEG, a circulation pump for the working fluid, Pentane, which for our simulation was a simple pump model required to pump 1 kg/s of the liquid phase working fluid. As with the other pumps of the system consideration is to be taken with this pump to make sure the installation is as efficient as possible to reduce losses to the largest extent possible.

Control process

At its core, both of the systems require very little in the way of control circuits to run and produce electricity. The TEG system is inherently self-starting as long as the cooling and heating flow are activated, and it will produce some output even if the cooling flow is stopped just with the ambient air as cooling. The ORC have the same requirement but needs to start the working fluid circulation pump before any power is produced. The baseline requirement for the control circuit should hence be that a start signal is sent to the WHR system when the FC is in operation to start the both systems pumps.

The systems should be self regulating but there is some merit to install sensors and allow for some optimization of the running process based on sensor data.

Utilities

Apart from the thermal liquid supply, data and power connections of both systems requires very little from the vessel's systems. Both units are self contained, and requires no extra cooling, heating or lubrication from the surroundings.

8 Discussions

The process of conceptualizing and effectively simulating a WHR system entailed a careful analysis of various solution concepts. The first set of potential concepts was examined with respect to criteria that mainly included working temperatures, usability in different ambient conditions, plausible use of output energy etc. A total of six WHR systems were analyzed, corresponding to the intended application, and accordingly explored further or eliminated.

One of the biggest challenges of finding an effective solution concept for this application is the working temperature. Due to the relatively low working temperature of a proton exchange-membrane fuel cell, the heat dissipated by the system is much lower than what most WHR systems operate at. This eliminated more than half the concepts from the initial list, leaving only three to be analyzed further. Thermoacoustics, Thermoelectrics, and the Organic Rankine Cycle emerged as the most viable contenders, and were then further analyzed in depth for efficiency and ease of operation - specifically for working temperature deltas ranging from 40 to 60°C.

Limiting dimensions or geometry of the conceptualized WHR system was not a major requirement due to the intended use pertaining only to vessels or other similar marine applications. This allowed the project and the design process a lot more flexibility, since the addition of a WHR system takes up too valuable space in other applications.

The Pugh Matrix used revealed that a Thermoelectric generator and an ORC are the two most suitable solutions for the intended application. The detailed analysis conducted on these two technologies required a number of assumptions to be made about the final system due to lack of information available. Research unveiled a number of theoretical solutions for low temperature WHR. This allowed the team to approximate certain parameters based on plausible assumptions. This might affect the viability of the solution concepts provided adversely when being implemented. However, the opposite holds true as well. The lack of development in fairly novel technologies, such as TA and TEG, leaves room for much better operating conditions which can be obtained with time through research and development. In the future, these two technologies could prove to be even more efficient than the ORC modeled. The ORC is a mature technology that has been improved over time which makes it less prone to getting better than the other two discussed which lack thorough analysis of all potential applications tremendously.

During the extensive amount of time put into this task by the team, it was made clear that while there are a wide array of systems that theoretically could be used for low temperature WHR. Most of them are simply not efficient enough when compared to the ORC. The industrial standard is what it is for a reason, and while research like this should be done regularly to further technology, and not take anything for granted, we have failed in providing a competitive option to the ORC. While disheartening to some, the simple truth is that the alternative options lose out in such a major fashion when it comes to efficiency, that they are too easily ruled out when it comes to commercial decision making for an industrial use like this. To further amplify this effect, the low potential of the system stemming from the fact that the temperature differential is extremely low, makes almost every system a net loss case scenario. Most methods are simply not effective at such low temperature, and this is especially obvious when compared to the industrial standard system, ORC.

While the previously mentioned problem caused by the low temperature differential posed a serious problem, the saving grace for the system was the marine application. This meant that the size of the system was no serious restriction, and that the weight did not cause any affliction on the efficiency of the solution. If the application was that of, for example, a car, every kilogram of additional weight caused by the system would lead to massive losses for the performance of the car itself. But because Volvo Penta was looking at a marine application for a larger vessel, one can almost freely increase the weight without having to balance it against such a negative side-effect. Another large benefit of the marine application was the infinite access to a cooling medium through the sea water, not having to use the less effect option of air cooling, the condenser has a large effect on the net output.

Our results quite clearly state that the ORC was the far superior option for low temperature WHR in a marine application, and while this will not change anytime soon, the TEG, the TA and other options earlier excluded systems are all subject to vast improvements as the technology is nowhere near as mature as the ORC. The world is seeing large amounts of research being done on these systems and it is not unreasonable to expect that they will at some point become competing options for an application such as this. Since a lot of research is being conducted on waste heat recovery, and because of the environmentally friendly aspect of the TEG system, it is a front runner for further development Furthermore, the sizable amount of resources being committed to research of semiconductors that might directly influence the efficiency of the TEG. As corporate entities are now being heavily rewarded for their work in this area, both because of the speed of which new regulations are being created, but also because of the positive change on their public image. As these have both become major aspects of corporate success in modern times, this could likely become a major argument for choosing it over the ORC, as TEGs Carbon Oxide footprint cannot be paid back during its life-cycle according to the average pay back time [40]. This argument currently pales when considering how efficient it is compared to its alternatives. If further research could lead to an increase in the output of a TEG, which currently looks to be on the horizon, along with the scalability and ease of operation, it could overtake as the new industry standard for WHR.

8.1 Meeting Customer Needs

What follows is a discussion on the costumer needs established earlier in the process as per Table 1

Efficiency

The objective efficiency target for the WHR system was set to be 5% increase of the overall fuel cell efficiency paired with a 15kW increase in electricity output. The ORC as simulated in Simulink meets the efficiency object with achieving a 5% overall increase in the 300kW fuel cell modeled. This equates to an additional output of 15kW after losses are accounted for. The TEG, on the other hand, does not meet the efficiency threshold as its overall increase in power is slightly less than 1%, or 1kW net power output.

Production Costs

Production costs for the ORC are determined to be competitive as all of its components are readily available to be manufactured and distributed without anticipated research and development. The components that make up the TEG, on the other hand, are far too expensive to justify given its comparably low efficiency. The Thermoelectric elements and modules that are needed in the TEG design are often made of toxic, rare earth metals. As technology advances with the invention of environmentally friendly and efficient materials, however, the TEG may become viable for industrial production. In summary, although the TEG is a reliable system in its own right, other more affordable applications currently exist to choose from for WHR on a marine vessel.

Operating Costs

The ORC requires frequent maintenance as the working fluid, Pentane, will need to be replaced periodically. Volvo Penta may not mind this recurring maintenance requirement as the financial responsibility will fall on the end-users. The system is also complex as it is comprised by five distinct subsystems. The TEG has no operation and maintenance costs as there are no moving parts or working fluid involved for operation.

Ambient Conditions

ORC proves to be the more efficient system with an aforementioned power output of 5kW. The working fluid, Pentane, plays a huge role in ensuring optimal operations at low temperature. A low boiling point of 36.1°C allows Pentane to easily turn into vapor at low temperatures. This helps in achieving a decent efficiency in WHR from a fuel cell stack dissipating heat at temperatures ranging from 60 to 80°C. The TEG is modeled to run at 70°C and above. The system is extremely durable and reliable, as it has historically been used in space probe applications. Each system would be suitable to operate in a marine vessel.

Maturity

The ORC is objectively mature as this system has been used dating back to the 1950's. Preliminary research revealed that this tried and tested method commonly increase the overall efficiency of power generation by generation 4-6% by means of WHR. Our system reached 5%. It has proven to be a challenge among researchers and industry professionals to increase the efficiency of the system past this level. Semiconductors and Thermoelectric materials used in the production of TEGs however are receiving a lot of attention due to their potential for advancement in efficiency. The advancement and decline in price of the TEGs subsystems has the potential to help the TEG become industrialized in the future.

Physical Dimensions

The ORC has many moving parts and is rather large compared to the TEG. This has negative implications regarding the viability of this system being used in smaller applications, such as automobiles. The TEG is rather compact with limited moving parts and would be viable for other applications. Both systems are sufficient for a marine vessel.

8.2 Environmental Risks and Hazards

Both the TEG and the ORC come with their own separate risks. For example, the TEG requires mining of telluride and bismuth for its semiconductors. A possible hazard is the potential of a violent reaction resulting from contact of bismuth telluride with strong oxides and the potential of toxic gas emerging from contact with moisture.[39] Additionally, doped bismuth telluride is known to cause non-fibrotic lesions in the lungs of exposed animals. There is also a known effect of "garlic breath" to exposed humans and a known irritant to the eyes.

When looking at the ORC system, the main component of the system that poses possible hazards is the ORC working fluid (Pentane). There are many levels of safety hazards at every stage of the component's life-cycle, including contact/safety, system design and disposal related hazards. In this case, the unavoidable leakage of hydrocarbons and Carbon Dioxide in practical use, poses a serious flammability risk.[7] It is therefore critical that a gas-detecting mechanism is in place along with the ORC system. Additionally the fluid's extremely low flash point of -49°C makes storing fluid and designing the containment pipes extremely important.[7] Pentane is also eco-toxic and must be disposed in a proper manner, especially given that the system is designed in the context of a marine application.

8.3 Risks

Risks are always present in mechanical systems like these, and designing a secure system with this in mind is of utmost importance for the engineers responsible. The TEG system being devoid of moving parts does provide it with a significant advantage in this regard, as stationary parts are under an almost insignificant risk of breakage. However, an individual TEG element could malfunction causing the electrical circuit to be disjoint and prevent the electricity to properly flow through it. Because of this, being able to open the system and replace wires must be possible in the final design. The ORC system does come with a lot more moving parts and thus, an elevated risk of mechanical failure when compared to the TEG. Still, under the assumption that something does malfunction, the ease of which the included subsystem could be repaired makes it superior to the TEG system from a service perspective.

8.4 COVID-19

While the COVID-19 situation around the world is currently hopeful because of the ongoing vaccination, there has been no avoiding its effect on the work done during the course of this spring term, and the team has not been exempt from this. The logistical complexities that were present during the process mostly related to the inability to have physical meetings. While the team members are used to this after having worked through the regulations for over a year, there is no denying that the cohesion of the teams and the quality of the meetings would have been improved had the team been able to physically meet. Video meeting software has been used to host both our own meetings and the meetings with the supervisors. These meetings have, at times, been a bit disorganized and not very well planned. They have been the responsibility of the students and regrettably the team did not make the most of them. It is believed that had they been physical meetings the team would value them higher and more work would have been put into making the most of them.

9 Conclusions

Recovering waste heat from energy systems is the only way of increasing efficiency. An in-depth analysis of two WHR systems, a TEG and an ORC, was conducted in order to conceptualize, design, and simulate an effective way of recovery low temperature heat dissipated from a proton-exchange membrane fuel cell. ORC proves to be a better alternative to TEG for the intended application. Simulations suggest that the ORC system is more efficient (5%) with a higher output of 15kW compared to 1-5kW in the case of TEG. Moreover, with ORC being a more mature technology, low maintenance costs and expenditure on research and development are to be expected. TEG is more costly and at the same time less efficient. This could change in the future with further development of the technology. However, since it is so novel, the true potential of high efficiency cannot be quantified for this application at the time of writing. In addition to the results obtained in the report, the Simscape models used for the solution concepts can be used by the sponsor, Volvo Penta, for further analysis of these technologies.

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A Individual Areas of Responsibilities

Hunter Di Domizio	Material properties
Chinmay Gupta	Fuel cell specifications
Jesper Lidqvist	2D Design/Chalmers Coordinator
Justus Lindqvist	MATLAB & Simscape
Shreya Manoj	CAD/Penn coordinator
Rosellen Martin	Economics
Deeksha Sharma	Simulink
Robert Sugumaran	CAD/Material properties
Fredrik Özaras	Pugh Matrix

B Risk Plan

Risk	Level	Risk Reduction	Corrective measure
Covid restrictions	Low	Plan work and communication to be available to all team members at any place	None
Non-distributed work	Moderate	Update the meeting notes after every meeting, distribute weekly workload after every Sunday meeting and update Gantt-chart accordingly.	Notify team members and distribute the work. Make sure connected tasks are planned and noted in the Gantt-chart.
High individual workload	Moderate	Ensure that the majority of members agree on the work distribution. Track the project progress and previous workload.	Notify team members and distribute the work. See if extra time is available, or if another team member can share the workload.
Poor communication between Chalmers & PSU	Moderate	Upload all documents to the online storage (Box). Only use communication channels with members from both sides.	Highlight to all team members the importance of using the proper communication channels. Seek advice from examiners/supervisors.
Team conflict	Moderate	Let everyone have their opinion heard. The majority decides when members disagree.	Discuss the problem with the team see if a solution can be found. Seek advice from examiners/supervisors.
Expanded scope of work	Moderate	Clearly stated focus areas of research. Limit detail depth to the relevant problem.	If risk to deadline or planning of work discuss with team on how to limit scope.
Missing competence	High	A large project team ensures spread of competence.	Put together a smaller team of project members with the best competency in the team and work together.
Planning errors	Moderate	Diligent update of the Gantt-chart.	Sunday team meeting planning the week should reference the Gantt-chart and plan any correction.
Temporary focus shift of team members	Moderate	Clear planning of the project, allow work to be planned ahead if focus needs to be shifted for other work.	Absent person is responsible to update the team on work done outside the planned time.
Unplanned absence	Moderate	Needs to be informed as soon as possible and estimated time of absence to be minimized.	Plan to divide the work between other members of the team if the work is time critical.
Unavailable client contact	Moderate	Work with the latest plan and information given by client.	Seek advice from supervisors/examiners at Chalmers / PSU.

C Guide for use: ORC model

1. Firstly, one needs to download and install the Coolprop file "PentaneTables".
2. Then, run the following MATLAB script to set the required variables:

```
PentaneTables
Tin=273.15+75;
Tout=273.15+15;
Tstart=273.15+20;
Pstart=0.1;
Regen=8;
Output=26;
N_carnot=1-(273.15+20)/(273.15+75);
```

3. Load the Simscape file named "ORC_Model".
4. Press Model Settings.
5. Go to Solver selection.
6. Choose ODE45.
7. Go to Simulation and set Stop Time to 600.
8. Press Run.
9. After the simulation has ran, press and open a scope to study how it varies of time.
10. If any additional parameters are to be studied, add an additional scope for it repeat step 7 through 10.

D Guide for use: TEG model

The simulation regime requires 3 distinct files to be used.

- Matlab Script: Final_Comsol_Matlab.m
- Simulink File: Thermoelectric_Power_Calculations.slx
- COMSOL File: crossflow_heat_exchanger_modified_final.mph

Matlab and Simulink scripts needs to be placed in the same folder to run together without modifications, the Comsol file runs separately to export value to the Matlab file.

To create a simulation the basic steps are:

1. Start COMSOL Multiphysics® and open the Comsol File.
2. Make any changes to files necessary under *Parameters1* in the *Global Definitions*. This step requires some intuition into running Comsol and it's functions. Small changes to geometry or flow regime should not require any change to the simulation setup and can be run as is to produce results.
3. Choose an output location for the result file. This is changed under *Results* - *Tables* - *Probe Table 4* were *Storage* - *Filename* can be changed to point to an appropriate folder.
4. Press *Compute* and let the simulation run.
5. Now open the Matlab script and import the by Comsol created value from your assigned location. The values should be added under the "Matrix sim Data" section of the code, and than ad the new data to the "ComsolOut" matrix under the "Fills out the results matrix" comment. Change "n" to the correct amount of data sets you want the code to compile.
6. If you want to add more data to the Matlab Script re-run the Comsol file and export the data after each iterations and fill into the Matlab Script.
7. When the Matlab Script contains the data sets you want to run you need to make sure that the "TEG Element Values" are set to the element you intend to simulate with.
8. The remaining "For loop" and subplots will create plots to interpret the results. Modify if needed to obtain other sets of information.
9. The Matlab Script will call the Simulink file to get the appropriate results. The Simulink file will only need modification if the number of TE elements in one HEX has changed from 7.
10. Press *Run* in the Matlab Script.