



**KTH Industrial Engineering
and Management**

Waste Heat Driven Membrane Distillation Integrated with Stirling Engine

Jonatan Talåsen
Niklas Bergman Larsson

Bachelor of Science Thesis

KTH School of Industrial Engineering and Management
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Abstract

In this thesis, the potential to purify water utilizing waste heat from a unit which stores thermal energy and converts it to electricity is studied. The unit, called TES.POD, is developed by Azelio AB and is in this thesis used as a heat source to drive an air gap membrane distillation (AGMD) unit developed by Scarab Development AB. Heat from the TES.POD and ambient air temperature constitutes a temperature difference over a membrane used as a driving force to vaporize a part of the water that transfer through the membrane, and later condensates as clean distilled water as the contaminations stays in the hot stream of feed water. An analysis has been conducted to determine quasi-steady performance of the combined system for estimating the amount of purified water that can be supplied when the TES.POD unit is in peak electricity discharge mode.

The 26 *kW* of waste heat accessible from the TES.POD is shown to enable two AGMD-modules producing purified water at a production of 7, 1l/h per unit having the feed water at 50°C and cooling water at 25°C. A correlation between the amount of waste heat and distilled water production is determined, as the TES.POD could be configured to produce less electricity and more waste heat at a higher temperature. The correlation showed that an 9% increase in cooling temperature, lead to an 30% increase in pure water output and a 33% decrease in electricity output.

The results show that when implementing the two companies' units together, a system that both provides electricity and distilled water is obtained. This is a system with a high demand, especially in off-grid areas with lack of both resources but with accessible renewable energy sources. Moreover, by using waste heat to purify water, it can also reduce the production cost compared to cases where conventional energy sources are used. The potential revenue of the production was estimated to 673 790 *SEK/year* with an implementation cost of 93 861 *SEK* with yearly operational expenses estimated to 14 080 *SEK/year*.

Keywords: Carnot batteries, Stirling engine, Azelio AB, Scarab Development, Thermal Energy Storage TES, Membrane Distillation, Air Gap Membrane Distillation, Waste heat integration, Water scarcity, Power on demand, Sustainability

Sammanfattning

I detta arbete undersöks möjligheten att rena vatten med spillvärme från ett system vilket lagrar termisk energi och av den producerar elektricitet, när det behövs. Systemet är utvecklat av Azelio AB och har produktnamnet TES.POD. Vattendestillationen utförs med en så kallad air gap membrane distillation (AGMD) modul, utvecklad av Scarab Development AB. Värmen från TES.POD och omgivningstemperaturen utgör, i AGMD-modulen, en temperaturdifferens vilken i sin tur skapar en partielltryckskillnad över membranet. Denna partielltryckskillnad låter en del av det förorenade vattnet som flödar i AGMD-modulen att förångas och passera genom membranet. Föroreningarna stannar kvar i det strömmande vattnet och ångan kondenserar som renat vatten.

Arbetet visar att de 26kW som finns att tillgå i form av spillvärme är tillräckligt för att driva två AGMD-moduler att producera $7,1\text{ l/h}$ destillerat vatten per modul. Detta är under förutsättningar att det förorenade vattnet är 50°C och kylvattnet är 25°C . I rapporten återfinns också ett samband mellan mängden spillvärme och produktionen av destillerat vatten, eftersom TES.POD kan konfigureras till att producera spillvärme vid en högre temperatur. Sambandet visade på att 9% ökning av spillvärmens temperatur motsvarar 30% ökning i produktionen av destillerat vatten och en minskad elektricitetsproduktion på 33%.

Resultatet visar på att integrationen av dessa två produkter bildar ett system som både producerar rent vatten och elektricitet när så önskas. Detta system har till synes en stor efterfrågan, speciellt i områden utanför fast el- och vattennätverk men med goda förnyelsebara energikällor. Dessutom, eftersom vattendestillationen sker med spillvärme, kan produktionskostnaderna vara lägre än då konventionella energikällor används. Den potentiella inkomsten från produktionen estimeras till $673\,790\text{ SEK/year}$ med en inköpskostnad om $93\,861\text{ SEK}$ samt årliga omkostnader om $14\,080\text{ SEK/year}$.

Nyckelord: Carnotbatterier, Stirlingmotor, Azelio AB, Scarab Development, Termisk Energi lagring TES, Membrandestillation, Air Gap Membrane Distillation, Spillvärmesintegration, Vattenbrist, Ström på begäran, Hållbarhet

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Nomenclature

| <u>Symbol</u> | <u>Name</u> | <u>Unit</u> |
|---------------|---|--------------------------------------|
| c_p | Specific heat capacity | $\left[\frac{kJ}{kg \cdot K}\right]$ |
| \dot{Q} | Heat transfer flow | [W] |
| \dot{m} | Mass flow | $\left[\frac{kg}{s}\right]$ |
| \dot{v} | Volumetric flow | |
| h | Enthalpy | $\left[\frac{kJ}{kg}\right]$ |
| T | Temperature | [°C] |
| k | Overall specific heat transfer coefficient | [J/kgK] |

Abbreviations

| | |
|---------|---|
| MD | Membrane Distillation |
| AGMD | Air Gap Membrane Distillation |
| TES | Thermal Energy Storage |
| RO | Reversed Osmosis |
| MED | Multiple Effect Distillation |
| MSF | Multistage Flash |
| CWT | Circular Water Technologies |
| PCM | Phase Change Medium |
| HTF | Heat Transfer Fluid |
| LHT | Latent Heat storage |
| SHS | Sensible Heat Storage |
| THS | Thermochemical Heat Storage |
| UN | United Nations |
| EES | Electrical Energy Storage |
| TES | Thermal Energy Storage |
| TES.POD | Thermal Energy Storage. Power On Demand |

OPEX Operated expenses

CAPEX Capital expenses

1. Introduction

In today's fast-growing climate the demand for energy, specifically renewable energy, is increasing and there is a need to make use of all available energy. The global demand for energy is calculated to increase with an astonishing 30 percent by the year of 2040 (Jones, 2018). One approach to handle an increased energy demand lies in the utilization of energy storage. By utilizing energy storage, the demand could be controlled by releasing the energy when needed and stored when the demand decreases, and the energy supply is in surplus. As most sources of renewable energy today comes from ocean waves, solar radiation, wind, and biogas it presents a large uncertainty around the nature's unpredictability (Sarbu & Sebarchievici, 2018). Due to the nature's vagaries, the energy needs to be stored for these varieties of renewable sources to be utilized in an efficient manner.

Simultaneously, another need is emerging- clean water. As clean water is a limited resource the demand for clean water is rising as the world's populations continues to grow. Research estimates that the annual growth for freshwater demand will be as high as over one percent (Boretti & Rosa , 2019). A large portion of this increasing demand comes from developing countries in Africa and Asia where industries in particular are projected to grow, creating this demand. Since these geographic regions are already suffering hard from water scarcity, this puts additional stress on already exposed areas (Boretti & Rosa , 2019).

The need for accessible, clean energy is so important and urgent that the United Nations (UN) has formulated it into one of their seventeen sustainability goals. Sustainability development goal seven, "affordable and clean energy", aims to ensure affordable, reliable, sustainable, and modern energy for all (United Nations, 2021). The effects of clean energy as a substitute for fossil fuel is also related to climate goal 13 from UN, "climate action", which highlights the negative impact that greenhouse gas emission has on the atmosphere. The goal is now, in conjunction with the Paris Agreement, focused on restricting the global warming to a maximum increase of 1,5°C compared with the pre-industrial levels. To realize the thirteenth sustainable development goal the world needs to accomplish net zero carbon dioxide emissions by the year of 2050 (United Nations, 2021). The goal is of utmost importance since the climate change, as it is progressing with its current pace due to continued increase in concentration of greenhouse gases, severely reduces the chances for achieving the remaining goals.

Following the global needs, KTH has initiated a pre-study where the purpose of this thesis is to analyze the feasibility for Scarab Development and Azelio, to integrate Scarab's membrane distillation module with Azeilo's Stirling engine. Azelio AB is a cleantech company that has developed a storage unit based on thermal energy storage (TES) called the TES.POD. The TES.POD utilizes stored energy to produce electricity with a Stirling engine. During the conversion, a byproduct, waste heat is obtained.

Therefore, the second company involved in this study will include is Scarab Development AB, a company working to produce clean water with the use of membrane distillation (MD) which is a heat-driven process. With the influence of Scarab Development and Azelio AB, parameters will be handed to discuss the integration between waste heat from Azeilo's Stirling engine and clean water membrane distillation.

To achieve these goals, energy storage will play a central role to integrate renewable energy into the power grids. The historical way to generate electricity has been through centralized generation which refers to the large-scale electricity production at centralized facilities (EPA, 2022). These large facilities then transmit electricity for long distances through high voltage power grids to distributors which lower the voltage and make it applicable for households to consume. A great threat to the classic way of producing electricity is especially in times of a higher electricity demand than production. When the renewable resources in Sweden during 2019 were not able to provide the sufficient production, the electricity companies were forced to, momentarily, start the coal-fired power plants and more nuclear reactors. This is an obvious setback in countries work towards their climate goals (Redaktionen, 2020).

An option to overcome this problem is through a decentralized electricity generation, a smaller scaled on-site production closer to the source of consumption. By shifting the production to on-site, people can become their own electricity producers and become self-sufficient. (Bauknecht, et al., 2020). The largest obstacle to realizing this option is difficulties regarding energy storage, where households have not been able to store their electricity in the past, but technology is advancing (Arvidsson & Perez, 2022).

The technologies for which to store energy can be broadly categorized into Thermal Energy Storage (TES) and Electrical Energy Storage (EES). EES can be divided into several subcategories where electrochemical energy storage in form of battery storage is one of the most widely spread technologies in today's applications (Aneke & Wang, 2016). However, this paper will mainly focus on TES as a competitive alternative to electrochemical batteries due to environmental advantages that comes from not exploiting rare earth metals. TES emits, compared to lithium-ion electrochemical batteries, 29 % less greenhouse gas emissions (RISE Research Institute of Sweden , 2020).

2. Research objectives

The overall objective is to create a technologically conceptual integrated cycle between the Azelio TES.POD and the AGMD-module from Scarab Development. The integration is based on utilizing waste heat from the TES.POD's Stirling engine and using it to heat feed water that is purified in the AGMD-module.

Further, from the created integrated cycle, these are the specific objectives of the thesis:

- To estimate how much distilled water the integrated cycle can produce during a day
- Create an economic analysis, based on the integrated cycle, judged from the electricity output in relation to the waste heat and distilled water amount.

3. Methodology

The report will be based on a literature study and quantitative research. The literature study provides background information about water scarcity and furthermore theory behind the Stirling engine and thermal energy storage as well as membrane distillation. The quantitative research focusses on gathering data from the two companies, Azelio AB and Scarab Development AB laying ground for calculations and possible implementations between the two systems working together.

Our model consists of a Thermal Energy Storage from Azelio AB, and the Scarab Development's membrane distillation module.

Some assumptions are made. The general assumptions are that:

- The research will be done in a steady state operation assumed for peak electricity production from Stirling engine.
- The total energy output from Azelio's TES.POD is transformed to either obtainable heat or electricity.
- The energy calculations are assumed to be ideal with constant pressure. Existing Azelio energy storage unit taken with MD unit sized to available dissipated heat during discharging process.

4. Background

4.1 Global water crisis

UN, the United Nations, reports that 2.3 billion people live in water-stressed countries. Furthermore, 733 million of these people live in high and critically water stressed countries meaning that there is scarcity in availability due to physical shortage, or scarcity in access due to the failure of institutions to ensure a regular supply or due to a lack of adequate infrastructure. UN also predicts that 700 million people worldwide could be displaced by intense water scarcity by 2030 (Nations, 2021). The water scarcity is linked to higher demands. Both industries and agriculture together with a rapid population growth is demanding more water. Further, in areas where population growth is most rapid is not seldom in poor areas where water already is in scarcity.

4.2 Water purification technologies

As mentioned, the demand for clean water is constantly rising in parallel with world population growth. There are two main water purification technologies, the thermal phase-change processes, and membrane, non-phase-change processes. Today, 66 % of all water desalination is done with Reverse Osmosis (RO) followed by Multistage Flash (MSF) at 21% and Multiple Effect Distillation (MED) at 7% (Khalifa, et al., 2015).

Desalination, however, is not the same thing as purification. Desalination solely reduces salt levels in the water whereas purification reduces other contaminations too. The AGMD-module used in this thesis both desalinates and purifies water.

RO is a membrane, non-phase-change process, which means that a membrane forms a physical separator between the feed water and end point. Applied pressure moves contaminated water through the semipermeable membrane and less contaminated water is produced (Yang, et al., 2019).

MED, on the other hand, is a thermally driven desalination process where the feedwater is heated to a boiling point and is fed in equal portions to various vessels. Later, the seawater is sprayed on tube evaporators containing the feedwater steam. The result is that the water sprayed on the tubes both condenses and evaporates and some of the evaporated feedwater condenses. The vapors produced in the first effect are used to heat the evaporators in the second effect and the condensing process continues in a chamber with lower pressure. The lower pressure and lower temperatures in next chambers enable the process to be repeated. The condensed water is in the first step brine water, but in later chambers fresh water (Qasim Khan, 2021).

The thermal phase-change processes take advantage of, as the name reveals, the phase change of water, from liquid to gas, to separate contaminations and dissolved salts by condensation and evaporation the water. The driving force behind is the pressure difference formed by the temperature difference.

4.2.1 Air Gap Membrane Distillation

The process used in this thesis is an Air Gap Membrane Distillation (AGMD) module which is a hybrid between the two main technologies, membrane and thermal. The module is

developed by Scarab Development. AGMD, has advantages of producing satisfactory results even with relatively low water temperatures between 50-90°C (Alsaadi, et al., 2014). This gives the technology large implementation possibilities using waste heat.

The AGMD module is constructed with tight stacked cassettes membrane with an air gap of 1-2 mm between each cassette.

The AGMD module is constructed with cassettes membrane's mounted tightly with an air gap of 1-2 mm, in a frame. In comparison to MD, the air gap, which is between the membrane and condensation surface, reduces heat loss otherwise formed by conduction. Mostly common there are four cassettes in one module. The AGMD module is constructed with two separated inlets, in one of the inlets streams hot feed water and in the other one streams cold water. There is also a tap to drain the purified condensate water (Alsaadi, et al., 2014).

4.2.1.1 Operation of AGMD

The principle of MD operation is that the temperature difference between the hot and cold water creates a pressure difference which, in turn, works as the driving force of the operation. A part of the hot feed water is, because of the pressure difference, evaporating and move through the membrane. The hydrophobicity of the micro-porous membrane prevents the liquid phase from wetting the membrane pores and vapor is the only phase to pass through the membrane. When the water vapor has passed through the membrane, it condenses on the cooling plate as purified water (Alsaadi, et al., 2014). The principle is shown in Figure 1 below.

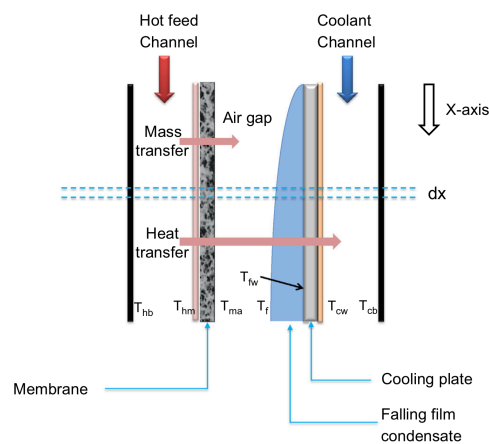


Figure 1. Principle of AGMD (Alsaadi, et al., 2014)

4.3 Stirling engine

The Stirling engine is a closed cycled external combustion heat engine, which means that the gas is permanently contained within the system and the energy converted comes from heat outside of the engine. It is operated by compression and expansion of a gas called the working gas. The invention is old, patented in 1816 by the priest and engineer Robert Stirling (Nationalencyklopedin, 2022).

The first law of thermodynamics is relevant in the Stirling engine case, as thermal energy is converted to kinetic energy. Referring to Figure 2, the engine is constructed with one cold

cylinder and one hot cylinder connected to a working fluid (helium). The hot cylinder is heated by a heat source and the cold one is cooled by a heat sink. The heat sink is commonly the ambient air, or, if the engine is used in marine environment, the ambient sea, lake, or river water which often has a lower temperature than the air.

In each cylinder there is a piston which in its turn is connected to a crankshaft where the engine produces work in form of kinetic energy. The kinetic energy arises when the working gas is expanded by the heat and pushes the piston to turn the crankshaft. Parallel with the working gas expanding by adding heat on one cylinder, the other cylinder is cooled down. This eases the movement even more because the volume of the working gas lowers with the temperature.

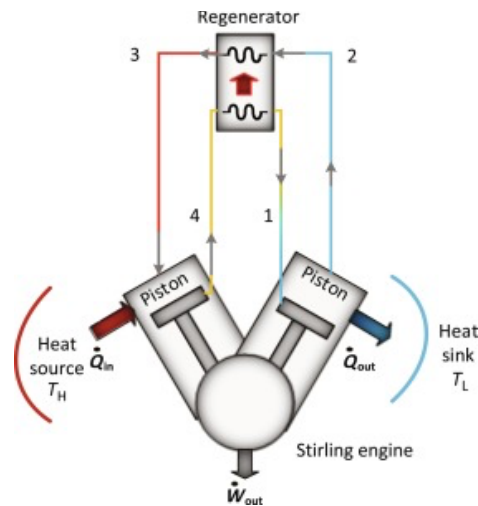


Figure 2. Sketch of alpha configured Stirling engine (Ibrahim Dincer, 2021)

There are three common configurations, the alpha, beta, and gamma configuration. They are all operated by the same principles, as mentioned, by compression and expansion of gas. All use two pistons which are moving and producing momentum. The gamma configuration has a single cylinder where only one of the pistons is producing works, the other on is loose fit and only serves to shuttle the working gas from the cold part of the cylinder to the hot part where it expands. The gamma configuration, on the other hand, has two cylinders. The cylinders are mounted tightly and are connected via tubing where the working gas flows between them. As in the beta configuration, one of the pistons is only used to shuttle the working gas. Figure 2 shows the alpha configuration, which is the configuration used by Azelio in their TES.POD. The alpha configuration contains two different cylinders, one cold and one hot. The working gas flows between the two through a regenerator (Gütte, 2022).

4.3.1 Stirling Cycle

The ideal Stirling cycle, which describes the working gas process in the Stirling engine, is described as below and can be viewed in the p-V diagram, see Figure 3 below.

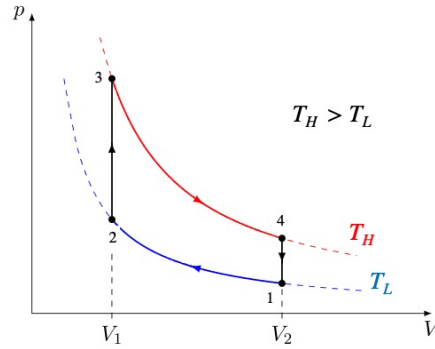


Figure 3. *p-V* diagram of the Stirling cycle (Ibrahim Dincer, 2021)

Process 1-2: *Isothermal compression*: The working gas is compressed isothermally while space discharges the heat to the heat sink. Therefore, the temperature of the heat sink is increased, absorbing \dot{Q}_{out} .

Process 2-3: *Isochoric heat addition*: Heating occurs at the regenerator under constant volume. The temperature of the working gas increases from T_L to T_H .

Process 3-4: *Isothermal expansion*: The working gas expands isothermally while space is heated externally with \dot{Q}_{in} by the heat source. At this stage, the engine produces useful work, \dot{W}_{out} .

Process 4-1: *Isochoric heat rejection*: Cooling occurs at regeneration component at constant volume. Regenerator absorbs heat from the working gas. The temperature of the working gas reduces from T_H to T_L .

When the working gas is heated in the hot cylinder, it is expanding, forcing the piston to move out of the cylinder. The cold cylinder, at the same time, lowers the volume of the working gas by the heat sink absorbing heat, helping the movement. The hot and cool gas passes the regenerator. This is one cycle.

Important to mention, there is an internal heat exchange, often called a regenerator, in the duct of the working gas. This is what mainly differs the Stirling engine from regular combustion engines using petrol or diesel. The regenerator exchanges heat from the heated expanded gas and cold from the compressed gas coming from the cold cylinder. This increases the temperature of the working gas when, in the cycle, going from the cold cylinder to the hot cylinder and vice versa. This means that the gas will not need to be heated as much when going from the cold side and will not need to be cooled as much when going from the hot cylinder to the cold one, which is energy saving and increases the efficiency of the Stirling engine, see equation 1 below.

The Stirling cycle's ideal efficiency is calculated by

$$\eta_{sc} = \frac{1}{1 + \frac{(1 - \eta_R)}{\kappa - 1} \cdot \left(1 - \frac{T_L}{T_H}\right) \cdot \frac{1}{\ln(v_2/v_1)}} \cdot \left(1 - \frac{T_L}{T_H}\right) \quad (1)$$

where η_R is the efficiency of the regenerator, T_L and T_H is being the highest and lowest temperature in the cycle, corresponding to the temperature of the hot and cold cylinder mentioned above. κ is the isentropic constant of the working gas (Havtun, 2014).

Equation 1 shows that the efficiency of the Stirling engine is directly dependent on the quotient of the two temperatures. In other words, the larger the difference between the temperatures, the higher the efficiency the Stirling engine will reach, an important fact.

As mentioned, the Stirling engine is an external combustion engine. Its efficiency is competition against internal combustion engines such as Diesel and Otto engines, commonly used in combustion engine cars, with similar power outputs. For example, a Diesel engine has an average efficiency of 35% and the Otto engine's average efficiency is 25% whilst the Stirling engine's average efficiency is 40% (Mohammad Hossein Ahmadi, 2016). However, even if the Stirling engine's efficiency is higher, other factors, mainly that the Stirling engine likes to change its power output level slowly, makes it complicated to apply the Stirling engine in, for example, a car (American Stirling Company, 2022).

4.3.2 Stirling engine from Azelio

Azelio's Stirling engine is of the alpha configuration and corresponds to Figure 2. Azelio is using the Stirling engine to convert thermal energy stored in their TES.POD to electricity. The thermal energy is formed by melted aluminum, stored at a temperature just under 600 degrees Celsius. A heat transfer fluid transfers the heat from the melted aluminum to the Stirling engine where it heats the hot cylinder, mentioned under 4.3 Stirling engine, driving a generator which produces electricity. The heat sink constructed by an air-cooled fluid streaming directly on the cold cylinder.

4.3.2.1 Waste heat from Azelio's Stirling engine

The Stirling engine used in this work are developed by Azelio AB. During peak electricity output, it produces 13 kW of electricity and 26 kW of waste heat.

Today, the waste heat is dissipated to the surrounding air. In Azelio's marketing, they present that their TES.POD, beyond delivering electricity, also delivers heat in the 55 – 65°C span. At peak electricity output, the temperature of the air is assumed to be 65°C. The earlier mentioned heat sink is commonly formed by the surrounding air.

4.4 Scarab Development AB and Azelio AB

Scarab Development is, according to their website, a "Swedish research company that focuses on sustainable, flexible, scalable and local production of ultra-pure water through clean energy." and is the parent company of five subsidiaries.

The distilled water produced from Scarab Development's AGMD-module is presented in following Figure 4 below.

| Type of contamination | Amount | Method | Detection limit | Test by | Result |
|--|-----------------------|-------------------------------------|-----------------|--|--------|
| Bacteria | 14 000 (after 7 days) | Membrane filter count | – | National Bacteriologic Laboratory, Stockholm | BDL |
| Chlorine | 3.4 mg/l | Photometric analysis (Perkin Elmer) | < 0.01 mg/l | Water Protection Association of South West Finland | BDL |
| Salt water | 31 000 ppm | Ion chromatography | < 1 ppm | VBB Viak Stockholm | BDL |
| Trihalomethanes | 1 000 µg/l | Gas chromatography | < 1 µg/l | University of Turku, Finland | BDL |
| Radon | 380 Bq/l | Alfa detection | < 4 Bq/l | Swedish Radiation Protection Institute | BDL |
| Cesium, Strontium, Plutonium, Radium | 2.4 Bq | Lithium Drifted Germanium Detector | < 0.1 Bq | Radiation Physics Department, University of Lund | BDL |
| Arsenic +3 | 10 mg/l | AAS Graphite | < 0.003 mg/l | Analytica AB, Stockholm | BDL |
| Arsenic +5 | 10 mg/l | AAS Graphite | < 0.003 mg/l | Analytica AB, Stockholm | BDL |
| Ag nanoparticles | 3100 µg/l | HPLC | < 2 µg/l | IVL Swedish Environmental Research Institute | BDL |
| SiO ₂ | 10 000 µg/l | AAS | < 5 µg/l | Vattenfall AB, Stockholm | BDL |
| Setralin and 20 other pharmaceutical residuals | 4 ng/l | HPLC | < 0.8 ng/l | IVL Swedish Environmental Research Institute | BDL |

*BDL = below detection limit

Figure 4. Test results of AGMD-module with different contaminations (Circular Water Technologies, 2021).

Where, as seen in Figure 4, the results are below detection limit on all contaminations tested. Compared to Swedish tap water, the water produced by Scarab Development's AGMD-module is purer with less contaminations. But the contaminations as pharmaceutical residuals and chlorin in Swedish tap water is not harmful (Svenskt Vatten, 2021).

Azelio AB is a Swedish company with the headquarter in Gothenburg. The company is listed on the Stockholm stock exchange and was founded in 2006. Azelio aims to make clean production affordable and reliable for its consumer with the help of their TES.POD which is their long-duration energy storage unit. The TES.POD aims to provide the additional electricity required in unstable grid locations or even off grid locations (Azeilo, 2022).

4.5 Air-cooled radiator

The air-cooled radiator is a sort of heat exchanger that, as other heat exchangers, is used to provides exchange of heat energy between medium streams that have different temperatures. The component is often seen in combustion engine cars where the ambient air flow streams through the radiator and chills a refrigerant, which in turn cool the engine. This component serves as the integration point between Stirling engine and AGMD system, thus meriting further examination.

The phenomena which create the heat exchange between the two medium streams are convection. Convection occurs at the interaction between a flowing medium and a solid wall, and the formula used to calculate the cooling power needed from the radiator is

$$\dot{Q} = \dot{m} \cdot c_p \cdot \Delta T [W] \quad (2)$$

where \dot{m} is the mass flow of the medium that is cooled, c_p the specific heat capacity of the medium and lastly ΔT is the temperature that thee medium should change (Havtun, 2014).

The construction of a radiator is, according to Figure 5, done with a pipe, seen as a brown, going back and forth forming a “plate” with gaps between each turn. Furthermore, on the pipe there is mounted flanges which increases the area of the pipe which is directly increasing the heat transferred by convection.

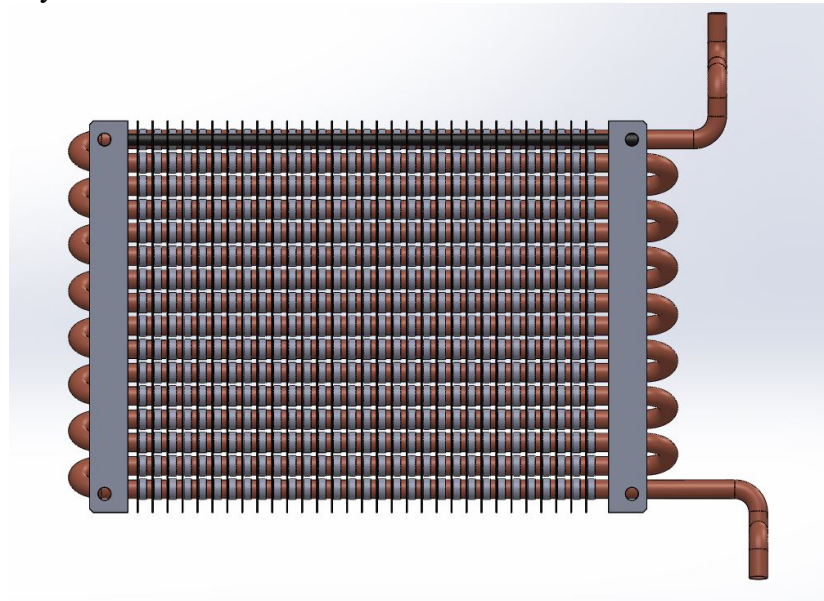


Figure 5. Radiator construction (Haider, 2021)

4.6 Thermal energy storage (TES)

Thermal Energy Storage (TES) can be diverged in to three different types of technologies: latent heat, sensible heat, and thermochemical heat storage (Cabeza, et al., 2021). TES can be used to store cold or heat to later be utilized through different processes. It acts as a bridge in the gap between energy consumption and energy generation. This gap is due to conflicts in time, power, temperature, or location (Cabeza, et al., 2021).

The TES cycle consists of three different phases: charge, storage, and discharge. Within these cycles, TES can be managed by two different concepts, either a passive or active systems. In a passive system the Heat Transfer Fluid (HTF) solely passes through the storage medium for charging and discharging. These systems normally consist of two different mediums, working like a regenerator heat exchanger. The mediums in a passive system are generally solid, formable and phase change materials (PCM) (Sonar, 2021). On the contrary to a passive system, an active system is distinguished by a forced convection in the storage material where the storage medium itself is circulating in the system (Sonar, 2021).

4.6.1 Latent heat storage (LHT)

In latent heat storage, the storage medium stores potential energy between the sub particles of the chosen material. The material of the storage medium is called Phase Change Medium (PCM). As the name of the medium suggest, this type of heat storage involves a phase change, usually the solid-liquid phase. The most frequently used PCM is water (Wu, 2010). This phase change occurs in the conversion between potential energy within the storage medium and heat. Moreover, the change of phases is what stores the energy, it can be done at

a constant temperature, making the process near isothermal. Thus, the capacity of latent heat storage can be determined by

$$Q = m \cdot \Delta_h \quad (3)$$

Where Q stands for the energy stored in joules [J] and m stands for the stored mass [kg] and Δ_h is the phase change enthalpy [J/kg]. Latent heat storage is more volume efficient than the sensible heat storage due to its enthalpy being greater than the medium's specific heat, leading to the latent heat advantage in storage density (Wu, 2010).

4.6.2 Sensible heat storage (SHS)

Within sensible heat storage there is no phase change for the storage medium, instead thermal heat is stored through sensible heat in liquid or solid substance. These storage media include substances like concrete and formable metals. The cost for these media is low but they all have moderate to high thermal conductivities. Regarding the liquid substances, water is the best compromise concerning the cost, environmental impact, heat storage capacity and density, even though molten salts are considered superior amongst the liquids (Sonar, 2021). The capacity of sensible heat storage can be determined by an approximation for certain media where specific heat for constant volume is valid and its stored mass in conjunction with the possible temperature difference.

Thus, the capacity of heat storage can be described by the following equation

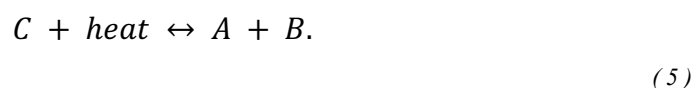
$$Q = m \cdot C_v \cdot \Delta T \quad (4)$$

Where Q still stand for the energy storage [J], m is the stored mass, C_v is the specific heat and ΔT is the temperature difference (Havtun, 2014).

4.6.3 Thermochemical heat storage (THS)

In contrast to LHS and SHS, thermochemical heat storage (THS) is a relatively new area within TES with much ongoing research and development. Even though LHS and SHS are the dominant technologies used domestically and industrially, research shows that this upcoming technology provides benefits of higher storage density, lower heat loss and lower charging temperatures (Aydin, et al., 2015). The disadvantage of THS is regarding its complexity and high investment costs, hence the commercialization of the technology has yet to flourish.

THS can be categorized and divided as sorption processes and reversible chemical reactions. Through a THS process, the energy is stored after a dissociation reaction, a chemical reaction that separates a compound into two or more components (Helmenstine, 2020), and is later restored by a chemically reversed reaction (Abedin & Rosen, 2011). This reaction can be described as



Where C is a thermochemical medium that absorbs heat and is chemically converted into two components, A and B , that can be stored separately. The energy is then released through the reversed reaction when the two components are reunited and reversed back to the compound C , creating an additional energy gain (Abedin & Rosen, 2011).

4.6.4 Thermal energy storage technology within Azelio

The TES.POD system that Azelio has created uses a latent heat storage technology where a PCM is heated by electricity input from renewable energy sources to just under 600 degrees Celsius. The PCM is an aluminum alloy that is used for its specific phase changing characteristics (Azelio, 2022), working between liquid and solid phase changes. The aluminum can also be recycled to later be reused in new TES.POD's with no negative effect on the metal's performance, creating an even greener solution to electricity storage.

The TES cycle is a passive cycle where the HTF is hydrogen that passes through the melted aluminum for charging and discharging. The HTF is then used in a Stirling cycle to produce electricity.

5. Implementation of systems

This section gives an overview of the system seen in Figure 6. Under this heading the cold and feed water side will be described in detail and the thought process for the cycle will be presented.

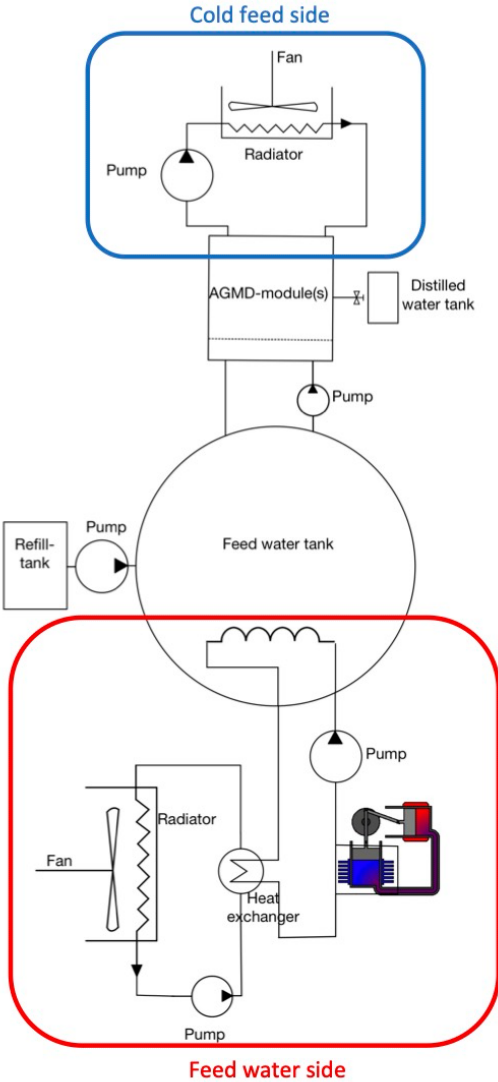


Figure 6. Overview of the system (the TES has been omitted in the sketch)

5.1 Components

The schematic figure of the integrated cycle is seen in Figure 6 and the included components can be found in

Appendix 1, where the component list is defined. Observe that the TES, which is the system's heat source, is omitted in the sketch. TES provides the system with heat from melted aluminum that has been heated through electricity from renewable resources. When electricity is required, the heat is transferred to the Stirling engine hot cylinder through a HTF, in this case hydrogen. The thermal integration is further discussed below, see 5.2 Feedwater side.

5.2 Feedwater side

The feedwater side are consisting of the Azelio TES.POD, a water tank, pipes, and a copper coil to transfer the heat from the Stirling engine in the TES.POD to the feed water.

The Stirling engine heat source is melted aluminum stored in the TES-tank. The heat transfers from the melted aluminum to the Stirling engine's hot cylinder via a heat transfer gas.

The Stirling engine heat sink is constructed of water streaming directly on the outside of the cold cylinder and exchanging heat. When the water passes the heat sink, it travels via tubes into a long copper coil placed in the water tank where convection transfers the heat from the coil to the feed water. The same water leads out of the water tank, through an air-cooled radiator, to lower its temperature, and on to the cold cylinder of the Stirling engine.

The configuration of the copper coil was calculated by the formula for a counterflow heat exchanger

$$\dot{Q} = k \cdot A \cdot \vartheta_m \quad (6)$$

where k is the overall heat transfer coefficient, A is the heat transfer area for the surface of the coil and lastly ϑ_m is the log-mean temperature differences between the two mediums (Havtun, 2014).

The overall heat transfer coefficient k is a complex coefficient depending on fluid velocities, viscosities, conditions of the heating surfaces, size of the temperature differences and is, because of this, assumed to the mean of different values and therefore an indication, not an exact value (The Engineering Toolbox, 2003).

The amount of energy needed from convection is equal to the amount of energy needed to heat the water returning from the AGMD-module. It is calculated by putting Equation 2 equal to Equation 6.

$$\dot{Q} = \dot{m} \cdot c_p \cdot \Delta T_{AGMD} = k \cdot A \cdot \vartheta_m \quad (7)$$

The surface area A was obtained from these equations. With the obtained area A , the necessary length of the coil was calculated with a predetermined diameter of $3/4$ inch or 1.91 cm. The parameters \dot{m} and c_p are the mass flow, \dot{m} [kg/s] and specific heat at constant pressure, c_p [J/kgK].

The refill tank connected to the feed water tank is set to complement the water losses from the integrated cycle due to the permute that leaves the cycle and fills the distilled water tank.

5.3 Cold feed side

The purpose of the cold feed side is to provide the AGMD module with cold water used to condense the vaporized water in the AGMD-module. The cooling liquid is water. It is pumped through tubes between the AGMD module and a radiator. The radiator needs to lower the cooling water temperature about 9°C as this is the mean of temperature rise when it passes through the AGMD module. This is achieved by having a fan passing ambient air through it. The ambient air is set to $T_{ambient} = 20^{\circ}\text{C}$, and it is assumed that the lowest temperature the radiator can obtain is 5°C above the ambient air temperature.

The needed cooling power of the cooling unit consisting of a radiator and a fan is calculated using Equation 2, and a pump is used to maintain the right waterflow.

5.3.1 Design of the feed water tank

The heat transfer between the feed water and heated water from the Stirling engine heat sink is generated through forced convection where pumps in the integrated cycle forces the water to move, thus increasing the energy transfer. The output from the hot water side of the AGMD-module is circulated back to the feed water tank. The temperature difference between the input and output from the AGMD-module is predetermined to $\Delta T_{AGMD} = 9^{\circ}\text{C}$, a parameter obtained from Scarab Development. Therefore, the temperature loss needs to be supplemented by external heat from the Stirling engine for the AGMD-module to be assumed to operate within a constant temperature range.

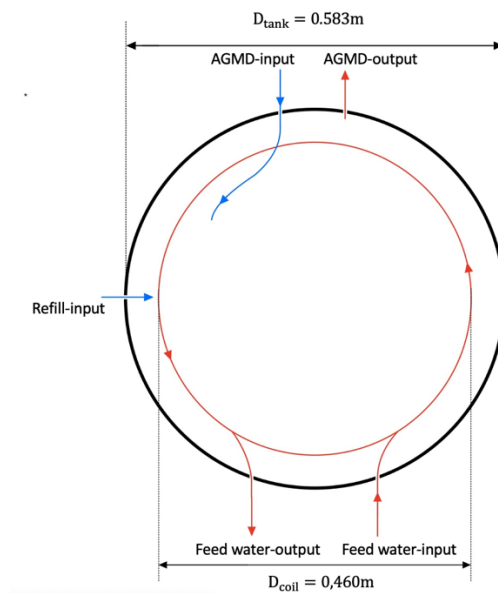


Figure 7. Overtop-view of the feed water tank

The feed water tank is designed as a cylinder with a volume of 400 liters, with an inner diameter of 0.583 m as illustrated by Figure 7. The idea behind the construction is to

facilitate the integration between existing water in the tank with the outlet water of the AGMD-module by shaping the tank after the copper coil, creating a swirl and a homogenous mixture of water. The tank contains 375 liters of water where the remaining 25 liters is volume loss due to the copper coil.

The length of the copper coil was calculated through Equation 6 above to 71,5m. From a standard calculation of the circumference of a circle, each circle of copper coil within the feed water tank was calculated to 1,45m. By dividing the obtained total length of the coil with the length of the circumference, the necessary number of rounds could be determined to 49. Furthermore, the tank with a predetermined height of 1,5m obtained a 2,86cm gap center to center between each round or an actual distance of 1,8cm.

As illustrated in Figure 8 below, the feed water tank consists of a copper coil and five different couplings for connecting tubes. The coil is filled with hot water, generated from waste heat of the Stirling engine. This water is circulated into the tank through the feed water-input and later led out through the output. The temperature of the hot air generated from Azelio’s TES.POD is a given parameter from Azelio, set to somewhere between 55 – 65°C. This research is done with the assumption of hot air generated in the highest possible temperature range and a 5°C temperature loss between the water and the hot air. Thus, the hot coil is assumed to provide a constant temperature of 60°C to the feed water tank. Further, the hot water within the tank is assumed to obtain 55°C, therefore an additional 5°C loss is considered since heat transfer by convection between the copper coil and the water is not fully efficient.

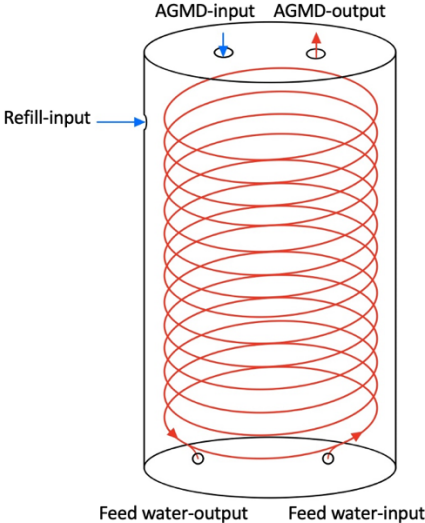


Figure 8. Side-view sketch of the feed water tank

The AGMD-input, containing cooled feed water that has circled through the AGMD-module, is designed to be placed on the lid of the tank together with the AGMD-output which provides the AGMD-module with the sufficient hot water. The tube from the output connection is reaching deep down in the tank while the tube from the input connection provides the tank with cold water on the surface.

Furthermore, the feed water-output is circulated back through a heat exchanger to decrease the temperature in the water tube that circles back to the heat sink in the Stirling engine. This is further illustrated by Figure 6.

5.4 Purified water production

The model for calculating the distilled water flow is adapted from Andrea Gabaldón Moreno master thesis (Moreno, 2018, p. 26) where Minitab were used to obtain an equation for the purified water flow. The equation is depending on F_c (flow of cold water), T_{ci} (temperature of cold water at inlet), T_{hi} (temperature of feed water at inlet).

5.5 Comments on the implementation

The components within Figure 6 are designed to be adaptable with standard parts to facilitate the implementation. The length of tubes and the size of pumps as well as the tanks can be modified to meet specific requirements from the user.

It is worth mentioning that this implementation acts as a pre-study and to create a fully functional system, more components are needed. For example, regarding the copper coil, valves are needed to release unwanted air in the coil. Also needed on the coil, is a water reservoir to refill water leaks.

Further on, a temperature sensor is thought to be mounted in the feed water tank. The purpose of this sensor is to control the outlet flow to the AGMD module. If the temperature of the feed water is below a certain limit, the outlet should be closed as the feed water needs more time to be heated.

On the cold feed side on the radiator cycle, a reservoir like the one mentioned on the copper coil, should be mounted with the purpose of refilling water losses by leaks.

There are four pumps used in the model, one with higher power rate than the other three. The power rates are chosen to satisfy the mass flow when all components are mounted on the same level. If not, the power rate needed could be both less or more.

6. Effect and consequences of the operating parameters

From Table 1 the consequences of operating parameters from the AGMD-module are illustrated. These parameters constitute a foundation for the technical analysis that is displayed and analyzed through graphs and words in the following chapter. Also, the equation described under 5.4 Purified water production, to obtain the yield is based on this data.

Table 1; Distilled water flow from different feed and cooling water temperatures (Moreno, 2018)

| Row | F_h [l/h] | F_c [l/h] | T_{ci} [K] | T_{hi} [K] | T_{co} [K] | T_{ho} [K] | ΔT [K] | Yield [l/h] |
|-----|----------------|----------------|-----------------|-----------------|-----------------|-----------------|-------------------|----------------|
| 1 | 780 | 600 | 21,7 | 65,7 | 28 | 58,2 | 44 | 6,5 |
| 2 | 900 | 780 | 21,7 | 65 | 28,4 | 57,7 | 43,2 | 6,7 |
| 3 | 900 | 780 | 21,8 | 65,3 | 28,4 | 57,9 | 43,5 | 7,6 |
| 4 | 1110 | 1020 | 28,1 | 64,1 | 33,1 | 58,5 | 35,9 | 8,9 |
| 5 | 1110 | 1020 | 26,2 | 66,8 | 32,7 | 60,8 | 40,5 | 10,8 |
| 6 | 1140 | 1020 | 35,7 | 75,5 | 40,2 | 69,2 | 39,7 | 14 |
| 7 | 1140 | 1020 | 30,1 | 76,2 | 36,1 | 68,8 | 46,1 | 15,4 |
| 8 | 1140 | 1020 | 25,1 | 75,5 | 31,4 | 67,7 | 50,5 | 16 |
| 9 | 1140 | 1020 | 17,2 | 75,1 | 25,3 | 66 | 57,8 | 17,5 |
| 10 | 1200 | 1140 | 25,6 | 80,4 | 34,1 | 71,2 | 54,9 | 18,9 |
| 11 | 1200 | 1140 | 15,7 | 80,7 | 25,9 | 70 | 65 | 20,3 |
| 12 | 1200 | 1200 | 30,6 | 65 | 33,7 | 61 | 34,50 | 8,20 |
| 13 | 1200 | 1200 | 30,8 | 62,2 | 34,3 | 57,7 | 31,40 | 9,00 |
| 14 | 1200 | 1200 | 26,6 | 61,8 | 30,6 | 57,3 | 35,20 | 9,40 |
| 15 | 1200 | 1200 | 35,2 | 71,3 | 39,4 | 66,2 | 36,10 | 10,20 |
| 16 | 1200 | 1200 | 49,8 | 80,2 | 53,9 | 75,5 | 30,40 | 10,30 |
| 17 | 1200 | 1200 | 15,5 | 65,3 | 19,9 | 59,7 | 49,80 | 11,30 |
| 18 | 1200 | 1200 | 19,7 | 71,7 | 26 | 64,3 | 52,00 | 15,30 |

6.1 Changing Stirling engine efficiency to achieve higher temperatures

As seen in Table 1 the distilled water production is higher when the temperature difference, ΔT , between the feed water and coolant water is large. However, this also depends on where the temperature difference is on the temperature scale. As for example, referring to row 14 in Table 1, the ΔT is 35,2 °C and distilled water production is 9,4 l/h. However, in row 16, the ΔT is lower at 30,4°C, but the distilled water production is higher at 10,3l/h. This is because row 16 is placed higher on the temperature scale.

Since a high distilled water production is of interest in this model, a variation of different electricity and thermal energy efficiencies are examined by modifying the Stirling engine working temperatures. This is analyzed to understand the changes corresponding to electricity production and distilled water production.

As mentioned under 4.3 Stirling engine, the Stirling engine efficiency is directly depending on the temperature difference between the lowest and highest temperature, the larger difference, the higher efficiency. In other words, to obtain more distilled water from the AGMD-module, the efficiency of the Stirling engine must be reduced, which also means that the electricity output will be less.

According to data from Azelio AB, the peak electricity production is

$$P_{electricity} = 13 \text{ kW}$$

and, when producing this amount of electricity, the waste heat is

$$\dot{Q}_{wasteheat} = 26 \text{ kW}$$

Furthermore, also according to data from Azelio AB (Lindquist, et al., 2021), the thermal efficiency of the module is 90%. The thermal efficiency is calculated by how much thermal energy is delivered to the Stirling engine divided by how much which is used, or in other words divided by the electricity and waste heat output and corresponds to

$$\eta_{stirling} + \eta_{wasteheat} = 0,9. \tag{8}$$

Research from an economical perspective is presented. The different waste heat temperatures were obtained by using following equation

$$\dot{Q}_{wasteheat} = \dot{m} \cdot c_p \cdot \Delta T \tag{9}$$

where $\dot{Q}_{wasteheat}$ is changed as the Stirling engine efficiency is.

Assumed that $\dot{m} \cdot c_p$ is constant, the $T_{wasteheat} = \Delta T + T_{ambient}$ for different obtained $\dot{Q}_{wasteheat}$ were calculated. $T_{wasteheat}$ corresponding to different Stirling engine efficiencies are shown in Figure 9.

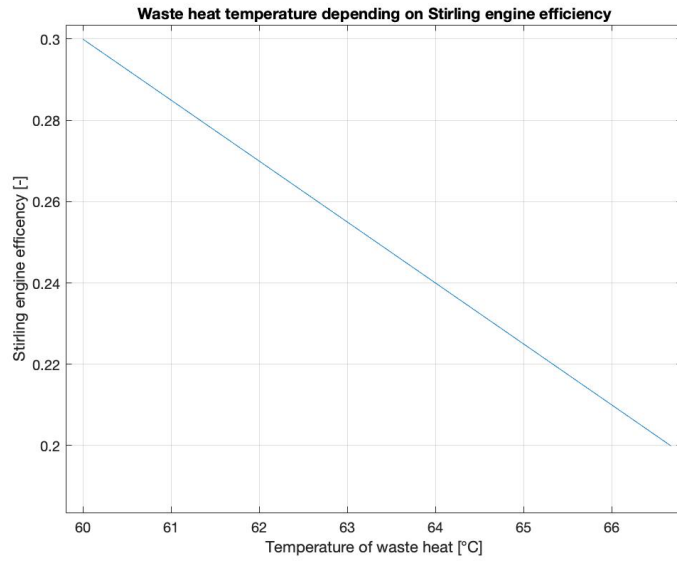


Figure 9. Waste heat temperature depending on Stirling engine efficiency

Further on, the Stirling engine efficiency changes corresponds to different distilled water flow shown in Figure 10.

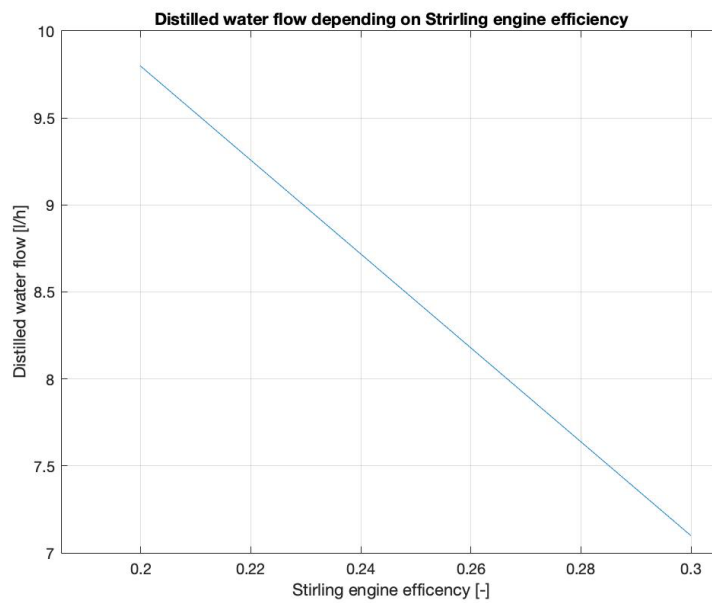


Figure 10. Distilled water flow depending on Stirling engine efficiency

As mentioned, the electricity output is affected when changing the Stirling engine efficiency. The amount of energy output in form of waste heat and electricity depending on the Stirling engine efficiency is shown in Figure 11. The consequence of these parameters is further discussed under 8.2 Economic conclusions

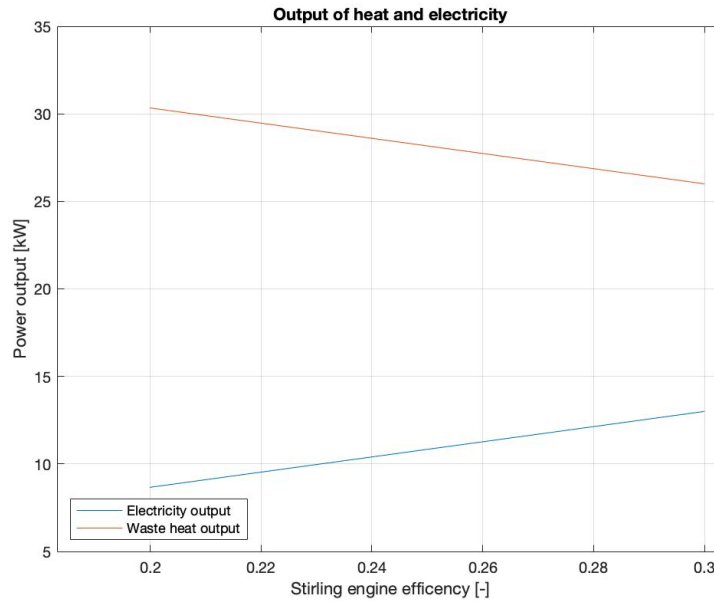


Figure 11. Output of heat and electricity depending on Stirling engine efficiency

6.2 Costs and potential revenue

Regarding economic analysis, the AGMD-module is thought to be implemented on an existing Azelio TES.POD. Therefore, when calculating costs, the TES.POD will be excluded and the costs constitutes of all other necessary components viewed in Table 2.

The end product is bottled water which is calculated to be valued at 10 SEK/l in grocery stores. However, costs for transporting, handling, intermediaries, as well as the margin that the grocery stores use lower the price that the raw product is worth. Analyzing what the raw product is worth is complex as it depends on several factors specific for different areas and procurements and will hence be excluded in this report.

The maintenance costs of the model constitute of membrane cassettes changes every 5 years and additional cost of new water tanks every 10 – 12 years. The lifespan of the AGMD module is, according to Scarab Development, expected to 5 – 7 years (Khan, 2022).

In Table 2 the yearly depreciation of respectively component is listed together with the expected lifespan and initial cost.

Table 2. Depreciation of components (Natrads, 2019) (Grimmer Motors LTD, 2016) (Smith's Plumbing Service, 2019) (GMB, 2018) (Compositehouse Manufacturer, 2016) (Everlasting Valve Company, 2021) (Home Depot, 2017) (TankForEverything, 2022) (Smith's Plumbing Service, 2019)

| Component | Expected lifespan (years) | Initial cost (SEK) | Depreciation (SEK/year) |
|-------------------------|---------------------------|--------------------|-------------------------|
| AGMD module | 6 | 25000 | 4166,67 |
| Air cooled radiator | 8 | 400 | 50 |
| Fan | 8 | 429 | 53,63 |
| Tubes | 40 | 200 | 5 |
| Pump | 10 | 1741 | 174,1 |
| Hose clamps | 10 | 90 | 9 |
| Ball valve | 25 | 200 | 8 |
| Isolated hot Water tank | 10 | 8500 | 850 |
| Refill water tank | 12 | 2785 | 232,08 |
| Distilled water tank | 12 | 2785 | 232,08 |
| Copper coil | 25 | 8700 | 348 |
| Total | | 52145 SEK | 6961,90 SEK/year |

In addition, to depreciation of components there are also service costs. All components need to be changed at their end of lifespan, but continuous maintenance services are thought to be decalcification of membranes, aerate the tubes, and cleaning of the fans. These chores do not require any authorization or major knowledge about the system and could be done by reading the instruction manual. These service costs are merged and included under the categorization of Operated Expenses, OPEX, that is assumed to be 15% of Capital Expenses, CAPEX.

Furthermore, the calculation of CAPEX illustrated in Table 2 is based on the integration of one AGMD-module. Therefore, when integrating a second AGMD-module the CAPEX is assumed to increase with a factor of 1,8. This factor is deliberately a little oversized in relation with the values one can expect to protect the implementation from unexpected expenses.

The potential revenue calculation is based on the distilled water production during peak electricity production and an ambient air temperature of $T_{ambient} = 20^{\circ}C$ and waste heat temperature of $T_{wasteheat} = 65^{\circ}C$. It is possible for the system, at peak performance, to be running 13 out of 24 hours a day all year around.

The potential running hours are calculated based on data given from Azelio. These mentioned that the TES.POD can be charged with 100 kW during 6 h. And as, referring to heading 6.1 Changing Stirling engine efficiency to achieve higher temperatures, the thermal efficiency is 90%. This means that the output is

$$P_{output} = \dot{Q}_{wasteheat} + P_{electricity} = \frac{26 + 13 [kW]}{0,9} = 43.33 [kW].$$

(10)

The running time is then calculated as

$$Production\ time = \frac{charge\ hold}{P_{output}} \frac{100\ [kW] \cdot 6[h]}{43.33\ [kW]} = 13,85\ [h].$$

(11)

From the integrated cycle, the pumps and the fan are external components that consumes electricity. The idea is to use the electricity produced by the TES.POD to provide for these components. Together, during a 13 *hour* production, they consume about 8,06 *kWh* which corresponds to 10,33 % of the electricity produced by the TES.POD.

7. Potential market opportunities

As discussed in the introduction to this thesis, the interest for a decentralized grid is growing because of its many advantages. For countries to be able to achieve the environmental goals that UN has stated there needs to be a clear shift concerning the usage of natural sources in energy production, and this is an urgent matter. The effects of greenhouse gases are being demonstrated all around the globe with more frequent intervals between natural disasters and large areas being heated to levels that are testing the limit of human survival. To give this planet a sustainable future, actions need to be taken. Thus, a decentralized grid, like Azelio's TES.POD, could be seen as a step in the right direction as the TES.POD creates energy without affecting the ozonosphere to the same extent as carbon dioxide emissions. The TES.POD could be used as a sustainable alternative to a diesel generator to provide electricity off-grid or during power failures. Since the TES.POD also is a small-scale energy storage it is easier to take care of the waste heat and use it to provide other household necessities.

Further on, a location like the Sub-Sahara Desert is viewed as an attractive potential area to implement this system because there is a demand for both of off-grid electricity, clean water, and heat. At the same time there are renewable energy resources, like the sun, available. A larger implementation consisting of several units of this system could provide a society with all these three to a relatively low cost.

Wind turbines are a growing field within energy production in Sweden, but also globally. The fact that Sweden in just over 10 years has gone from a couple of hundred turbines to reports around 4336 wind turbines installed by 2020 could show the potential upswing wind turbines might have in the future (Lejestrand, 2022). Since Sweden install most of their wind turbines along the coastline of Sweden, there is an unlimited amount of sea water available. This creates a potential market opportunity for the integrated cycle as this could provide the cycle with water to distill and simultaneously meet the need for energy storage along the coastline of these wind turbine plants. Azelio could also use the sea water for the cooling process in the heat sink of the Stirling engine which would reduce the electricity consumption since no further cooling unit would be necessary.

8. Applications of water distillation module integrated with Stirling Engine

In this section a conclusion of the economic and technologic aspects of the integrated cycle is presented as well as the result of the factual parameters that the integrated cycle could be assumed to provide. Furthermore, a comprehensive description on future developments is discussed to approach the idea of a commercialized product.

8.1 Technical conclusions

Illustrated in Figure 10 the distilled water flow from the AGMD-module with the highest possible Stirling engine efficiency of $\eta_{Stirling} = 0,3$ provides 7,1 l/h of distilled water. During 24h, the system is calculated to provide electricity during 13h (referring to 6.2 Costs and potential revenue), this means the distilled water amount is projected to provide 92,3 liters during a day at nominal peak electricity power output.

Furthermore, when decreasing the efficiency, $\eta_{Stirling}$, the estimated temperature of the waste heat increases. For example, when decreasing the Stirling engine efficiency to $\eta_{Stirling} = 0,20$, the projected temperature of the waste heat increases to $T_{wasteheat} = 66,67^{\circ}\text{C}$ and the distilled water flow increases to 9.8 l/h and 127,4 l/day, corresponding to a 38% increase per day with the same reasoning as described above. The electricity output thus decreases from 13 kW to 8.66 kW, corresponding to a 33% decrease. Since the electricity output is to be valued as a main priority, a decrease in the electricity production to increase the water distillation production is not reasonable, especially when the increase of distilled water production is percentage less than the decrease of electricity production.

The total amount of dispatched heat energy from the Stirling engine with the standard Stirling efficiency set to $\eta_{Stirling} = 0,3$ is stated to 26kW. From Equation 7 the necessary energy required to maintain 55°C to the AGMD-output when the system is running is 12,92kW. With these numbers specified, the implementation of a second AGMD-module should in theory be running simultaneously to release all available energy for the energy equation to be valid. This can be practically implemented by connecting two AGMD-modules in parallel to each other. This implies that the surface area of the copper coil needs to be twice the size to dispatch the energy to the feedwater tank. This further implies that the feed water tank needs to be redesigned to fit into the new length of the coil as well as enlarge the distilled water tank and the refill tank to appropriate sizes.

Further, a correlation between $T_{wasteheat}$ and distilled water flow was found to be that 8.75% increase in $T_{wasteheat}$ gives a 29.9% increase of distilled water flow.

From Equation 2, the energy required to run the cooling unit for one AGMD-module is calculated to 12,5 kW. Therefore, a 120W fan is used to provide the sufficient energy effect. This energy is required to be supplied externally to the system to obtain the required cool down temperature to the AGMD-inlet on the cold feed side. Further, the 4 pumps required for the implementation of the system, apart from the existing pump already integrated in the TES.POD. These four pumps consist of three pumps á 50W and one larger pump of 350W to facilitate the flow in the copper coil. If the integration of a second AGMD-module would be implemented, two additional pumps need to be added to generate the sufficient waterflow in the cold feed water cycle as well as to the AGMD-output.

The existing cooling unit in the TES.POD enable the system to run without the AGMD-module implementation by removing the waste heat by chilling the cooling water.

8.2 Economic conclusions

Effects of potentially increasing the distilled water production obtained by changing the Stirling engine working temperatures is presented in Figure 10. However, since the main purpose of the Azelio TES.POD is to provide electricity when needed, there is no interest to lower the electricity output from Azelio's side since this would not be a financially justifiable solution. Another downside to lower the efficiency of the Stirling engine concerns the increased overall electricity usage from the TES.POD to provide sufficient energy to the external component in the system. Thus, less electricity from the total production can be distributed to other sources, which again must be viewed as a priority from an economical perspective. Therefore, these calculations are based on water production without changing the Stirling engine efficiency.

The potential market value for the distilled water, assumed the water is bottled and sold in groceries, is 336 895 *SEK/year* from one module. With two AGMD-modules connected in parallel the revenue will double to an estimated 673 790 *SEK/year*. These revenues are estimated with the assumptions that a water bottle costs 10 *SEK/l* and that these modules run or 13h a day for a whole year.

But, as mentioned, there are costs before the customer can buy it, depending on multiple variables extending to outside the scope of this thesis.

If the water is used in Swedish tap water, the customer price is somewhere around 0,04 *sek/liter* (Privata Affärer, 2009) and the potential revenue per AGMD-module is then calculated to 1347,6 *SEK/year*.

The system with two integrated AGMD-modules is estimated to have a CAPEX of 93861 *SEK* and with the reasoning in accordance with 6.2 Costs and potential revenue, OPEX is estimate to 14080 *SEK/year*. The total yearly depreciation using mentioned components in Table 2 is 6961,9 *SEK/year*. The depreciation with two AGMD modules is estimated to 12531,4 *SEK/year*.

The cost to have the system running with two AGMD-modules for 6 years (the lifespan of the AGMD module) would be 159 668,4 *SEK*.

As seen, the potential market value when selling the water as bottled water is 250 times higher compared to market value as tap water and is the economically defensible choice since the depreciation overtake the revenue when selling the purified water as tap water.

However, since the module is presumably used off grid as a decentralized electricity source, these numbers are presented mostly to give a perception about market value. Valuing what the distilled water is worth off grid is complicated and there is seldom set a price.

8.3 Future developments

For the presented integrated cycle to be commercialized, some adjustments are required. As previously mentioned, the current cycle is created as a potential product, viewed as a pre-study, where supplements must be added to create a sufficient product for its purpose. For instance, the cycle needs to contain sensors to measure the flows in tubes as well as volume in tanks to create a more dynamic system with the possibility to send out an alarm if something were to go wrong. Moreover, a second cooling unit could be added before the heat exchanger in the TES.POD to further decrease the temperature of the water that later will cool down the cold cylinder in the Stirling engine, thus, creating a friendly environment for the Stirling engine to operate in.

This work is also based on assumptions, all mentioned earlier in the report. Further investigations and experiments would be needed to replace the assumed numbers with calculated numbers.

The work is based on assumptions regarding the heat loss during the convection as well as during the capture of the waste heat. These losses are assessed to be 5°C each but need further investigation to obtain the actual numbers, thus this will affect both the economic and technical output of the cycle to some extent. Furthermore, it is reasoned and assumed that the lowest temperature the radiator can produce is limited to the external temperature plus an additional 5°C. This assumption might also need further investigation to ensure the appropriate size of the radiator.

The value of the overall heat transfer coefficient k is one of the main parameters that may not be entirely correct in and affects the results regarding length of the copper coil. Also, worth to gather exact data for, is what temperature the water used as the Stirling engine heat sink will have since this is important for the systems outcome.

Further, an assumption is made that the TES.POD is producing electricity and heat for 13 hours out of a 24-hour cycle at a nominal peak power output. In reality, the TES.POD might not reach its peak capacity and the production is dynamic with fluctuating production of heat and electricity during the discharge period. Therefore, it would be interesting to do a case study about what production of electricity and water that is possible to obtain in a specific area for a certain period, while considering the access to renewable energy sources and ambient air temperature in that area.

The MATLAB code, attached in Appendix 2. MATLAB code, is however dynamic and if, after experiments, another value is obtained on a parameter, it could easily be changed and the results corresponding to the new value will be shown. The code also forms a basis when doing research about implementing the system in a specific area, mention above.

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Appendix 1. Component list

| Component | Specification | Quantity |
|--------------------------------|--|----------|
| Air cooled radiator | 12,51 kW cooling power | 1 |
| Fan | 120 W | 1 |
| Azelio TES.POD | - | 1 |
| Tubes | PVC 3000mm | |
| Pump(s) | 3*50W, 1*350W | 4 |
| Hose clamps | 20x27mm | 10 |
| Valves | Profec valve, type 100 $\frac{3}{4}$ " | 1 |
| Scarab Development AGMD-module | - | 1 |
| Feed water tank | 400 liter, $D_i=583$ mm, $H = 1500$ mm | 1 |
| Refill water tank | 1000 liter | 1 |
| Distilled water tank | 1000 liter | 1 |
| Copper coil | Length = 71500 mm, $D_y = 21,05$ mm, $D_i = \frac{3}{4}" = 19.05$ mm, $H = 1400$ mm, coiled with diameter 46 mm, $n = 49$ rounds | 1 |

Appendix 2. MATLAB code

```

%% Waste heat from TES
Qprick_wh = 20000; %[W]
density_water = 997; %[kg/m^3]
volume_flow_in = 1200; %[dm^3/h]
volume_flow_distilled = 7.1; %[l/h]
convert = density_water*10^-3*(1/3600); %for calculations l/h to kg/s
mprick_agmd = volume_flow_in*convert; %[kg/s]
mprick_out = mprick_agmd; %[kg/s]
mprick_distilled = volume_flow_distilled*convert; %[kg/s]
cp_water=4181; %[J/kg*K]

%hot side
Twh = 65; %[C]
Tcoil = Twh-5; %[C] assumption that the coil will be 5~C lower than the waste heat
Thwt = Tcoil-5; %[C]
Tf_in = Thwt; %[C]
delta_agmd_inout = 9; %[C] temperature difference between the AGMD inlet temp and outlet temp
Tf_out = Tf_in - delta_agmd_inout; %[C]

%cold side
Tambient_air = 20; %[C]
Tc_in = Tambient_air+5; %[C]
Tc_out = Tc_in + delta_agmd_inout; %[C]
delta_agmd = Tf_in-Tc_in; %[C]

%refill, mass flow from the refill tank
mprick_refill = mprick_distilled; %we refill the same amount as gets distilled

%Needed cooling power in radiator
P_radiator_kylslinga = mprick_agmd*cp_water*delta_agmd_inout;

% COIL i feed water tank, convection. The water needs to be heated 9~C. What Area does the
coil have to be to fulfill the convection?
R = (0.0254*(3/4)+0.002)/2; % Outer radius of tube copper coil, 3/4 inches
Qpricknecessary_convection = (mprick_out*cp_water*delta_agmd_inout + mprick_refill*cp_water*(-
Tambient_air+Thwt)); % the energy that need so be transferred from the coil to the feed water
inn the tank
k = (340+455)/2; % Water-copper-water,heat transfer coefficient
https://www.engineeringtoolbox.com/overall-heat-transfer-coefficients-d\_284.html
theta1 = Thwt - Tf_out; % for log-mean temperature calculations
theta2 = Tcoil- Thwt; % for log-mean temperature calculations
tetha_m = (theta1-theta2)/(log(theta1/theta2)); %log mean temperature
Qprick_convection = k*(2*pi*R*length)*tetha_m == Qpricknecessary_convection;% equation solved
to calculate the necessary lenght of the coil
solution_length = solve(Qprick_convection, length); % necessary lenght for heat transfer by
convection [m^2]

area = double(2*pi*R*solution_length); % [m^2] surface area of coil
coil_length = double(solution_length); %[m] length of coil

%TANK dimensions
syms R_hwt
height_tank = 1.5; %[m]
volume_tank = 400*10^-3; %[m^3]
ekvationens = pi*R_hwt^2*height_tank == volume_tank; % [m^3] equation to match the volume with
radius
svaret = solve(ekvationens, R_hwt); % inner radius of the coil (cc)
R_hwt = double(svaret); % obtained radius
volume_heat_coil = (R^2*coil_length*pi); %[m^3]
volume_water = 10^3*(volume_tank-volume_heat_coil); %[dm^3]

time_heating = (volume_water/(volume_flow_in/3600))/60; %[min] what time it takes to heat the
incoming water
circumference_one_round = 2*pi*0.23; % [m] (radius of coil = 0.23m)

number_of_rounds = round(solution_length/circumference_one_round );% [varv]
gapcc_rounds = (height_tank-0.1)/number_of_rounds; % [m]
gap_rounds = gapcc_rounds-R ;% [m]

% Neccasary mass flow Stirling Engine and in the coil
mprick_stirling_needed = Qpricknecessary_convection/(cp_water*(5));

% STIRLING ENGINE ECONOMICAL ANALYSIS

```

```

discharge_el = 13000; %[W]
discharge_heat = 26000; %[W]
energy_in = (13000+26000)/0.9; %[W] Thermal efficiency according to Azelio = 90%
T_heat = 60;
eta_el = discharge_el/energy_in; % [-]
eta_heat = discharge_heat/energy_in;% [-]

deltaT = T_heat- Tambient_air;

syms mprick_cp
mprick_cp = solve(mprick_cp*deltaT == discharge_heat);
constant = double(mprick_cp);

% Changing striling efficiency (eta_stirling) and obatianing graphs of the
% changes
matrix_eta_el = [];
matrix_T_heat=[];
matrix_el = [];
matrix_heat = [];
matrix_yeild = [];
i = 0;
while eta_el > 0.20
    eta_el = eta_el-i
    discharge_el = energy_in*eta_el;
    discharge_heat = discharge_heat*(1-eta_el);
    eta_heat = 0.9-eta_el;
    discharge_heat = energy_in*eta_heat;
    T_heat = (discharge_heat/constant)+Tambient_air
    Tf_in = T_heat-5;
    Yeild = -78.2+0.0581*volume_flow_in+0.179*Tc_in+1.246*Tf_in-0.000372*volume_flow_in*Tc_in-
0.000701*volume_flow_in*Tf_in %[l/h]
    matrix_eta_el = [matrix_eta_el;[eta_el]];
    matrix_T_heat = [matrix_T_heat;[T_heat]];
    matrix_el = [matrix_el;[discharge_el]];
    matrix_heat = [matrix_heat;[discharge_heat]];
    matrix_yeild =[matrix_yeild;[Yeild]];
    i = i+0.00001;
end
f1 = figure("Name", "Output of heat and electricity");
f1 = plot(matrix_eta_el, matrix_el);
hold on
f1 = plot(matrix_eta_el,matrix_heat);
legend({'Electricity output', 'Waste heat output'}, 'Location', 'southwest');
title("Output of heat and electricity");
xlabel("Stirling engine efficiency [-]");
ylabel("Energy [W]");

f2 = figure("Name", "Waste heat temperature depending on Stirling engine efficiency");
f2 = plot(matrix_eta_el,matrix_T_heat);
title("Waste heat temperature depending on Stirling engine efficiency");
xlabel("Stirling engine efficiency [-]");
ylabel("Temperature of waste heat [°C]");

f3 = figure("Name", "Distilled water flow depending on Stirling engine efficiency");
f3 = plot(matrix_eta_el, matrix_yeild);
title("Distilled water flow depending on Strirling engine efficiency");
xlabel("Stirling engine efficiency [-]");
ylabel("Distilled water flow [l/h]");

% What is the electricity consumption caused by implementation components
% pumps and fan
electricity_consumtion_components = 50*3+350+120; %[W]
Electricityconsumtion = (electricity_consumtion_components)*10^-3*13; % [kWh]
electricity_produced = 13*6; % kWh
procentuall_andel = Electricityconsumtion/electricity_produced;% [-]

```