Improving the Engine Room of a Yacht

New technologies applicable in the engine room of a boat and a case study of the potential of trigeneration system in improving efficiency

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Abstract

The aim of this project is to improve the energy efficiency of a sailing yacht engine room by reducing the inputs and maximizing the outputs and simultaneously striving to reduce the weight. The document is structured in three sections; an introduction about the important concepts and the case, a theoretical part with the technologies that are applicable in the project and that could improve it and finally, an analysis and suggested improvements of the system.

This project strives to explain the energy concepts, explore new ways of converting energy resources into useful forms of energy and storing this energy that could be applied in the engine room of a boat. Moreover, a system analysis is performed and used to design a proposal for a new system and to identify if this new system uses the energy in a more efficient way.

Language: English Key words: engine room, boat, new technologies, efficiency

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1. Introduction

1.1. General introduction

"*The environment is where we all meet; where all have a mutual interest; it is the one thing all of us share."*-Lady Bird Johnson

"I think the environment should be put in the category of our national security. Defense of our resources is just as important as defense abroad. Otherwise what is there to defend?"-Robert Redford

Eliminating pollution problems is the 21st century goal. The responsibility to achieve this goal is distributed. Companies should invest more to come up with new and more efficient technologies. Consumers are also important; they need to become more responsible and efficiency conscious, only in this way will the market be driven to change by consumer demand. The engineers' responsibility is to be aware of both and try to implement their demands into new projects. Saving the environment is best for companies and it is also best for the world.

This project is a real project for the company Baltic Yachts and it is about applying technologies in the engine room enabling a reduction of weight and an increase in efficiency. All the equipment and the relation between them can be modified to achieve this goal.

The philosophy of the company is to build light, fast and strong yachts using the latest technologies; consequently, they are also pioneers in research and development. The idea of the project is to continue the company philosophy in developing or applying new ways to improve the general efficiency and reduce the weight of the boat. Weight is the most important parameter but efficiency is also very important in a light boat because the energy resources are limited. This project is only the first part of a larger project aiming at improving the system in the totality of the boat.

This thesis consists basically of three important parts. Firstly, some general concepts to the project such as the concept of energy and the first law of thermodynamics are introduced. The second part discusses possible technologies applicable to the engine room. These technologies are focus on improving equipment or reusing lost energy. This part will be used to determine the new system, the equipment and the system itself. The first two parts build up the knowledge needed in order to analyze the system in section three and to design the proposal for a new system.

1.2. Baltic Yachts

The company Baltic Yachts was founded in 1973. This company is located in Ostrobothnia on the west coast of Finland, where a professional team is working to make the customers sailing yacht dreams come true. The philosophy of the company is to build light and fast yachts with all the latest technology.

Originally, Baltic Yachts was situated in Bosund (Ostrobonia region) in Western Finland. The company builds high tech performance sailing yachts using state of the art materials and technology. The first boat completely made of carbon fiber was manufactured in 1995 but the company has been using carbon fiber since 1979. In 2002 the first boat more than 100 feet long was sailing. These big boats are the reason why the company moved part of the functions to Jakobstad. Today, the company makes boats that can be up to 200 feet with the latest technologies.

1.3. Objective

The objective of this project is defined by the company and it consists of finding a way to improve the engine room design through simultaneously reducing weight and increasing efficiency. In other words, a new system which increases the efficiency with the lightest possible equipment has to be developed. Consequently, higher power per kilogram value has to be achieved.

2. Theoretical part

2.1. Energy

The word "energy" appeared in the 16th century. It originates from the French word **énergie** or late Latin from Greek **energeia**, from en-'in, within' + ergon 'work'. This word has more definitions that are very far from the original meaning, it is used in economy and other topics. However, the meaning that is of interest to us is the one used in physics. Defined by the Oxford dictionary with the following words: "The property of matter and radiation which is manifest as a capacity to perform work (such as causing motion or the interaction of molecules): ***a collision in which no energy is transferred."***

The 1st law of thermodynamics says that energy cannot be created or destroyed, only transformed. Therefore, the only way to generate energy is to take this energy from an energy resource. In the transportation field the energy resource is the fuel.

2.2. The First Law of Thermodynamics

Thermodynamics is the physics branch which studies the energy transfer process. The first postulate of thermodynamics says that when objects with different temperatures are put together, the temperatures tend to equalize. This phenomenon happens because the hotter object gives energy to the cooler one, causing heat transfer.

2.2.1. Heat (sensible and latent)

Heat (Q) is defined as the kinetic energy of the total atoms and molecules of a substance. This concept is used to refer to the thermal energy transfer. When some substances receive heat, two things can happen: the state of the substance does not change (sensible heat) or it experiences a change of state (latent heat). The formulas for these situations are completely different.

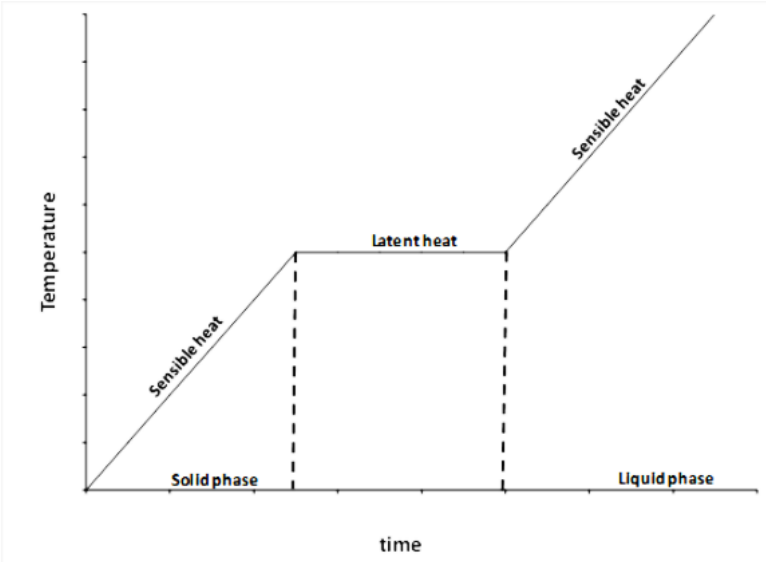

Figure 1. Substance changes of temperature[1]

Sensible heat

The sensible heat (Q_s) is measured by:

$$Q_s = (T_2 - T_1) \cdot C \cdot m$$

Where: C is the specific heat coefficient of the substance (J/Kg·ºC), m is the mass of the substance (Kg) and (T2-T1) the different between the initial and final temperatures (ºC).

The specific heat coefficient (C) is the amount of heat required to change a unit mass of a substance by one degree in temperature. There are two types of specific heat coefficients; when the process happens in a constant pressure (C_p) and when the process happens in a constant volume (C_v). Moreover, these values change with temperature, the difference is high in gases and approximately zero in liquids and solids.

If both sides of the actual equation are divided by the time, the following equation to calculate the power ($\dot{Q}_s$) is found:

$$\dot{Q}_s = (T_2 - T_1) \cdot C \cdot \dot{m}$$

Where: C is the specific heat coefficient of the substance (J/Kg·ºK), $\dot{m}$ is the mass flow (Kg/s) and (T2-T1) the difference between the initial and final temperatures (ºK).

[1] Source. NC state university

Latent heat

The latent heat (Q_l) is measured by:

$$Q_l = l \cdot m$$

Where: m is the mass of material undergoing a phase change (kg) and l is the latent heat of the phase change (J/kg).

The latent heat of a specific substance changes depending on the phase change.

If both sides of the actual equation are divided by the time, the following equation to calculate the power (Q_l) is founded:

$$\dot{Q}_l = l \cdot \dot{m}$$

Where: m is the mass flow of material undergoing a phase change (kg/s) and l is the latent heat of the phase change (J/kg).

2.3. Transportation future challengers

Energy consumption has increased since the first industrial revolution in 1840 and it is expected to continue growing over the next 50 years. However, the situation is very different now because developed countries have reduced the tax on demand and other underdeveloped countries like China and India have started to play an important role in energy consumption. These countries have low concern about climate change and they have a high consumption of coal. On the other hand, renewable energy has improved a lot and it has had a high acceptance rate by consumers.

In the transportation sector there has been a large increase. This sector is based on oil products, and-hence produces a large amount of CO_2 and other air pollutants. In 2002, the transportation sector accounted for 21%[2] of all CO_2 emissions worldwide. Therefore, the energy system needs to change to renewable energy with greater speed. The transportation

[2] Source. Kreith F. and D. Yogi Goswami. (2008).Energy conversion. Broken Sound Parkway NW. Taylor and Francis group. Print

sector is one of the areas where reducing the GHG emissions has to be prioritized because the actual system is not sustainable.

However, to supply the increase of consumption it is necessary to use fossil fuels in the next years. The reason is that all the changes have to be progressives; the procedure is increase the efficiency rate at the same time changing to renewable resources.

3. The engine room of a boat and technologies applicable in the engine room

3.1. The engine room

The engine room of a boat is the space in a boat where it is possible to find almost all the technological equipment which generates the power for movement and other useful outputs like cold air for the air-conditioning or hot water. One reason for concentrating all this equipment like compressors, engine, generators, and pumps in one place is striving to insulate the noise, heat and vibrations that this equipment produces.

Space is limited and all the equipment has a specific position that reduces the space. All the equipment and the connections between them are designed carefully to achieve this purpose. Moreover, a ventilation system is needed to reduce the high temperatures generated in a room with a lot of machinery.

The engine room has to supply enough electricity, hot water and mechanical power to cover the needs of the boat. For this purpose, there is different essential to achieve this goal. The most important elements that are common in all engines rooms are the following ones:

- **The engine** is the most important element in the engine room and it transforms an energy resource into an useful form of energy. The main task of the engine is creating the propulsion power moving the boat. The most common type of engine in this application is internal combustion engines because diesel and petrol are the fuels which dominate the current transportations market. However, new technologies are continuously developed and merging the market.
- **Generator** (mechanical to electrical power) transforms mechanical to electrical power is called alternator. This element enable using the mechanical power the engine produces generating electricity to cover the power demand.
- **Generators** (fuel to electrical power) is a combination between the engine and the alternator and it is used to supply the electricity demand instead of the engine and the generators that are explained before. The generator which generates electricity from

fuel is used when the engine is in mode off or when the electricity power demand is higher than the power produced by the engine and the alternator.

- **Electrical batteries** have two different purposes. The first is starting the engine when some initial energy is needed and the second is to compensate the high and low levels of production to give a constant supply.
- **Air-conditioning machine** uses electrical power to produces cold water for the air-conditioning system of the boat. However, it can be replaced by an absorption chiller if the energy source is hot water instead of electrical power.
- **Water heater and hot water accumulator.** These two elements usually work together. The water heater increases the temperature of the water and then the hot water is kept in the accumulator for later use. Storage of hot water is necessary because the time to warm the water is usually longer than the time to consume it.
- **Circulation pumps** are part of the refrigeration system. Its function is moving the water to reduce high temperatures in the equipment. However, there are other pumps that move the potable water inside the boat.
- **Water intake system** is a complex system required to take in the seawater used in the refrigeration system avoiding bubbles and solid impurities to.

There are some relevant technologies that are implemented or could be applied in the engine room of a yacht. The most important technologies to understand and improve the engine room are focused in the engine, storage systems and reusing energy technologies.

3.2. Engine technologies

The engine is the most important part in the engine room because it produces all the power of the system. This power comes from an energy resource (fuel) and the engine transforms this fuel into useful power such as mechanical or electrical. However, there are losses in this process. In boats the engine power is used to move the boat or to produce electricity in case there is not electrical generator.

3.2.1. Internal combustion engines and the different cycles

The most common types of combustion engines are the Otto engine (spark ignition) and the Diesel engine which uses compression to ignite the combustible. The rotary engine called Wankel is another technology that can be found in the vehicle industry but this is not currently used in boats.

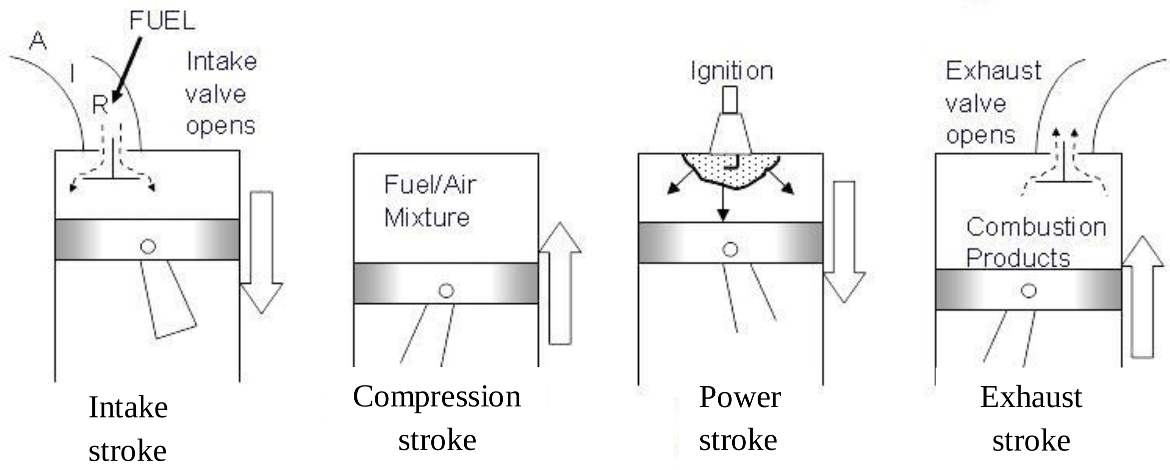

Figure 2. Internal combustion (4 strokes)

For understanding how the engines work and to study some parameters like the compression ratio which governs the thermal efficiency an idealization is needed. The main idea is to take the following assumptions which make the process more understandable:

1. The working substance is air.
2. The air is assumed to behave as an ideal gas with constant specific heats.
3. Heat is added to the cycle from an external source.
4. Expansion and compression processes are isentropic.

Ideal Otto cycle

The cycle consists of the following process:

1→2: Isentropic compression
2→3: Constant volume heat addition
3→4: Isentropic expansion
4→1: Constant volume heat

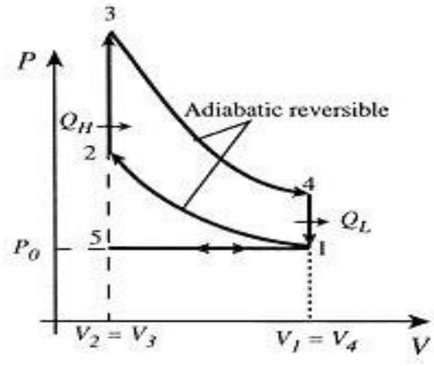

Figure 3. P-V Ideal Otto cycle

Thermal efficiency for an Otto cycle is defined as the ratio of work output to heat input.

$$\eta = 1 - \frac{W_{out}}{r^{k-1}}$$

Where: k is the ratio of specific heats ($k=C_p/C_v$) and r is the compression ratio (r=V1/V2).

With this equation is it possible to determine the following graphic of the efficiency:

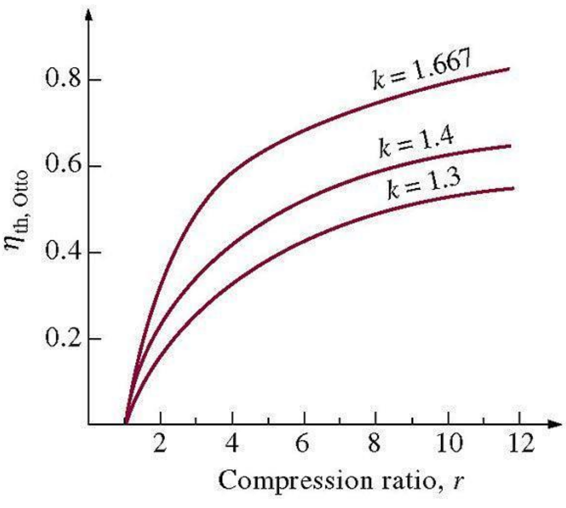

Figure 4. Efficiency of an otto cycle[3]

With a high heat capacity ratio ($k=V_1/V_2$) the efficiency increase. However, this ratio is limited by auto-ignition (knock) and high NO_x emissions problems that accompany high compression ratios.

[3] Source. The McGraw-Hill Companies. The thermal efficiency of the Otto cycle increases with the specific heat ratio k of the working fluid

Ideal Diesel cycle

The cycle consists of the following process:

1→2: Isentropic compression

2→3: Constant pressure heat addition

3→4: Isentropic expansion

4→1: Constant-volume heat rejection

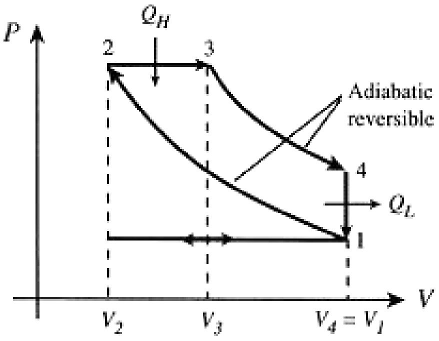

Figure 5. P-V Ideal Diesel cycle

The thermal efficiency of an ideal diesel cycle:

$$\eta = 1 - \frac{1}{r^{k-1}}\left[\frac{r_c^k - 1}{k(r_c - 1)}\right]$$

Where: k is the ratio of specific heats ($k=C_p/C_v=1.4$), cut-off ratio ($r_c=V_3/V_2$) and r is the compression ratio (r=V1/V2).

With this equation the following graphic of the efficiency can be determined:

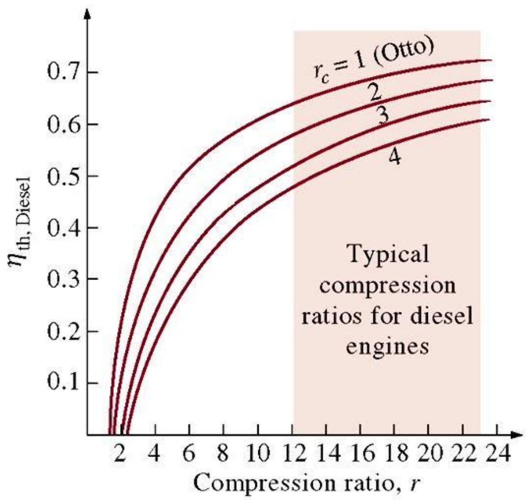

Figure 6. Efficiency of a Diesel cycle[4]

The efficiency not only depends on the compression ratio, r, it also depends on the cut-off ratio $r_c=V_3/V_2$.

[4] Source. The McGraw-Hill. FIGURE 9-22 Thermal efficiency of the ideal Diesel cycle as a function of compression and cutoff ratios (k = 1.4).

Miller and Atkinson cycles

One goal of this project is improving efficiency: therefore it is necessary to speak about the Miller and the Atkinson cycles. They are basically the Otto cycle and rotary cycle but with some modifications to improve the efficiency.

Ralph Miller patented the Miller cycle in 1957. Miller saw that a big amount of the power generated in the power phase is used in the compression phase. To try to solve this problem, he delayed the time the admission valves remained opened. In consequence, some combustible come back without taking part in the combustion. There was a loss of power but less power was necessary in the compression phase.

If you calibrate the specific time correctly, you will obtain an efficiency improvement. In conclusion, the Miller cycle is an evolution of Otto cycle because the mechanical components are the same in both engines. The Atkinson cycle is exactly the same but is applied in rotary engines with the same idea, to improve the efficiency. Comparison between an Otto (left) and a Miller cycle (right).

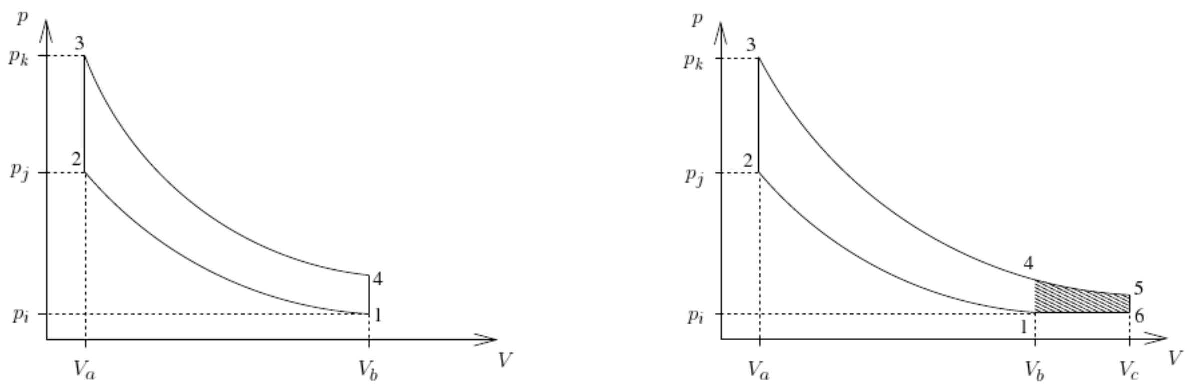

Figure 7. Comparison between Otto (left) and miller cycle (Right) [5]

The work of the cycle is the area inside the cycle lines because the work can be determined with the following equation:

$$W = \int P \cdot dV$$

Consequently, the efficiency increases 15 % more than in the normal cycle.

[5] Source. EEWORLD

3.2.2. External combustion engines (Stirling)

The Stirling engine is based on two different external sources, one hot and the other one cold. Inside the engine there is a working gas that produces the movement. Gases such as helium and hydrogen that permit rapid heat transfer. The advantages of this technology are low emissions and a high efficiency. In addition, many types of fuels could be used to raise the temperature in the hot source, like biomass or solar energy. On the other hand, it generates less power with the same weight, only works in low revolutions and it needs more time than the internal combustion to be ready.

The Stirling engine was patented in 1816 by Rev. Robert Stirling. This engine competed with steam engines in the industrial revolution. It was safer than its competitor. Although this technology had been forgotten for a while, it has appeared again because the Stirling cycle engine can be the most efficient device for converting heat into mechanical work.

The cycle consists of the following process:

1→2 Isothermal compression
2→3 Isochoric heat addition
3→4 Isothermal expansion
4→1 Isochoric heat rejection

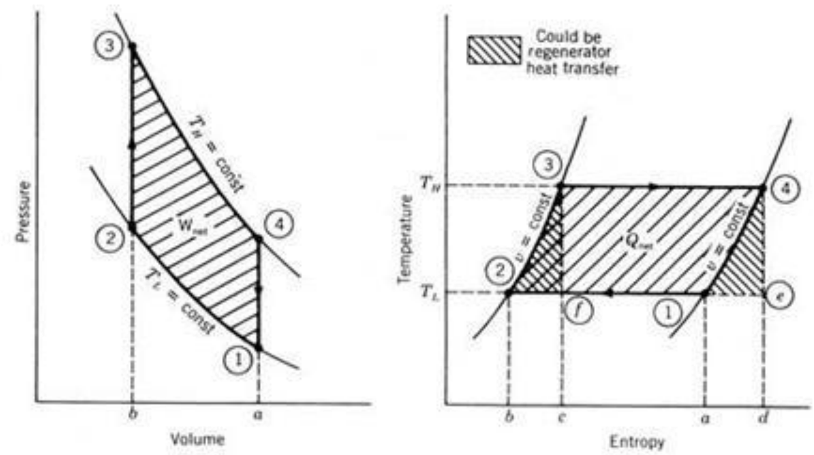

Figure 8. Stirling cycle[6]

[6] Source. Bowyer, J. M. (1984), "The Kinematic Stirling Engine as an Energy Conversion Subsystem for Paraboloidal Dish Solar Thermal Power Plants".

The work that is produced by the ideal Stirling cycle is represented by the area 1-2-3-4 on the P-V diagram. The Stirling cycle is the best approximation to the Carnot cycle (maximum theoretical thermal efficiency) if a regenerator is integrated into the design. The regenerator can be used to take heat from the working gas in process 4-1 and return the heat in process 2-3.

Recall that the Carnot cycle represents the maximum theoretical efficiency of a thermodynamic cycle.

Carnot efficiency:

$$\eta = 1 - \frac{T_{cold}}{T_{hot}}$$

3.2.3. Chemical engines (fuel cells)

The fuel cell is a technology that was developed to use hydrogen as fuel. It is a device which transforms a chemical fuel with an oxidant into electricity. It consist of two electrodes (anode and cathode), separated by an electrolyte. The negative pole (anode) is electrically connected to the positive (cathode) through an external circuit. An electrolyte is an electric insulator that can transport protons and ions.

The fuel is provided at the anode where the oxidation reaction is produced and the electrons are delivered to the external circuit and oxide ions and protons pass though the electrolyte. The electrons from the external circuit arrive at the cathode where an oxidation reaction is produced with O_2.

The advantages of fuel cells are high fuel efficiency (30% or 90% if you use a cogeneration system), zero emissions when the fuel is hydrogen, the possibility to use other fuels, the ease with which their sixe can be adapted depending on needs, and a very quiet operation.

Moreover, the fuel cells can be used as a storage system, they can produce hydrogen along with the electricity (the most common method consist in splitting water into oxygen and hydrogen fuel by a process called electrolysis) and use this hydrogen to produce electricity.

There are lots of types of fuel cells, but the most common ones are the following types:

- **Polymer electrolyte membrane fuel cells (PEMFC)** use a Proton Exchange Membrane Fuel Cells as an electrolyte and porous carbon electrodes containing platinum. This platinum works as a catalyst too. The temperature is around 60-80ºC and the efficiency is between 40% and 50%. Platinum is extremely sensitive to carbon monoxide, making it necessary to employ an additional reactor to reduce the CO in the fuel gas if the hydrogen comes from a hydrocarbon fuel. Consequently, the installation is much more expensive and the hydrogen fuel has to be more pure (CO concentration < 100 ppm (Araujo, 2012)).
- **Direct methanol fuel cells (DMFC)** are similar to PEMFC with one difference; the catalyst is the anode itself which obtain hydrogen from liquid methanol. The efficiency is around 40% and the working temperature between 50ºC and 100ºC. However, there is a very important problem called fuel permeability. This is a chemical short-circuit or crossover from the anode to the cathode so the generation of electricity does not work.
- **Alkaline fuel cells (AFC).** In this type of fuel cells the electrolyte is made with an alkaline dissolution, the conduction is produced by OH^- ions. The working temperature is between 100ºC and 250ºC and the efficiency is around 70%. The only problem is the formation of alkali carbonates but this is solved by using pure hydrogen, H_2.
- **Phosphoric acid fuel cells (PAFC)** use concentrated phosphoric acid as an electrolyte, which conducts the protons. The electrodes use platinum as a catalyst. The working temperature is around 200ºC and the efficiency is 40% to 80% if you use a cogeneration system.
- **Molten carbonate fuel cells (MCFC)** have a combination of alkaline carbons which are fixed in a ceramic matrix ($LiAlO_2$) as an electrolyte. The working temperature is higher than in the previous ones, around 700ºC. The anode electrode is made with Ni and the cathode with NiO. The nickel in the anode works like a catalyst and reduces the price compared to the platinum. The common value for the efficiency is 60% and it could be 85% with cogeneration. The main problems are the shorter life span and the formation of water in the anode which dilutes the fuel.
- **Solid oxide fuel cells (SOFC)** are based on the capacity of certain ceramic oxides to transport ions and they use this ceramic as electrolyte too. SOFC remove the need for a metal catalyst and have efficiencies between 60% and 85%. However, they have an important problem with high temperatures: 600-1000ºC.

3.3. Energy storage technologies

Storage technologies play an important role in the energy sector because it is easier to produce electricity in one place like a nuclear generation plant and then use this energy for everything, than to produce electricity in every single engine in, for example, the field of transportation.

Another reason is the stabilization in a renewable technology or cogeneration energy system, where the production and the demand do not go together. The stabilization of the system is always necessary if the system is not constant, the production or demand are not fixed. For example, in a cogeneration system the energy has to be stored for a later use.

There are lots of technologies applied for storing energy but the ones that could be used in a boat are presented below.

3.3.1. Electrochemical (batteries)

Electrochemical batteries work by generating different polarity loads at the ends of a conductive thread, causing electrons to move. There are two plates of different materials which are connected to each other with conductive material and between them there is an aqueous environment with a chemical component which reacts when electrons are moved. When the polarity of the circuit is changed the reactions happen in the other direction (recharge).

There are lots of different types of batteries; lead-acid, lithium-ion, nickel-cadmium, nickel-metal hydride, sodium-sulfur, zebra and flow batteries, vanadium redox, polysulfide bromide, zinc-bromin, electrolytic hydrogen (used in fuel cells). The most common ones are represented with their properties in the following table:

Table 1. Comparison of batteries types

	LEAD ACID BATTERIES			
Feature	Flooded	VRLA	Lithium Ion	Vanadium redox flow battery

Energy density (Wh/L)	80	100	250	10-20
Specific energy (Wh/kg)	30	40	150	15-25
Regular maintenance	Yes	No	No	No
Initial cost ($/kWh)	65	120	600	500-300
Life cycle	1,200 @ 50%	1,000 @ 50% DoD	1,900@ 80% DoD	No limitations
Typical stage of discharge window	50%	50%	80%	80%
Temperature sensitivity	Degrades significantly above 25ºC	Degrades significantly above 25ºC	Degrades significantly above 45º	Degrades significantly above 50ºC
Efficiency	100% @20hr rate 80% @ 4hr rate 60% @ 1hr rate	100% @ 20hr rate 80% @ 4hr rate 60% @1hr rate	100% @20hr rate 99% @ 4hr rate 92% @ 1hr rate	The cell's efficiency exceeded 99%, while round-trip efficiency measured 84%.
Voltage increments	2V	2V	3,7V	1,4V

3.3.2. Direct electric (ultra-capacitors and SMES)

Ultra-capacitor

This element works like a capacitor that is capable of storing energy by sustaining an electric field. Typical electrolytic capacitors can reach capacities of the order of hundreds μF while ultra-capacitors even have a capacity of 3.000-5.000 F. However, this technology can support only a low voltage between the layers, which means that to achieve higher nominal voltages series of several cells are connected. The principal advantages are the velocity with whichan ultra-capacitor can be recharged and its low weight. However, the life of the charge is very short.

SMES (Superconducting magnetic)

This is a system that permits storing the energy in a magnetic field which is created by the flow of direct current in a superconducting coil. For applications to transportation it is not very useful because it only behaves well at low charge discharge rates, although the efficiency is very high with 97%- 98% values.

3.3.3. Direct thermal (sensible and latent heat)

Thermal energy can be collected for later use without changing the type of energy. Direct thermal storage is useful for storing energy from systems that provide heat as an output and have a subsequent thermal demand such as hot water. Sensible heat storage and latent heat storage are the two fundamental categories.

Sensible heat

Sensible heat is the most common type; the temperature of the working substance is increased without any phase change. Normally, the state of the substances is liquid. In the case that this fluid is water, the temperature will be lower than 100ºC. If the temperature is higher than 100ºC, the pressure number has to be higher than the atmospheric value, making the installation more expensive.

Latent heat

Latent heat is absorbed or liberated by a phase change or a chemical reaction. The advantages of this technology are that it can store the same amount of energy with less weight and less space. These advantages make this technology very useful for boats.

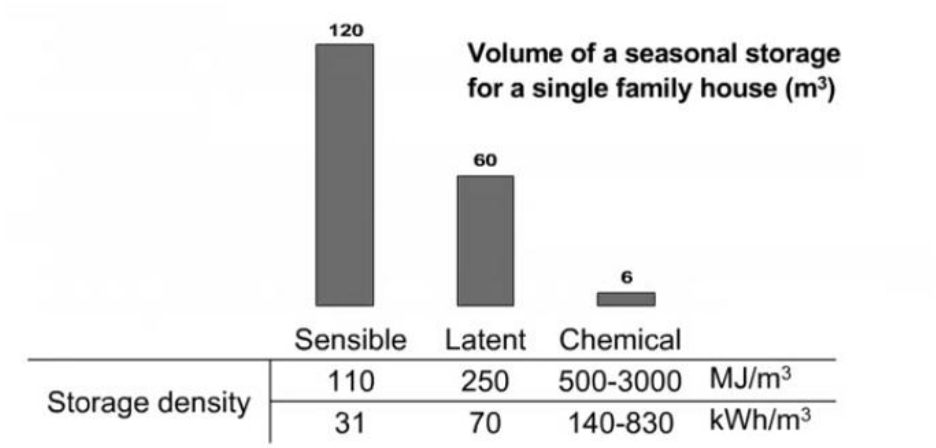

Figure 9. Characteristics of different compact heat storage[7]

3.4. Reusing energy technologies

Technologies that reuse energy transform energy losses into useful energy. The most common are thermal losses so these technologies try to use them for another use. For example by converting the thermal to electrical energy or using the thermal energy for another useful goal.

3.4.1. Direct energy conversion (thermoelectric)

Direct ways to transform energy outputs into other useful income energy are very helpful to improve the system. It is possible to make an important efficiency improvement and to reduce the space making the system less complex compared to other methods.

The advances in materials science during the 1940s and 1950s and the consequents discoveries in the field of semiconductors made possible the fabrication of thermoelectric generators. These are small and have high reliability, long life and do not produce vibrations. The working temperature range is very large, 200K to 1300K. However, because of the price and the low efficiency (less than 10%) this technology has taken a backseat until now, whereas some industries like the automation industry are trying to research it. The first results are appearing, for example the ATEG, a device that converts some of the waste heat of an internal combustion engine into electrical power.

[7] Source. ECN (Energy storage Centre in the Netherlands)

The basic device is a thermoelectric module which consists of several p- and n- type materials connected in parallel electrically and thermally, and bonded with ceramic plates on the sides. The properties such as efficiency change a lot depending on the size, shape and number of thermoelectric couples.

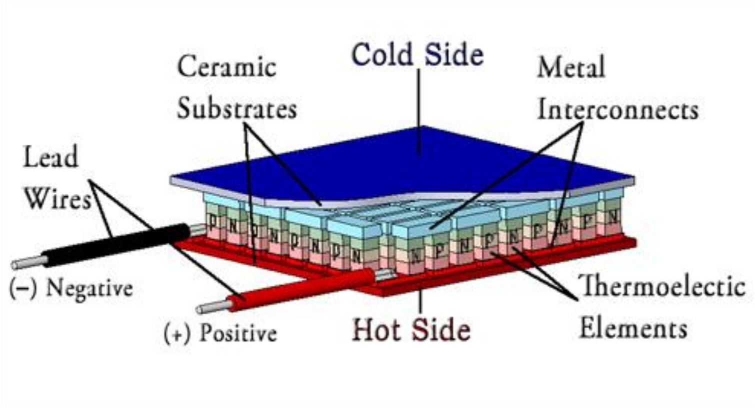

Figure 10. Thermolectric module[8]

3.4.2. Cogeneration technology (trigeneration)

Cogeneration technology CHP (Combined Heat and Power) appeared in the nineteenth century with the industrial revolution. It put the heat power that was lost in steam engines to other uses. The technology has changed a lot since the industrial revolution but the efficiency of engines continues to be very low, less than 40%. Consequently, using the losses is necessary to increase the useful energy.

The main change in cogeneration technology is the way has adapted to small engines and systems. Micro-cogeneration is one of the best ways to improve the general efficiency in a system such as a boat.

Trigeneration (CCHP)

Trigeneration technology is a specific form of cogeneration technology that can be used for heating and cooling too. This is very advantageous in hot places, where air-conditioning is necessary during the summer.

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[8] Source. Module (Scientific and Production firm)

Heat process

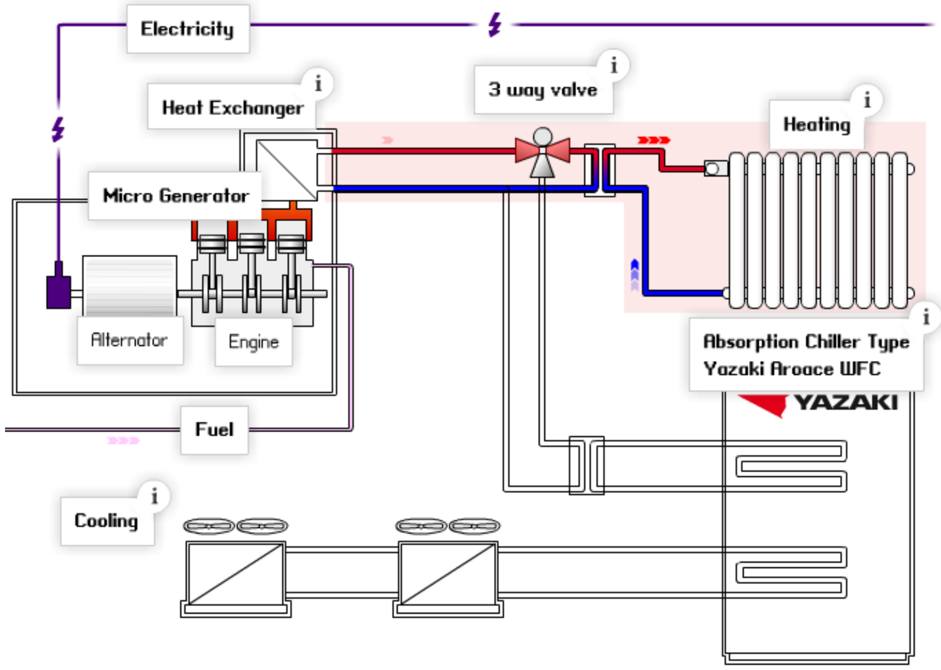


Figure 11. Sketch of CCHP that is adapted to an engine (heat process)

Cold process

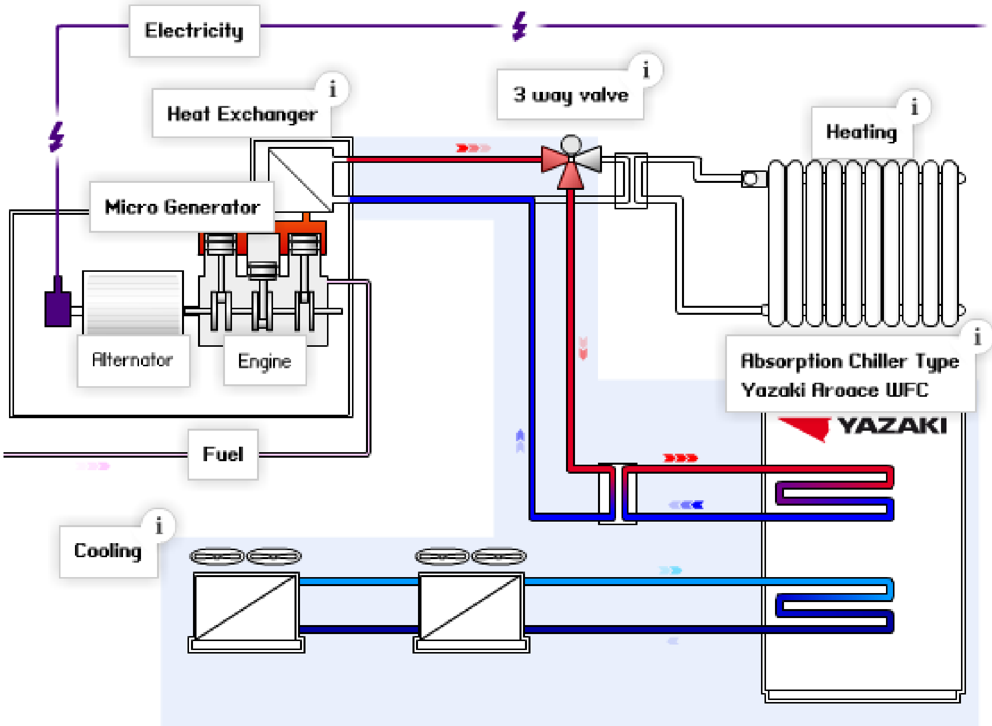


Figure 12. Sketch of CCHP that is adapted to an engine (cold PROCESS)[9]

[9] Source. YAZAKI Environment and Energy Equipment Operations (EEEO) milestones

A trigeneration system has some particular parts which are shown in the following example of a trigeneration installation that is installed in an engine:

- **Recovery energy losses.** The engine produces useful power from fuel and air but generates some thermal losses. To reuse the temperature for the engine there are the refrigeration system that takes the heat out of the inside of the engine. Moreover, the escape of gases and oil generate thermal losses too. When there is a generator (alternator), this is another hot point in the system and can also be used to raise the temperature.
- **Three way valve** has a main function in the CCHP system because it allows selecting the hot water direction depending on needs, increasing or reducing the temperature of the boat.
- **Storage tank** is installed at the beginning of the central heating installation.
- **Absorption chiller** is the most complex part in the trigeneration technology and consists of a refrigerator that uses a heat source to produce cold.
- **Fan cool units** are the last step in the refrigeration cycle and it is the machine that provides a cool air flow from the chilled water.

4. Case study

4.1. Study system

4.1.1. Description

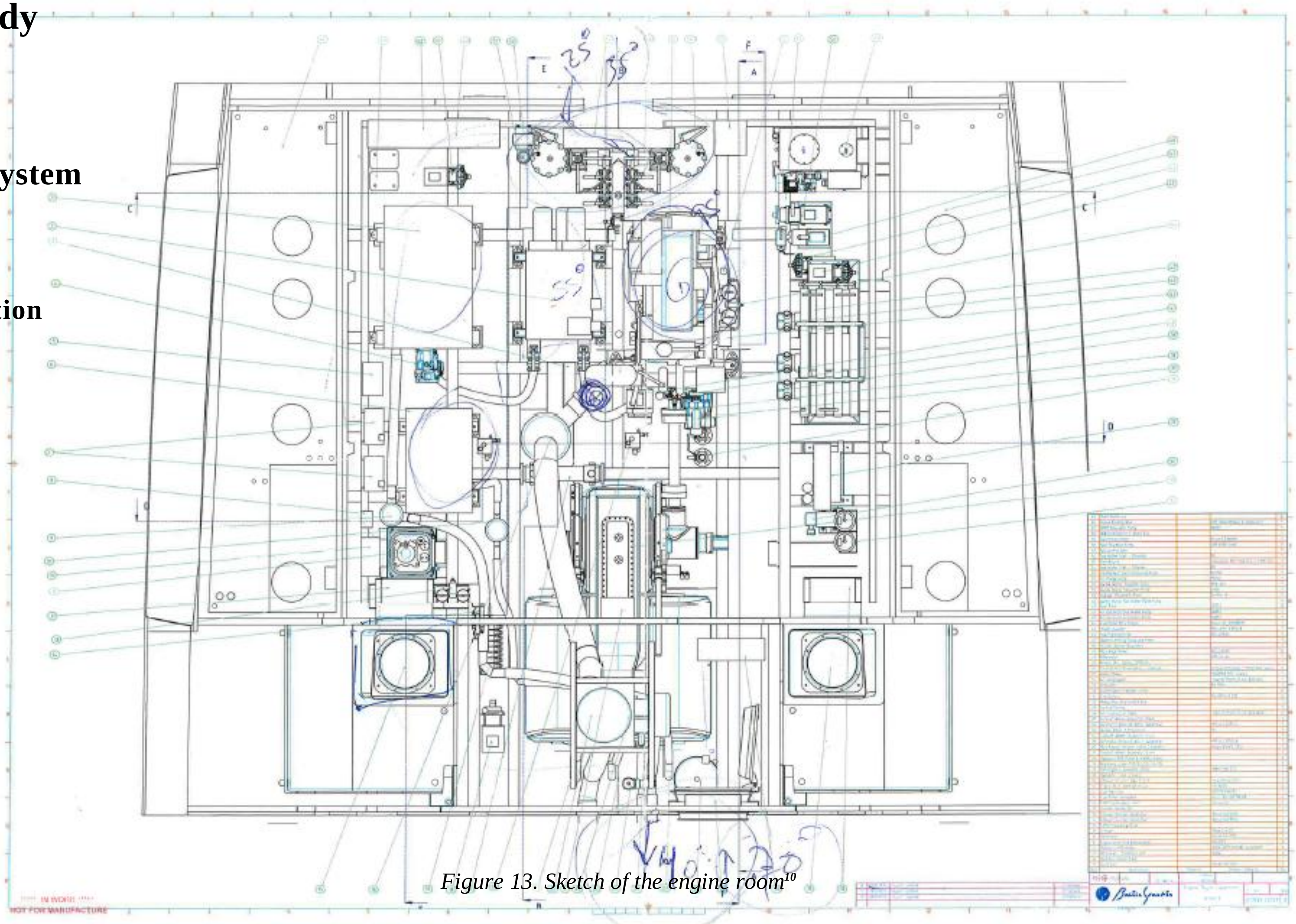


Figure 13. Sketch of the engine room[10]

[10] Source. Baltic yachts (20.01.2016)

The engine room has the following equipment:

Table 2. Equipment of the engine room[11]

63	Start Batteries			2
62	Engine Control Box		CAT Data Module & Instrument	1
61	FAMU Seawater Pump		IWAKI	1
60	24V Distribution / Start Box			1
59	Fuel Polish Filter		Racor P510MAM	1
58	Fuel Transfer Pump		CEM CE03 24VD	1
57	PLC control Box			1
56	Sea Water Inlet - Manifold		BY	1
55	Main Engine		Caterpillar C8.7, 641 bhp / 2300 rpm	1
54	Sea Water Inlet - Strainer		BY	1
53	Disinfectant Solution Dosing Pump		EcoMar	1
52	Oil change pump		Marco	1
51	Waste Water Transfer Pump		SBR 24V	1
50	Waste Water Seawater Pump		CM22	1
49	Sewage Treatment Plant		EcoMar 16	1
48	Water Maker Sea Water Feed Pump			2
47	Fuel Tank		3200 L	2
46	Air Condition Sea Water Pump		IWAKI	1
45	Air Condition Circulation Pump		IWAKI	1
44	Fuel Filter Main Engine		Racor 75_900MAXM	1
43	Chiller Inverter		MarineAir VARC48	3
42	Fire Fighting Pump		050-24VDC	1
41	Electric Priming Pump and Filter			1
40	MC-624 Balmar Regulator			1
39	Main Bilge Pump		050-24VDC	2
38	Alternator		400 Series	1
37	Blower 24V Jabsco 35770 4"			1
36	Through Hull Penetration - Seacock		Composite Flange / Metal Ball Valve	2
35	Water Maker		IDROMAR MSK Duplex	1
34	Air Compressor		Kaeser Premium Car 200/30W	1
33	Propulsion		BY RPS	1
32	Watermaker Prefilter Jumbo			2
31	Fire Damper		FW ETPS-E 500	2
30	Marex Main Eng Control Box			1
29	Control Panels			1
28	Air Compressor Tank		Kaeser Premium Car 200/30W	1
27	Exhaust Water Separator Drain			1
26	Generator Exhaust Water Separator		Vetus LGS7550	1
25	Waste Water / Bilge Loop		BY	1
24	Exhaust Water Separator Drain			1
23	Generator Exhaust Water Separator		Vetus LGS5038	1
22	Main Engine Exhaust Water Separator		Halyard HWS-080E	1
21	Exhaust Water Separator Drain			1
20	Hydraulic PTO Filter & Safety Valve			2
19	Blocksma cooler P13-1P-L600 PF-MV			1
18	Refidrigation Seawater Pump		IWAKI MX-250	1
17	Hydraulic Valve Group 8			1
16	Exhaust Silencer Main Engine		Halyard HD01635	1
15	Engine Room Ventilation Fan		FW 50JH	2
14	Fuel Manifold		B13001-404002	1
13	Fuel Filter Generator		Racor 75-500 MAXM	2
12	FAMU Compressor Unit		Marine Air	1
11	Inverter Panda 25i			1
10	Exhaust Silencer Generator		Vetus NLP50HD	1
9	Exhaust Silencer Generator		Vetus NLP75HD	1
8	FAMU Freqvency Drive			1
7	Charger		Mass 24/100	2
6	Generator		Panda 25i PMS	1
5	Engine Room Fire Extinguisher		FP-2000	2
4	Hydraulic PTO Pump		A10VD85EP1DS/53L-VUC11N00P	2
3	Oil Cooler / Filtration Unit		Hydac	1
2	Hydraulic Power Pack			1
1	Generator		Panda 60i PMS	1

[11] Source. Baltic yachts (20.01.2016)

4.1.2. System analysis

The system is very complex and the number of elements is enormous so first of all, groups have to be made to identify the relevant elements. To determine the level of synthesis is one of the most important parts because it will make analysis of the system boundaries easier and at the same time allow us to see the relation between the various parts. Another important aspect is to define the activities, goals and performance. The purpose of this system is to generate sufficient energy to supply the boat´s demand.

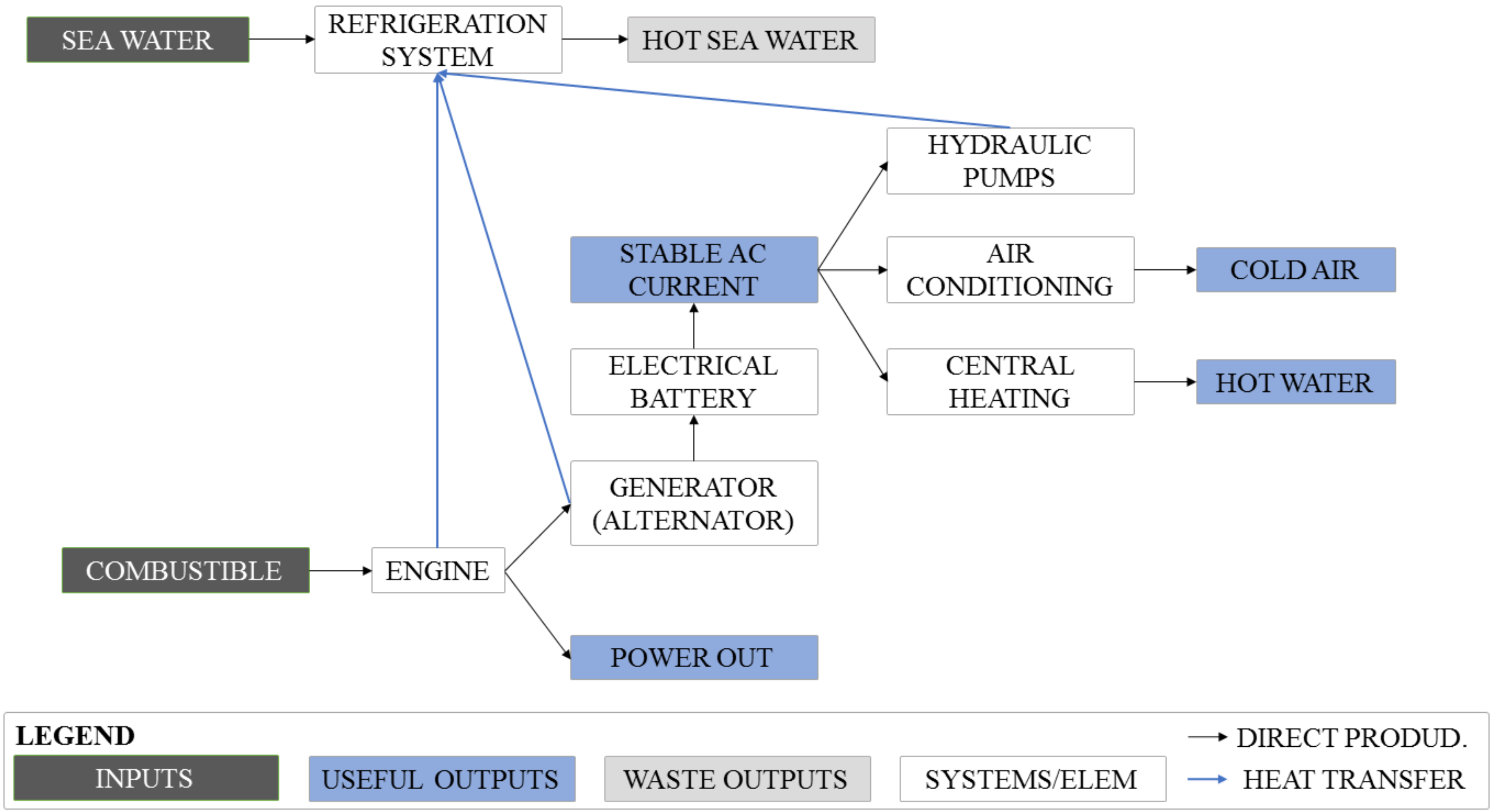
The system works by decision-analysis and information handling, to try to improve its efficiency changing the basic components or the relation between the parts.

The system analysis uses the Churchman Theory. Charles West Churchman was an American philosopher and systems scientist who determined the following purposes of system analysis:

- The system's general objectives and the performance indicators of the system will be very clear.
- The environment: the fixed restrictions
- The system resources have to be present.
- The system's components / parts, their activities, goals and performance indicators. Think functions / tasks instead of structures
- The management of the system. It is important to have the ability to change it.

All of these qualities are relevant in making a functional systems analysis that permits us to find more efficiency in relation to the working parts. It is impossible to find an improved efficiency level, if the systems analysis operates poorly.

Analysis sketch of the actual system



4.2. Improvement

4.2.1. Equipment improvements

To improve the equipment it is possible to apply some of the technologies described in section 2. In the case that it is possible to change the actual diesel engine for another type, different technologies have to be compared to try to find the best option for supplying the needs. The same is true for the other equipment which generates losses like the hydraulic pumps or the generator. In a complex analysis the aspects that have to be analyzed are the mechanical yield, efficiency, installation and maintenance prices and of course the noise, the vibrations and the weight.

- **Engine.**

  Stirling technology (more efficiency but less power for the same weight) does not have enough advantages nowadays to replace the actual internal combustion engine. The weight is the same challenge which has made the fuel cells technology unviable for this type of boat. However, the new engines by Atkinson and Miller may be in the immediate future.

  In a long term the situation could change a lot; the pressure to reduce the use of fossil fuels could be enough to change the actual combustion engine on the boat to natural gas engine or hydrogen fuel cells, instead of diesel. Natural gas and Hydrogen could dominate the fuel market in the next years.
  If natural gas economy takes more importance in the following years, the Stirling will be more relevant engines for boats. On the other hand, if hydrogen economy wins, fuel cells will be the best option, specifically, the Phosphoric acid fuel cell (PAFC). The phosphoric acid fuel cells have a low working temperature, has a high efficiency if a cogeneration system is used and needs hydrogen less pure.

- **Batteries**

  Renewable energy and electric boats can play a very important role in the future so batteries play an important role too.

  Ultra-capacitors have some advantages like the speed at which they can be recharged and the lower weight suggests that they may be a useful addition to boats however the life of the charge is very short. This problem makes this technology useless on boats. Superconducting magnetic batteries have the same problem as ultra-capacitors.

  In conclusion, only electrochemical batteries can be used nowadays in the transportation field. In electrochemical batteries Ion-lithium batteries are superior because they reduce the weight by more than 60%, this type of battery is being used in some sports cars like Porsche 911 GT3, Porsche 911 GT3 RS y Porsche Boxster Spyder and they could be an option to reduce the weight.

- **Hot water accumulator**

  Hot water accumulators are always necessary on a boat to supply this need immediately. There are two types of accumulators, the sensible and latent (explained in section 2). The efficiency is the same for both technologies (very high) but if the important parameter is the weight the advantages of latent technology which can store the same amount of energy with less weight and less space, makes the latent accumulator better.

4.2.2. Reusing energy improvements

There is possible to improve the efficiency of the engine room changing the refrigeration system. The boat does not currently have any way to reuse this wasted energy, in consequence loses a large quantity of thermal energy. The refrigeration liquid used is sea water, which is taken by complex equipment to avoid bubbles. The water temperature at the beginning is approximately 25ºC and 40ºC at the end of the circuit. To use this energy some technologies could be applied such as cogeneration or thermoelectric power generation.

In the cogeneration this waste energy is used to produce hot water and in trigeneration to produce cold and hot water. The trigeneration technology is a good solution for this boat because the part that consumes most energy is the air-conditioning system.

On the other hand, if thermoelectric power generation is applied the waste energy can be used to produce electrical energy. Although, the electrical energy has more applications in the boat, the efficiency of this technology is much lower. For this reason, it is better to use cogeneration when there is a hot water demand.

In conclusion, the best technology for this system is the cogeneration, more specifically the trigeneration. Nevertheless, if the amount of hot water produced is more than the needs, cogeneration can be combined with thermoelectric technology.

4.3. Proposed system

In the proposed system trigeneration technology is used to improve the system, improve the efficiency and generate more power sustaining or improving the power to weight ratio of the system. Changing the relations between the equipment is better than changing the equipment of the installation. The reason is that no other technology has enough advantages to replace the actual ones. In the study case the company is not much in favor of changing the important equipment such as the engine because of warranties.

The new system design does not have a refrigeration system with sea water; the intake system can be deleted so the weight is reduced. However, the absorption chiller is heavier than the current air-conditioning equipment.

Another challenge to achieve the goal of eliminating the sea water refrigeration system is the electrical generator which works when the engine is in mode off. To refrigerate this equipment there is the option to use the auxiliary refrigeration circuit in the trigeneration system.

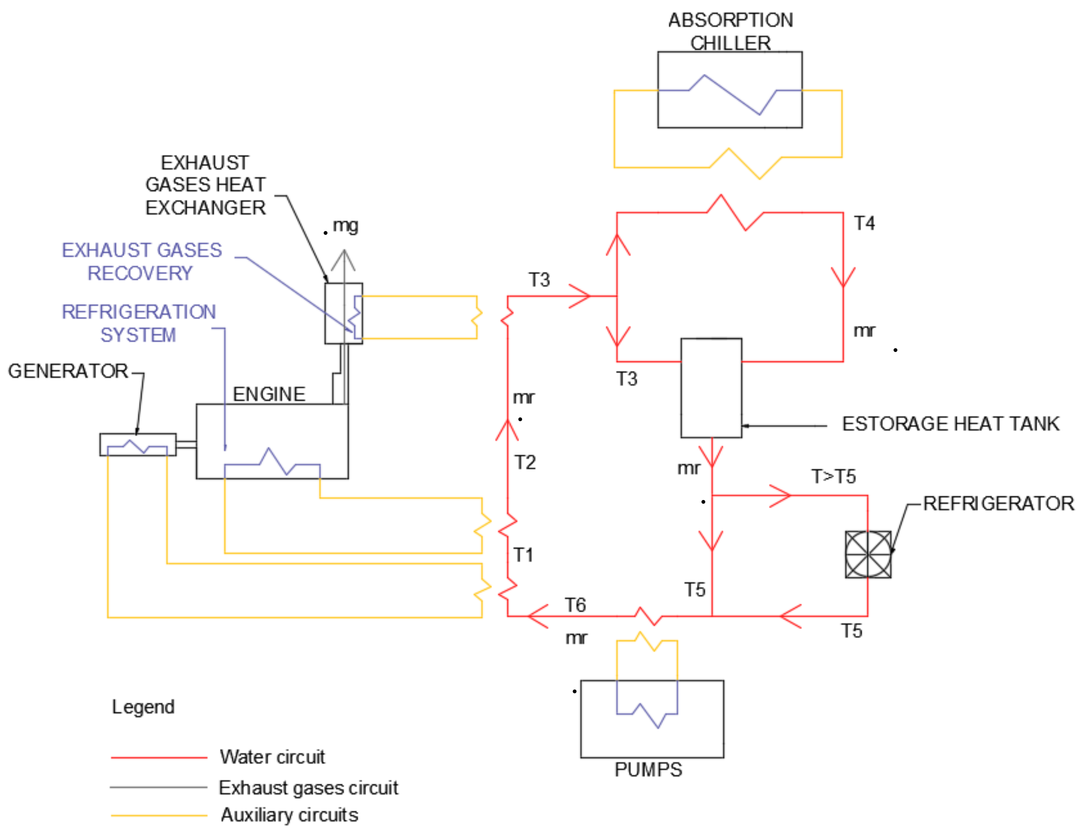


Figure 14. Proposed trigeneration system (real)

Equipment installed:

- Absorption chiller: Yazaki (scs)
- Exhaust gas exchanger: Ejbowman (10-60-3743-6)

The auxiliary circuits can be neglected because the efficiency which is assumed in these circuits is 100%. Moreover, the pumps and the generator increase the complexity of the calculations and the power which is generated is very low compared to the power of the engine, thus they can be neglected in this study.

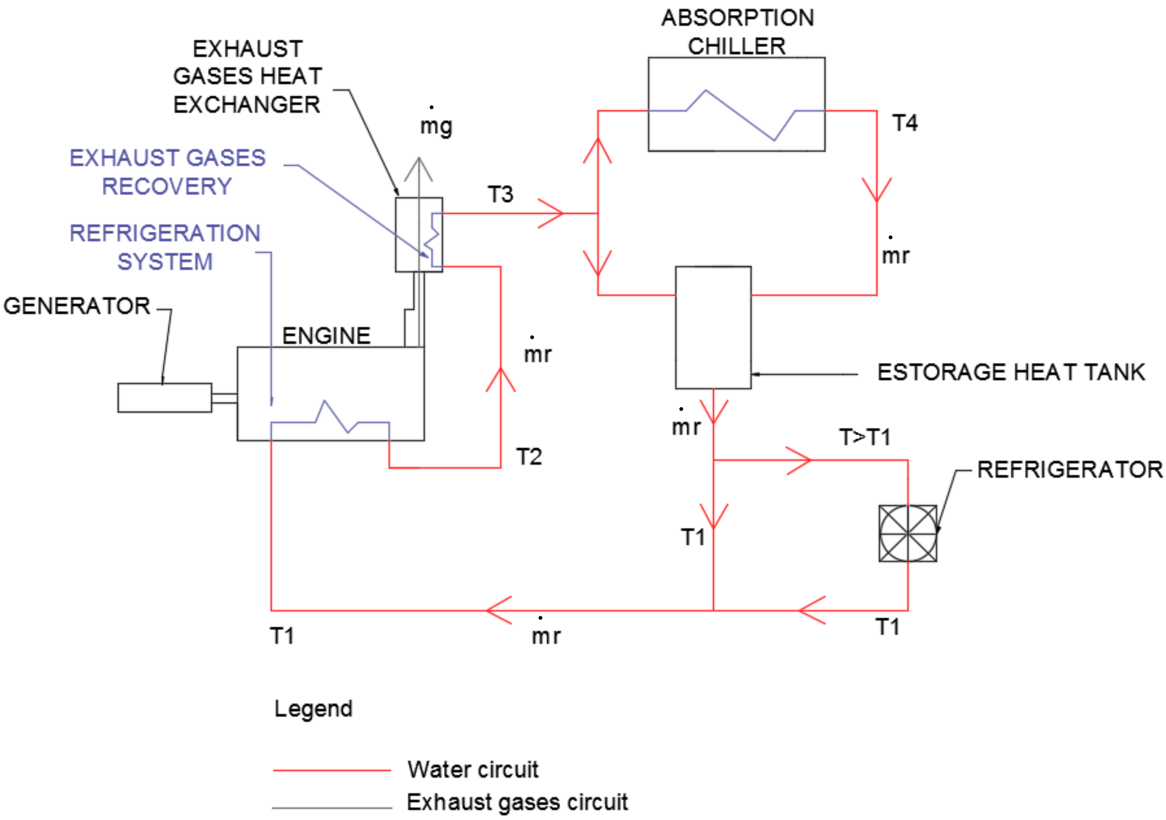
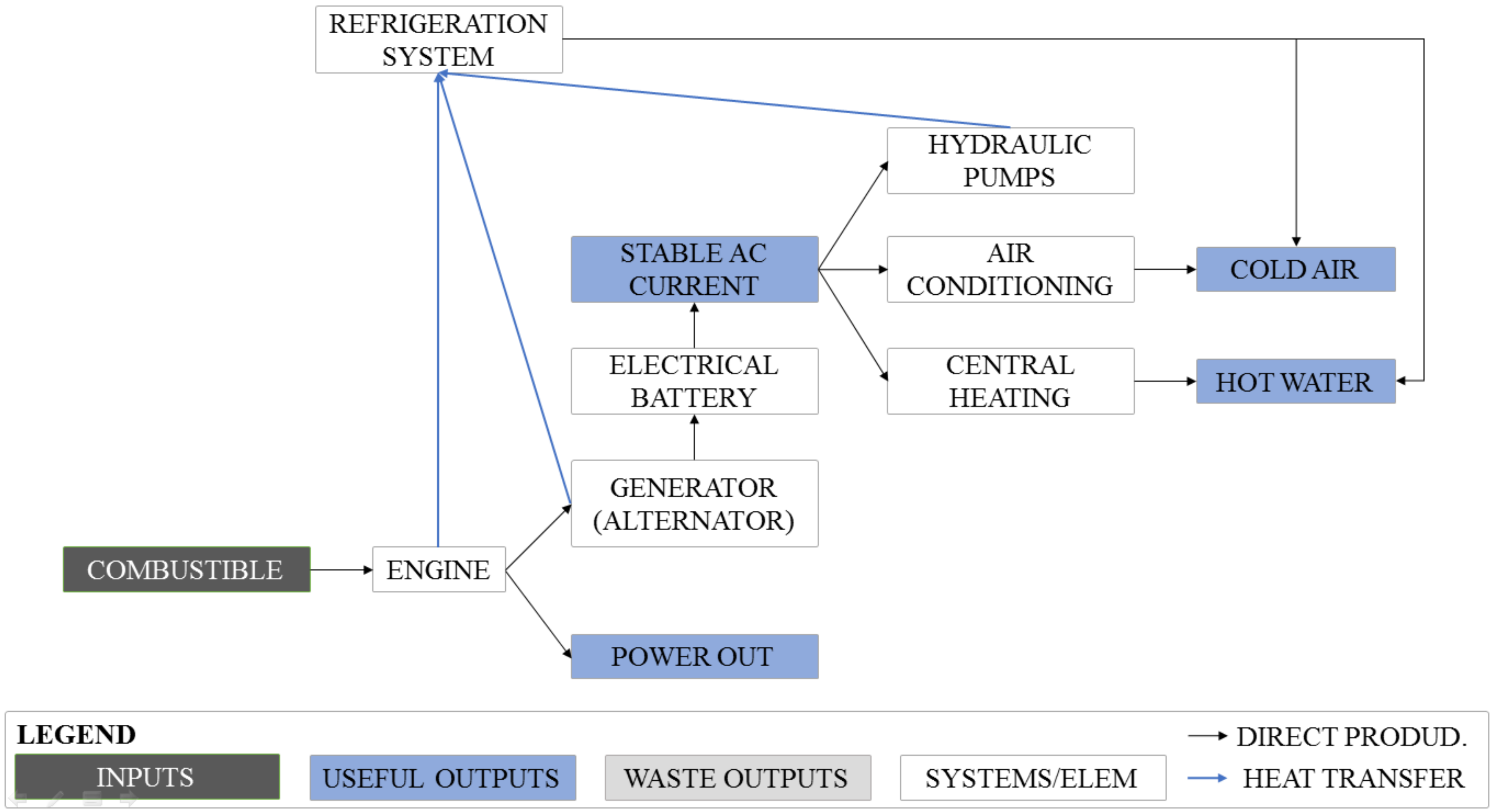


Figure 15. Proposal for a trigeneration system (simplification)

Analysis sketch of the proposed system



4.3.1. The energy resource

The proposed system uses the energy of all elements that have thermal losses and that need a refrigeration system. However, though the engine is the only part considered in this study in order to simplify the calculations, the results are representative enough. This is the reason why a diesel engine with 478kW is the only element represented in this study. This type of engines loses approximately 75% of the energy as heat, vibrations and noise.

4.3.2. Systems of heat recuperation

The cogeneration system basically consists in using the waste thermal energy to generate hot water and in the case of trigeneration cold too. In the engines there are the following three systems with these particular properties and they can be used to take this energy out:

- The main system to reuse the energy is the exhaust escape gases. In a normal engine these gases can go up to very high temperatures, between 400ºC and 500ºC. At the exit of the gases it is possible to take the amount of energy that increases the temperature around 150ºC by a boiler recovery. This limitation is because 150ºC is the dew point temperature for these gases (the temperature that the gases start to condensate). This temperature cannot be surpassed.
- Another system is the refrigeration system (the water circuit that takes out the excess of heat inside the engine). This system moves a big amount of water but the temperatures are not very high. Moreover, there is a minimum exit and entrance temperatures because it has to achieve another purpose, decrease the temperature of the engine.
- The lubrication system of the engine is another way to obtain energy. The temperature of this part is 80-90ªC. In a Formula 1 engine it is normal to use a refrigeration system with oil but in our engine the oil is stored in the carter and there is no refrigeration system focused on evacuating the excess temperature.

In our system only the heat from the refrigeration system and the exhaust gases is used. The same water from the refrigeration system takes the heat of the hot exhaust gases. Then this water is used to produce cold in the absorption chiller or it goes directly to the accumulator to be used in the central-heating or as hot water.

4.3.3. Temperatures, flows and powers

The calculations which are made to find out the following numbers are explained in the calculations[12]:

Temperatures:

- Temperature 1: T_1= 32ºC
- Temperature 2: T_2= 51.9ºC
- Temperature 3: T_3= 96.19ºC
- Temperature 4: T_4= 90.96ºC

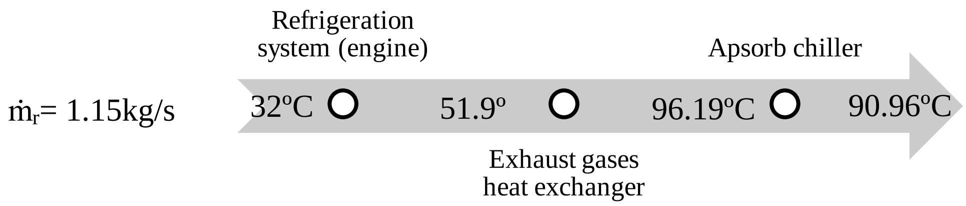


Figure 16. Temperatures in the heat recovery system (heat process)

Flows:

- Water flow of the refrigeration system: $\dot{m}_r$ =1.15kg/s
- Gases flow of the exhaust gases system: $\dot{m}_g$ =0.569kg/s

Powers:

- Mechanical power: 478kW
- Thermal power of the refrigeration system: 95.9kW
- Thermal power of the exhaust gases: 212.9kW
- Total power of the proposed system: 787kW

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[12] 5.2. Calculations of the proposed system

4.4. Comparison between the systems

4.4.1. kW/kg

- The current system: 0.352kW/kg
- The proposed system: 0.5kW/kg

- The kW extra divided with the kg extra: 1.4 kW/kg

4.4.2. Efficiencies

For the current efficiency there are no data in our system but the value is between 25% and 40% for this type of engines, so the final efficiency value is between these results:

- Current efficiency: 25%

  Proposed system efficiency: 41%

- Current efficiency: 40%

  Proposed system efficiency: 66%

5. Calculations

5.1. Characteristics values of the systems

The data and assumptions for the new and the current system are the following ones:

Engine properties[13]:

- Current useful power of the engine: $P_0=\dot{Q}_0= 478kW$
  - Efficiency of the actual system (only the engine): η_0= 25-40%

- Refrigeration system:
  - Temperature in the entrance of refrigeration system (engine): T_1= 32ºC
  - Maximum temperature in the exit of refrigeration system (engine): T_2=51.9ºC
  - Heat rejection to raw water cooling system: 95.9kW

- Exhaust system:
  - Exhaust stack temperature : $T_{entrance,gases}$= 504ºC
  - Temperature in the end of the exhaust gases heat recovery: 150ºC
  - Exhaust gas flow: $\dot{m}_g$ = 2048.3kg/hr ≈0.569 kg/s

Current systems information[14]:

- Weight of air-conditioning system: 210kg

$$Airconditioning\ main\ chillers\ weight \cdot pieces = 70kg \cdot 3 = 210kg$$

- Weight of sea water intake system: 75kg

[13] Source. Catalogue CAT (annex)
[14] Source. Discussions/dialogs with Baltic Yachts. (10.03.2016)

5.2. Calculations of the proposed system

5.2.1. Powers of the trigeneration system

There are two different systems that generate power which is used by the trigeneration system to warm the water. The refrigeration system of the engine and the heat recovery exhaust gases.

Power of refrigeration system

The power of the refrigeration system is defined by the CAT engine catalogue with the following value[14]:

- Refrigeration system: $P_{ref} = \dot{Q}_{ref}$ =95.9kW

Power of the heat recovery exhausts gases

To determinate the power value of the heat exhausts gases heat recovery; these data have to be used:

- Exhaust stack temperature : $T_{entrance,gases}$= 504ºC
- Temperature in the end of the exhaust gases heat recovery: 150ºC
- Exhaust gas flow: $\dot{m}_g$ = 2048.3kg/hr ≈0.569 kg/s

If the first law of thermodynamics is used, the power of the exhaust system is:

$$P_{exh} = \dot{Q}_{\mathrm{exh}} = (\mathrm{T}_2 - \mathrm{T}_1) \cdot \mathrm{C}_{\mathrm{p1}} \cdot \dot{\mathrm{m}} = (504 - 150) \cdot 1.057 \frac{kJ}{kgºK} \cdot 0.569 \frac{kg}{s} \approx 212.9kW$$

Where: C_p1 is the specific heat coefficient of the substance (kJ/Kg·ºK), ṁ is the mass flow (Kg/s) and (T2-T1) the different between the initial and final temperatures (ºK).

The C_{p1} (air) value is calculated by the following equation:

$$C_{P\_1} = \frac{C_9(T = 504ºC) + C_p(T = 150ºC)}{2} = \frac{1.098 \frac{kJ}{kgºK} + 1.016 \frac{kJ}{kgºK}}{2} = 1.057 \frac{kJ}{kgºK}$$

Total power for the proposed system

The total power for the proposed system is:

$$P_f = mechanical\ power + thermal\ power$$

$$P_f = mechanical\ power + (P_{ref} + P_{exh})$$

$$P_f = 478kW + 95.9kW + 212.9kW \approx 787kW$$

5.2.2. Hot water flow in the refrigeration system

The refrigeration system generates 95.9kW. If an exchange with an efficiency of 100% and the following data of the engine are considered:

- Thermal power that it has to be taken out: $\dot{Q}_{ref}$ = 95.9kW
- Temperature in the entrance: T_1=32ºC
- Temperature in the exit: T_2=51.9ºC

It is possible to find out the required mass flow of the refrigeration system ($\dot{m}_r$):

$$\dot{m}_r = \frac{\dot{Q}_{ref}}{C_{p\_a} \cdot \Delta T} = \frac{95.9kW}{4.18\frac{kJ}{kgºK} \cdot (51.9 - 32)} \approx 1.15kg/s$$

Where: $\dot{Q}_{ref}$ is the thermal power that it has to be taken out (kW), Cp_a is the specific heat coefficient *of the liquid water (kJ·/Kg·ºK), and ΔT is the difference between the initial and final temperatures.*

5.2.3. Exit temperature in the heat recovery

In the system the water takes the thermal power of the refrigeration system and it is the same water which takes the thermal power of the exhaust gases recovery too. The temperature increase in the exhaust gases recovery depend s on the following data:

- Water flow: $\dot{m}_r$ =1.15kg/s
- Temperature entrance in the exhaust gases recovery: 51.9ºC
- Useful thermal energy from exhaust gases: $\dot{Q}_{exh}$ = 212.9kW

If the first principal of thermodynamics is used, the following increase in temperature is obtained:

$$\Delta T = \frac{\dot{Q}_{exh}}{m_r \cdot C_{p\_a}} = \frac{212.9kW}{1.15\frac{kg}{s} \cdot 4.18\frac{kJ}{kgºK}} \approx 44.29ºC$$

Where: $\dot{Q}_{exh}$ is the thermal power that it has to be taken out (kW), Cp_a is the specific heat coefficient *of the liquid water (kJ·/Kg·ºK), and $\dot{m}_r$ is the mass flow (kg/s).*

The final temperature in the exit of the heat recovery (T_3):

$$T_3 = 51.9ºC + 44.29ºC = 96.19ºC$$

5.2.4. Temperature in the exit of the absorption chiller

To find out the temperature in the exit of the absorption chiller (model: LWM-W003) the following data about the installation and the equipment are used:

- Useful cold power of the absorption chiller: 17.584kW
- COP or efficiency of the absorption chiller: 0.7
- Flow of the hot water: ṁr =1.15kg/s
- Temperature in the entrance of the absorption chiller: T_3 = 96.19ºC

First of all, the power that the machine consumes to produce the useful cold power:

$$\dot{Q}_{consume} = -17.584kW \cdot \frac{1}{0.7} \approx -25.12kW$$

If the first principal of thermodynamics is used, this increase is obtained:

$$\Delta T = \frac{\dot{Q}_{consume}}{\dot{m}_r \cdot C_p} = \frac{-25.12kW}{1.15\frac{kg}{s} \cdot 4.18\frac{kJ}{kgºK}} \approx -5.23ºC$$

Where: $\dot{Q}_{consume}$ is the thermal power that it has to be taken out (kW), Cp is the Heat capacity (kJ·/Kg·ºK) of the water, and $\dot{m}_r$ is the mass flow (kg/s).

The final temperature in the exit of the heat recovery (T_4):

$$T_4 = 96.19ºC + (-5.23ºC) \approx 90.96ºC$$

5.3. Comparison between the systems

5.3.1. kW/kg of the current system

To calculate this number, the weight of the current system and the power that it generates is needed.

- Weight of the engine: 1071kg
- Weight of the air-conditioning system: 210kg
- Weight of sea water intake system: 75kg
- Power of the engine: 478kW

The kW/kg value is determined with the following equation:

$$\frac{P_0}{m_{actual}} = \frac{478kW}{1071kg + 210kg} \approx 0.352\frac{kW}{kg}$$

5.3.2. kW/kg of the proposed system

To calculate this number, the weight of the proposed system and the power that it generates is needed.

- Weight of the engine: 1071kg
- Weight of the absorption chiller: 365.142kg
- Weight of the exhaust gases recovery: 146kg

- Power of the proposed system: $P_f = 787$ kW

The kW/kg value is determined with the following equation:

$$\frac{P_f}{m_{proposed}} = \frac{787\ kW}{1071kg + 146kg + 365.142kg} \approx 0.5 \frac{kW}{kg}$$

5.3.3. kW/kg of the extra weight of the new system

To calculate the kW/kg of the extra weight, the difference in power and the added weight in the boat are needed.

Power change

Difference of useful power between the actual and the new system (thermal power of the trigeneration system):

$$\Delta P = P_f - P_0 = 787kW - 478kW = 309kW$$

Weight change

To make this balance the weight of the equipment added to the boat and the weight of the equipment taken out is needed. There is some extra equipment but another part could be deleted. However, the electrical boiler has to be kept, as a security system in case the trigeneration is not enough or some problem happens with the trigeneration system.

Table 3. Weigh variance

Equipment	Mass (kg)
EXTRA WEIGHT	
Recovery boiler exhaust gases (Ejbowman: 10-60-3743-8)	146kg
Absorption chiller (Ibersolar:LWM-W003)	365.142kg
REDUCE WEIGHT	

Sea water intake system	75kg
Air-conditioning system	210kg

kW/kg of the extra weight

The kW/kg of extra weight is:

$$\frac{\Delta P}{\Delta m} = \frac{309kW}{226.142kg} \approx 1.4\frac{kW}{kg}$$

5.3.4. Efficiencies of the systems

For the current efficiency there are no data in our system but the value is between 25% and 40%, so the final efficiency value is between these two possible calculation results:

- Calculation of the final efficiency of the engine when η_0= 25%:

$$\eta_f = P_f \cdot \frac{\eta_0}{P_0} = 787kW \cdot \frac{25}{478kW} = 41\%$$

Where: η_0 is the efficiency of the current system (%), Pf is the final power of the system (kW), and P_0 is the current power of the system (kW).

- Calculation of the final efficiency of the engine when η_0= 40%:

$$\eta_f = P_f \cdot \frac{\eta_0}{P_0} = 787kW \cdot \frac{40}{478kW} = 66\%$$

Where: η_0 is the efficiency of the current system (%), Pf is the final power of the system (kW), and P_0 is the current power of the system (kW).

Table 4. Comparison efficiencies (results)

Actual efficiency of the engine (%)	η_f CHP (%)
25	41
40	66

6. Conclusion and personal reflection

6.1. Conclusion

A study of the technologies that could be applied in the engine room was essential to have enough knowledge to determine the best way to improve the engine room.

In the current system all the waste thermal energy produced by the equipment is evacuated by the refrigeration system to the sea. Reusing this amount of energy is the main idea of the proposed system.

The trigeneration system that was proposed is a very good option to increase the efficiency of the system. This efficiency increase depends on the initial efficiency. It increases to 41% if the initial was 25% or increases to 66% if the initial efficiency was 40%[15]. Therefore, in any case, the improvement is more than 15% and 309 kW of extra power is produced. This thermal power is used to produce both hot water and cold.

Another comparison is the kW/kg between the proposed and the current systems. These numbers makes it clear that the trigeneration method is better in the power to weight ratio.

- kW/kg of the current system: 0.352 kW/kg
- kW/kg of the proposed system: 0.5 kW/kg

The kW per every kg that is added in the installation (1.4kW/kg) is another interesting number. The number comes from the variance of power and mass between the current and the proposed system.

The total weights of the boat increases but at the same time the increase in efficiency means less fuel to carry and of course less economical expense. Moreover, a high efficiency is synonymous with fewer emissions, so this leads to a more environmentally friendly boat. Therefore, it can be concluded that the project could be implemented in the boat.

15 Table 5. Comparison EFFICIENCIES (results)

6.2. Personal reflection

In this project I had the possibility to find new technologies in the industrial energy market. Then I analyzed a real system, the focus of the analysis being on the relation between the parts because most equipment was already fixed by the company. However, my knowledge about the different technologies gives an idea about the future and the different technologies that improve specific parts of the system. These changes will add to the global efficiency of the boat.

Another reason to be grateful for this project is the fact that I could combine both my degrees. The first part where I studied new technologies is focused on mechanical engineering. Secondly, the purpose of this project, improving the efficiency and at the system analysis, are basically environmental work. In this project I had the possibility to mix my passions: technology improvements and environmental awareness.

I am very proud of the results of the project. It found some shortcomings in the engine room system, some blunderings between the parts. At the same time it shows future lines of work from a more personal point of view, I am happy I had the possibility to work on a real project. Moreover, visiting the company made me feel like an engineer and I learned about many projects that I wish to work on, such as: a way to use green water for the toilets, replacing the current system of refrigeration (two different systems) by more efficient one and, of course, a kind of solar technology that uses all the sun-light that shines on the exterior of the boat.

The only downside was the lack of time. I really would like to spend more time on the project, work in it and find out all the necessary calculations to make the design and, the prototype. It is my dream to finally see my project working in a real boat.

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8. Appendices

8.1. Equipment selection

8.1.1. Exhaust gas heat exchanger selection

The important parameter to select the recovery exhaust gases equipment is the power that it has to collect. However, all this properties could be considered:

- Heat power take of the gases: $P_{exh} = \dot{Q}_{exh} = 212.9kW$
- Engine power: $P_0 = 478kW$
- Gases temperature in the entrance of the exhaust gas heat exchanger: $T_{entramce,gases}$ =504ºC
- Gases temperature in the exit of the exhaust gas heat exchanger: 150ºC
- Gases flow: $\dot{m}_g$ =0.569 kg/s

The equipment which is selected is the Ejbowman: 10-60-3743-6. This equipment has the perfect characteristics for this trigeneration system.

Type	Gen Set rating		Performance		
	Typical Engine power kW	Exhaust gas flow kg/min	Exhaust gas outlet temp °C	Heat recovery kW	Exhaust gas pressure drop kPa
2-25-3737-4	16	1.2	210	9.5	2.4
2-32-3737-5	16	1.2	170	10.5	2.8
3-32-3738-5	32	2.4	210	19	2.4
3-40-3738-6	32	2.4	170	21	2.8
3-60-3738-8	32	2.4	120	23	3.4
4-32-3739-5	60	4.5	210	35	2.2
4-40-3739-6	60	4.5	170	39	2.4
4-60-3739-8	60	4.5	120	43	3.0
5-32-3740-5	90	6.7	210	52	2.1
5-40-3740-6	90	6.7	170	57	2.4
5-60-3740-8	90	6.7	120	65	2.9
6-32-3741-5	140	10.5	210	82	2.2
6-40-3741-6	140	10.5	170	90	2.4
6-60-3741-8	140	10.5	120	101	3.0
8-32-3742-5	250	18.7	210	147	2.3
8-40-3742-6	250	18.7	170	160	2.5
8-60-3742-8	250	18.7	120	181	3.0
10-32-3743-5	400	30.0	210	236	2.4
10-40-3743-6	400	30.0	170	256	2.6
10-60-3743-8	400	30.0	120	288	3.1
12-32-3744-5	600	45.0	210	353	2.3
12-40-3744-6	600	45.0	170	380	2.5
12-60-3744-8	600	45.0	120	425	3.1

	A	B	C	D	E	F	H	J	K	L	M	N	P	R	Kgs
	mm	mm	mm	mm	mm	mm	mm	mm	mm	Flange	mm	mm	mm	mm	
6-32-3741-5	1082	668	762	168	210	130	120	140	11	DN60*	104	170	4x18	28	51
6-40-3741-6	1284	870	964	168	210	130	120	140	11	DN60*	104	170	4x18	28	53
6-60-3741-8	1792	1378	1472	168	210	130	120	140	11	DN60*	104	170	4x18	28	75
8-32-3742-5	1152	648	752	219	240	180	150	180	14	DN80*	130	200	8x18	40	85
8-40-3742-6	1354	850	954	219	240	180	150	180	14	DN80*	130	200	8x18	40	98
8-60-3742-8	1862	1358	1462	219	240	180	150	180	14	DN80*	130	200	8x18	40	121
10-32-3743-5	1232	608	752	273	265	250	180	220	14	DN100*	154	225	8x18	55	132
10-40-3743-6	1434	810	954	273	265	250	180	220	14	DN100*	154	225	8x18	55	146
10-60-3743-8	1942	1318	1462	273	265	250	180	220	14	DN100*	154	225	8x18	55	181
12-32-3744-5	1332	538	738	324	320	300	220	270	18	DN150*	204	280	8x18	55	190
12-40-3744-6	1534	740	940	324	320	300	220	270	18	DN150*	204	280	8x18	55	208
12-60-3744-8	2042	1248	1448	324	320	300	220	270	18	DN150*	204	280	8x18	55	262

*Flange specification in accordance with BS EN1092 - 1:2007 (BS 4504-6)
*Flanschspezifikation nach BS EN1092 - 1:2007 (BS 4504-6)
*Specifiche flangia conformi a EN1092 - 1:2007 (BS 4504-6)

Figure 17. Exhaust Gas Heat Exchanger Performance Table[16]

[16] Ejbowman catalog 2015

8.1.2. Absorption chiller selection

The main important parameters to determinate the equipment is the cold power that it can supply and the weight. The other important parameter is the temperature in the entrance of the equipment. Moreover, the flow and the temperatures are not a fixed parameter.

Parameters for the selection:

- Minimum cold power: 11.6kW[17]
- Temperature in the entrance: 96.19ºC

To determinate the equipment some catalogues have been locked for. There are three possibilities distinguish in front of the others:

[17] Source. 8.2. Absorption chiller needs

1. Ibersolar model

MODELO		Unidad	LWM-W003	LWM-W004	LWM-W005	LWM-W007	L W
Temperatura agua enfriada		C°					
Temperatura nominal enfriamiento		kW	99	134	165	215	
Circuito agua enfriada	Caudal		17,1	22,8	28,5	37,0	
	Pérdida de carga	mAq	2,2	2,9	5,3	6,5	
	Diámetro conexión	DN		65			80
Circuito agua enfriamiento	Temperatura	C°					
	Caudal		37,4	49,8	62,3	81,0	
	Pérdida de carga	mAq	2,5	3,6	6,3	2,3	
	Diámetro conexión	DN		80			
Circuito agua caliente	Temperatura	C°					
	Caudal		8,0	10,7	13,4	17,4	
	Perdida de carga	mAq	1,1	1,2	2,6	0,8	
	Diámetro conexión	DN	40			65	
	Dia. Válvula de control	DN		40		50	
Característi-cas eléctricas	Fase, voltage, frecuencia	V					
	Corriente total	A		5,6			
	Dimensión cable						
	Circuito de control	kVA		3,7			
	Bomba absorbedor 1	kW(A)		1.2 (3.0)			
	Bomba absorbedor 2	kW(A)					
	Bomba refrigerante	kW(A)				0.2 (1.	
	Bomba de purga	kW(A)					
Dimensiones	Largo	mm	2020		2520		2547
	Ancho	mm	1344		1346		
	Alto	mm	1952		1965		
Peso	Operativo	ton	2,1	2,3	2,7	4,1	
	Con embalaje	ton	1,8	1,9	2,3	3,5	

Figure 18. Catalogue Ibersolar

Technic information Ibersolar:
This machine has a COP =0.7
The common hot water in the entrance is 85-90ºC

2. Biobestenergy model

Modelo HWAR - L Series		Unidad	L019	L030	L040	L050	L060	L075	L090	L11(
Potencia frigorífica		kW	70	105	141	176	211	264	316	387
		usRT	19,9	30	40	50	60	75	90	110
Agua enfriada	Temperatura ent./ sal.	ºC	12/ 7							
	Caudal	m³/h	12	18,1	24,2	30,2	36,3	45,4	54,4	66,5
	Caída de presión	mH_2O	6,9	4,9	5,1	9,7	10,6	10,4	11,0	9,6
	Conexión	mm		65				80		
Agua de refrigeración	Temperatura ref./ cal.	ºC	29/ 34							:
	Caudal	m³/h	28,6	39,5	52,8	66,1	79,3	99,1	119	145
	Caída de presión	mH_2O	5,3	6,3	6,6	12,6	14,0	10,9	7,2	10,8
	Conexión	mm	65	100				125		
Agua caliente	Temperatura ent./ sal.	ºC	90/ 80							
	Caudal	ton/h	8,3	8,4	11,2	14	16,8	21	25,2	30,8
	Caída de presión de carcasa	m³/h	0,7	0,8	1,1	1,9	2,2	1,5	1,6	0,7
	Caída de presión válvula de control	mH_2O	0,7	2,1	3,8	2,2	3,2	5,0	7,1	4,3
	Conexión	mm		50				65		
	Válvula de control	mm		40		50			65	
Electricidad	Suministro	-								3Ø, 400V
	Bomba solución	kW (A)		1,2 (4,0)				1,5 (4,0)		
	Bomba refrigerante	kW (A)		0,2 (1,1)				0,3 (1,5)		
	Bomba de vacío	kW (A)								0,4 (1
	Panel de control	kW (A)								0,2 (1
	Total corriente	A	6,8	7,1				7,5		
Medidas	Largo (L)	mm	1.608	2.095		2.598		2.597		:
	Ancho (W)	mm	1.075	1.077		1.095		1.244		
	Alto(H)	mm	1.880	1.880				2.255		
Peso	En vacío	ton	1,6	2,1	2,2	2,6	2,7	3,6	3,7	4,6
	En carga	ton	1,8	2,3	2,5	2,9	3,1	4,1	4,2	5,2
Espacio para cambio de tuberías		mm		1.900		2.400		2.400		
Volumen de agua de máquina	Circuito agua enfriada	ℓ	54		61	73	77	117	129	155
	Circuito agua refrigeración	ℓ	140		161	187	198	312	344	432
	Circuito agua caliente	ℓ	57		69	80	90	112	124	148

Figure 19. Catalogue Biobestenergy

Technic information Biobestenergy:

The pressure of chilled water circuit and cooling are based on 1,0MPa (150 psig) and 1,6MPa (230psig) for the hot water circuit.

The water flow is cooled USRT 0,6048m3 / h, 1,321m3 / h for cooling water and 0,280tn / h for hot water.

Fouling factor for absorber and condenser is 0.0001 m2.h. ºC / kcal, 0,0001m2.h. ºC / kcal for evaporator and generator.

It is available as an additional model for high temperature hot water (100-150)

3. Yazaki models

Specifications - Imperial Units YAZAKI

Specifications		WFC-	SC5	SC/SH10	SC/SH20	SC/SH30	SC50
Cooling Capacity		Mbtuh	60.0	120.0	240.0	360.0	600.0
Heating Capacity {WFC-SH Only}		Mbtuh	---	166.3	332.6	498.9	---
Chilled/Hot Water	Cooling Temperature	°F		54.5 Inlet / 44.6 Outlet			
	Heating Temperature	°F		117.3 Inlet / 131.0 Outlet {WFC-SH Models Only}			
	Evaporator Pressure Loss	PSI	7.6	8.1	9.6	10.1	6.4
	Max Operating Pressure	PSI		85.3 / {High Pressure Option Available on Select Sizes}			
	Rated Water Flow	GPM	12.1	24.2	48.4	72.6	121.1
	Allowable Water Flow	% of Rated		80% - 120%			
	Water Retention Volume	Gal	2.1	4.5	12.4	19.3	33.6
Cooling Water	Heat Rejection	Mbtuh	145.7	291.4	582.8	874.2	1457.0
	Temperature	°F		87.8 Inlet / 95.0 Outlet			
	Absorber Pressure Loss	PSI	5.6	12.3	6.6	6.7	6.6
	Condenser Pressure Loss	PSI	5.6	Included in Absorber	6.6	6.7	3.2
	Max Operating Pressure	PSI		85.3 / {High Pressure Option Available on Select Sizes}			
	Rated Water Flow[1]	GPM	40.4	80.8	161.7	242.5	404.5
	Allowable Water Flow	% of Rated		100% - 120%			
	Water Retention Volume	Gal	9.8	17.4	33.0	51.3	87.2
Heat Medium	Heat Input	Mbtuh	85.7	171.4	342.8	514.2	857.0
	Temperature	°F		190.4 Inlet / 181.4 Outlet			
	Allowable Temperature	°F		158.0 - 203.0			
	Generator Pressure Loss	PSI	11.2	13.1	6.7	8.8	13.6
	Max Operating Pressure	PSI		85.3 / {No High Pressure Option on Any Size}			
	Rated Water Flow	GPM	19.0	38.0	76.1	114.1	190.4
	Allowable Water Flow	% of Rated		30% - 120%			
	Water Retention Volume	Gal	2.6	5.5	14.3	22.2	39.7
Electrical	Power Supply		115 / 60 / 1	208 volts AC / 60 Hz / 3-Phase			
	Consumption[2]	Watts	48	210	260	310	670
	Minimum Circuit Amps	Amps	0.89	0.6	0.9	2.6	4.7
	MOCP	Amps		15			
Capacity Control				On - Off			
Construction	Dimensions[3] Width	Inches	23.4	29.9	41.9	54.3	70.3
	Dimensions[3] Depth	Inches	29.3	38.2	51.2	60.8	77.2
	Dimensions[3] Height	Inches	69.1	74.8	79.1	80.5	82.1
	Weight Dry	lbs	805	1100	2050	3200	4740
	Weight Operating	lbs	926	1329	2548	3975	5955
	Noise Level	dB(A)	38	49		46	51
Piping	Chilled/Hot Water	Inches	1-1/4 NPT	1-1/2 NPT	2 NPT		3 NPT
	Cooling Water	Inches	1-1/2 NPT	2 NPT		2-1/2 NPT	3 NPT
	Heat Medium	Inches	1-1/2 NPT		2 NPT	2-1/2 NPT	3 NPT

1 - Minimum cooling water flow is 100%.
2 - Power consumption does not include external pumps or motors.
3 - Height does not include removable lifting lugs but does include level bolts. Width/Depth does not include the junction box or mounting plates.
4 - All specifications are based on water in all circuits and a fouling factor of 0.0005 ft²hr°F/BTU.
5 - If heat medium temperature exceeds 204.8°F (96°C), the chiller or chiller/heater will shut down and require manual reset.
6 - Do not exceed 85.3 PSI (588 kPa) in any operating circuit unless the high pressure option is chosen. High pressure option allows 113.9 PSI (785 kPa) in the Chilled/Hot Water and Cooling Water circuits only. There is no high pressure option for the Heat Medium circuit.
7 - Noise level is measured in a free field at a points 1m away from the cabinet and 1.5m above ground level.

Figure 20. Catalogue Yazaki

The weight is: 805Ibs = 365.142kg

The cold power: 60Mbtuh = 17.584kW

Selection:

The option selected is the Yazaki scs model absorption chiller. This one is the lighter and the restrictions (exit temperatures and the flow) are more flexible. Consequently, it is the best option in our trigeneration system.

8.2. Absorption chiller needs

Assumptions:

- Cold demand in the hot areas: 100 frigorias/m^2
- Boat square meters: $100m^2$

This machine generates the cold from the hot water calculated before (T=97.69ºC). To select the machine we have to focus in the following restrictions:

- The frigorific power has to cover the demand of the boat.
- We only install one machine, instead of more than one

To find the dimension of the absorption chiller the following assumptions are made:

- Common cold demand in the hot areas: 100 frigorias/m^2 ≈ 116.279W/m^2 ≈ 0.116kW/m^2
- Boat useful square meters: $100m^2$

If the boat has $100m^2$, the necessary cold power is:

$$Cold_{power,needed} = 0.116\frac{kW}{m^2}\cdot 100m^2 = 11.6kW$$

The following calculations are made to determinate if the trigeneration system can supply enough energy for the refrigeration but at the same time it can supply the needs for the hot water too.

The absorption chiller (yazaki scs model) has 70% of efficiency, it is obtained the following value of the necessary energy from the system to cover the cold power demand:

$$P_{cold,average} = 11.6kW\cdot\frac{100}{70} = 16.57kW$$

First of all it is necessary to find the cold demand percentage respect to the total thermal energy demand and then it could be possible to determinate the amount of power that it can be used to the refrigeration system. If this number is higher than the power needs (16.57kW), the system has enough capacity.

The boat will sail in hot areas (A4) and we can consider the thermal consumption of the boat similar as the house consumption.

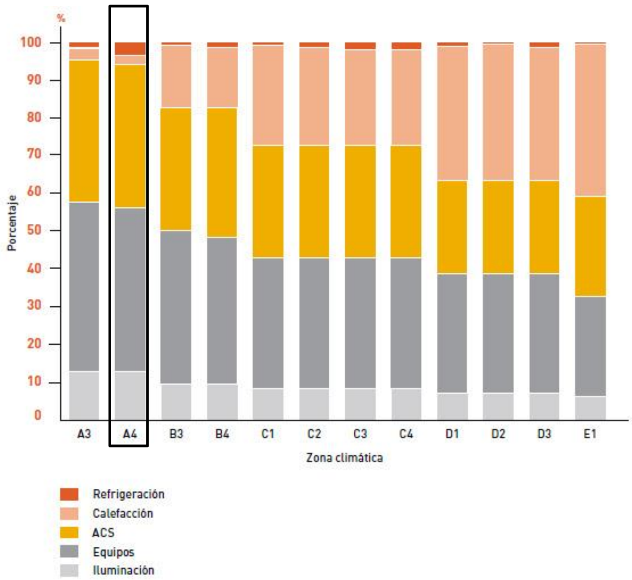

Figure 21. Percentage thermal demand in a house (one year[18])

Zona climática	Iluminación	Equipos	ACS	Calefacción	Refrigeración	Piscinas	Otros	Demanda eléctrica	Demanda térmica	Total
A3	7	26	21	2	1	0	0	33	24	57
A4	7	26	21	2	2	0	0	33	25	58
B3	7	26	20	10	1	0	0	33	32	65
B4	7	26	21	10	2	0	0	33	33	66
C1	7	26	21	20	0	0	0	33	42	75
C2	7	26	22	20	1	0	0	33	42	75
C3	7	26	22	20	1	0	0	33	43	76
C4	7	26	21	20	1	0	0	33	42	75
D1	7	26	22	31	0	0	0	33	53	86
D2	7	26	22	31	0	0	0	33	54	87
D3	7	26	22	31	1	0	0	33	54	87
E1	7	26	23	40	0	0	0	33	63	96

Figure 22. Energy demand unifamiliar house (kWh/m2.year)[19]

The cold power percentage refers to the total thermal consumption:

$$cold_{demand}(\%) = \frac{2}{25} \cdot 100 = 8\%$$

[18] Source. Document by the idea in the framework of the Renewable Energy Plan (PER) in Spain 2011-2020.7
[19] Source. Document by the idea in the framework of the Renewable Energy Plan (PER) in Spain 2011-2020.

The useful power is 787kW. This power is distributed between the cold production and the hot water. The cold water is 8% so the absorption chiller could use the following power:

$$Power\ for\ the\ absoprtion\ chiller = 787kW \cdot \frac{8}{100} \approx 62.96kW$$

It is possible to see that the necessary power is lower than the power for the absorption chiller. In conclusion, the installation is enough to supply the power for the cold system.

8.3. Properties of the engine

C8.7

MARINE PROPULSION ENGINE

CAT

478 bkW (641 bhp) @ 2300 rpm E Rating (High Performance)
Heat Exchanger Cooled-Sea Water Aftercooled

GENERAL ENGINE SPECIFICATIONS

Basic Engine Specifications

I-6, 4-Stroke-Cycle-Diesel

Displacement	8.71 L (531.5 in³)
Rated engine speed	2300 rpm
High idle speed	2530 rpm
Low idle speed (programmable)	600 rpm
Peak torque	2332 N•m @ 1700 rpm
Bore	117 mm (4.61 in)
Stroke	135 mm (5.31 in)
Aspiration	Supercharged-Turbocharged-Aftercooled
Governor	ECU
Fuel system type	Common Rail
Length	1200 mm (47.2 in)
Width	887 mm (34.9 in)
Height	983 mm (38.7 in)
Weight, net dry (approx.)	1071 kg (2361 lb)
Rotation (from flywheel end)	Counterclockwise
Flywheel housing/flywheel	SAE No. 01M
Flywheel teeth	149

Tolerances

Power	+/- 3%
Exhaust Stack Temperature	+/- 8%
Inlet Air Flow	+/- 5%
Intake Manifold Pressure	+/- 10%
Exhaust Flow	+/- 6%
Specific Fuel Consumption	+/- 3%
Heat Rejection	+/- 5%
Fuel Rate	+/- 5%

Cat® C8.7 SWAC
Marine Propulsion Engine
Image shown may not reflect actual engine

Emission Compliance

Recreational
EPA Tier 3 (E5 Cycle – Recreational Only)
IMO II (EPA, GLSeeBG)
Recreational Craft Directive (EU) RCD

Commercial
EU Stage IIIA
IMO II (GL, SeeBG)
CCNR Stage II through reciprocity with EU Stage IIIA

Power Output Considerations

Power produced at the flywheel will be within standard tolerances up to 45°C (113°F) combustion air temperature measured at the turbocharger air compressor inlet, sea water temperature up to 32°C (89.6°F), and fuel temperature up to 50°C (122°F) measured at the engine inlet. Power rated in accordance with NMMA procedure as crankshaft power.

General Remarks

- For installation instructions refer to Project Guide LEBM0034.
- For general dimensions refer to drawing 468-1067.
- For detailed information about fuel, oil, and cooling water treatment, please refer to "Caterpillar Commercial Diesel Engine Fluids Recommendations" (SEBU6251).

AIR SYSTEM

Combustion Air Inlet System

Intake combustion air flow	29.8 m³/min (1052.4 cfm)
Intake combustion air temperature up to	45°C (113°F)
Max. allowable intake air restriction	5.0 kPa (20 in H2O)

Engine Room Ventilation Air

Heat rejection to atmosphere	20.2 kW (1149 BTU/min) @ 25°C (77°F) ambient temperature

COOLING SYSTEM

Jacket Water Cooling System

Cooling water refill capacity .... 41 L (10.8 gal)
Coolant medium .... Cat® Extended Life Coolant (ELC) or equal
Expansion tank pressure cap .... 100 kPa (14.5 psi)

Raw Water Cooling System (SWAC)

Heat rejection to raw water cooling system .... 95.9 kW (5,454 BTU/min)
Flow raw water pump 442-7488 – max. .... 360 L/min @ 1.3 m H_2O
min. .... 294 L/min @ 9.7 m H_2O
Raw water pump maximum inlet restriction. .... 3 m (9.8 ft) H_2O
Raw water temperature engine out to gear oil cooler (max.) .... 51.9°C (125°F)
Raw water temperature from gear oil cooler 448-9439 if equipped (max.) .... 52.4°C (126°F)
Gear oil cooler 448-9439 heat rejection capability .... 10.4 kW (591.4 BTU/min)
Raw water connection engine inlet .... 63 mm (2.50 inch) SAE J1231 Hose Connection
Raw water connection engine outlet .... 50 mm (1.97 inch) SAE J1231 Hose Connection
Sea water strainer mesh hole diameter (max) .... 1.6 mm (0.063 in)

EXHAUST SYSTEM

Exhaust Gas Data

Exhaust gas flow (total) .... 2,048.3 kg/hr (4,515.7 lb/hr)
Exhaust stack temperature .... 504°C (399°F)
Engine exhaust connection V-band clamp .... 150 mm (5.91 in)
Max. allowable system backpressure .... 10 kPa (40.1 in H_2O)
Max. allowable static weight on turbine outlet .... 0 kg (0 lb)
Max. allowable static bending moment on turbine outlet .... 0 Nm (0 ft-lbs)

Specified system backpressure shall not be exceeded in any circumstances. Caterpillar advises to limit value of maximum allowable backpressure to 50% for new (clean) installations. Minimum diameter of customer piping should be according to "Customer piping diameter overview for Caterpillar engines."

FUEL SYSTEM

Fuel flow supply line (max) .... 220 L/hr (58.1 gal/hr)
Fuel flow return line (max) .... 125 L/hr (33.0 gal/hr)
Fuel rate at rated speed .... 123.8 L/hr (32.7 gal/hr)
Total fuel supply restriction (max.) .... 30 kPa (8.9 in Hg) (4.4 psi)
Fuel restriction across priming pump and clean filter .... 15 kPa (4.4 in Hg) (2.2 psi)
Allowable fuel restriction of OEM supplied components .... 15 kPa (4.4 in Hg) (2.2 psi)
Fuel temperature engine inlet (max.) .... 50°C (122°F)
Fuel return line restriction (max.) .... 20 kPa (5.9 in Hg) (2.9 psi)
Fuel supply/return connection .... 3/4-16 SAE J514 (-8), 37° FLARE
Minimum fuel supply line inside diameter .... SAE -10 (15.9mm) (5/8 in)
Electric fuel priming pump inlet/outlet connection .... 7/8-14 SAE J1926-1 (No. 10) STOR

Diesel fuel grade .... US Diesel #2 / EN590 / Biodiesel 7% max

LUBE SYSTEM

Sump type .... Center Sump
Sump capacity .... 34 L (9.0 gal)
Oil change interval .... 250 Hr
(may be modified by S•O•S℠ testing)
Max. installation angle (fore-aft) .... 10 degrees
Max. operating angle (fore-aft) .... 20 degrees
Max. operating angle (athwart ship) .... 22.5 degrees
Quality diesel engine oil (min.) .... CI-4 10W30 or 15W40
(compliant with Caterpillar specification ECF-2)

STARTING SYSTEM

Electrical Starting System (24V)

Electrical starting motor .... 24 VDC
Cold starting .... 670 CCA
[at 0°C (32°F) ambient temperature]
Recommended battery capacity .... 2 x 88 Ah, series

Electrical Starting System (12V)

Electrical starting motor .... 12 VDC
Cold starting .... 670 CCA
[at 0°C (32°F) ambient temperature]
Recommended battery capacity .... 2 x 88 Ah, parallel

SOUND DATA

Exhaust Sound Power Level Overall – Grade 3 environment

.... 128.1 dB(A)

Mechanical Sound Pressure Level Overall – grade 3 environment

At distance 1.0 m (3.28 ft) .... 101.4 dB(A)

Performance data is calculated in accordance with tolerances and conditions stated in this specification sheet and is only intended for purposes of comparison with other manufacturers' engines. Actual engine performance may vary according to the particular application of the engine and operating conditions beyond Caterpillar's control.

Power produced at the flywheel will be within standard tolerances up to 45°C (113°F) combustion air temperature measured at the air cleaner inlet, and fuel temperature up to 50°C (122°F) measured at the engine inlet. Power rated in accordance with NMMA procedure as crankshaft power. Reduce crankshaft power by 3% for propeller shaft power.

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The International System of Units (SI) is used in this publication.