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Energy Solutions in an Off Grid Intensive Energy System

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Abstract: Over the years, there has been an increase in energy consumption. In order to combat this increase, more energy production is needed**.** Since the resources (fossil fuels) on earth for energy production are limited and will end, it is necessary to find alternatives. One of the alternatives are the Trigeneration Systems. In this study, a trigeneration system is implemented in an isolated tropical island and technical-economic feasibility is studied. The preparation of the case study was carried out on the island Pulau Ubin located in Singapore. Initially, two basic energy production systems were implemented, these didn't contain energy recovery in the engines. Then, a trigeneration system was developed, in which an absorption chiller was used to harness energy that would be dissipated in the engines of base systems. After the implementation of the trigeneration system, an economic analysis of this project was carried out, in order to verify whether or not there is technical-economic feasibility. Given the indicators obtained, the Net Present Value > 0 at the end of the project's useful life and the Internal Rate of Return > Refresh Rate, it is concluded that the use of a trigeneration system on the island Pulau Ubin is feasible.

Keywords: Cogeneration, Trigeneration, Absorption Chiller, Technical-Economic Feasibility, Economic Analysis.

INTRODUCTION

The development of economic globalization has been growing over the years. This development is accompanied by an increase in energy demand. According to the International Energy Agency (IEA), energy consumption has increased dramatically from 1975 to 2015 (almost doubled)[Chen, G.Q, 2018]. In order to combat the increase in consumption, it is necessary to produce a greater amount of energy. To produce electric energy, there are several technologies that are used, such as engines and turbines in thermoelectric plants. The gases released in the energy generation processes in the thermoelectric plants, have energy content. This energy content is normally lost by the chimneys of the plants to the atmosphere in the form of heat. If the heat is harnessed, the efficiency of the processes is improved, and losses are avoided [Feidt, M, 2017]. Conventionally, the production of heat energy and electricity is carried out in different systems. With the development of cogeneration systems, it is possible to produce electricity and heat through the same process. In the generation of electrical energy, heat is released into the atmosphere, part of which can be used to satisfy the heat needs of consumers. Being a typically decentralized process, Cogeneration allows to satisfy the consumer's heat and electrical needs, guaranteeing a efficiency of 80 to 95% [Consulting, D.F.I, 2016]. The use of systems that allow the production of heat and electricity separately guarantee a lower efficiency, this is due to the amount of energy that is lost in these systems when compared to Cogeneration systems. Since there are more energy losses when producing electricity and heating separately, it is necessary for these systems to use a bigger amount of fossil fuels (when compared to cogeneration systems) to satisfy a determined energy demand [Consulting, D.F.I, 2016]. The technologies normally used in Cogeneration are based on: Alternative Internal Combustion Engine, External Combustion Engine, Steam Turbine, Gas Turbine, Fuel Cells and Hybrid Photovoltaic Thermal Solar Collectors.

The concept of trigeneration is an extension of the principle of cogeneration, besides the production of heat and electricity, exist the production of cold. Trigeneration systems are implemented when there is a need for cooling, using for example, equipments such as absorption chillers to produce cold. [Feidt, M, 2017; Baghernejad, A, 2016]. Figure 1 presents a diagram referring to the connection of Trigeneration systems with Cogeneration systems.

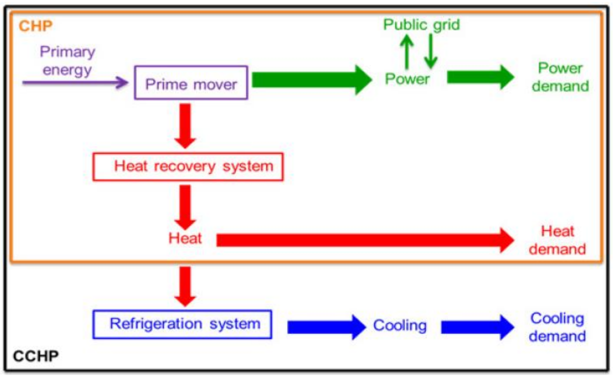

Figure 1: Principle of Trigeneration

In relation to the figure presented, the area enclosed by the acronym CHP (Combined Heat and Power) represents the constitution of Cogeneration systems, while the area enclosed by

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the acronym CCHP (Combined Cooling, Heat and Power) represents the constitution of Trigeneration systems. The implementation of Trigeneration systems has several advantages. One of these is based on more efficient, economical and reliable use of primary energy compared to the cogeneration system. This advantage is guaranteed because the heat lost in the prime mover, is recovered through a heat exchanger and used in heating and cooling systems [Feidt, M, 2017; Baghernejad, A, 2016]. The technologies used for the Trigeneration Systems are based on Absorption Chillers, Adsorption Chillers, Desiccant Cooling Systems and Ejector Cooling Systems.

The present work has the main objective of implementing a trigeneration system in an isolated remote zone (case study - island) and studying its technical-economic feasibility. This study makes sense to be carried out, since sometimes, in isolated remote areas, the connection to the power grid is either not possible to be made, or it is very expensive, so it is necessary to find an alternative. If the use of this system is feasible, it is possible to present a good alternative to conventional systems for the production of energy on islands. In this way, several energy advantages are obtained, as previously mentioned.

CASE STUDY

Definition of the Case Study and Energy Needs

For the development of the work, it was defined as the location of study case, the island Pulau Ubin. This island contains about 200 people, is located northeast of Singapore and has an area of approximately 1020 hectares (10.2 km^2) [Chua, K.J, 2013]. In article [Chua, K.J, 2013], energy simulations were performed using the eQuest analysis tool. After the simulation, the values of electric power, cooling power and heating power are obtained for a typical day in January. Besides the needs of a typical January day, the simulation also obtained the values of average hourly energy consumption in each month of the year. The simulations presented by article [Chua, K.J, 2013] were performed for the installations in table 1.

Table 1: Parameters of Simulated Installations

Building Type	Nº of units	Useful area per unit (m^2)	Description
5 Storey hotel	1	10 219	1 Basement level
Resort	3	6 039	-
Restaurants	8	465	Assumed operation hours from 11 am to 11 pm
Residential homes	30	140	Single family unit

In order to develop a more complete case study, two different consumption profiles of the island were studied. One of the profiles used is the January's power profile, which is already given in the article [Chua, K.J, 2013]. The other profile studied was the power profile of May. The month of May was chosen because is the month with the most variation in average hourly energy consumption in comparison to the profile of January (figure 2).

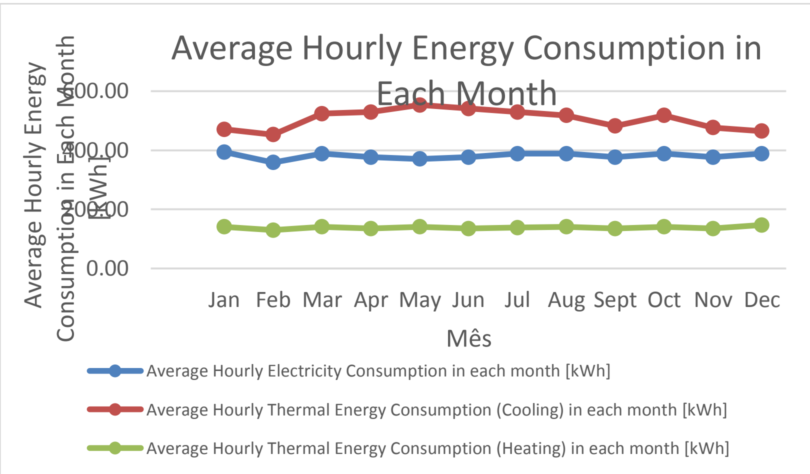

Figure 2: Average Hourly Values of Energy Consumption in Each Month

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The demand of energy for cooling, refers to the thermal energy removed from installations by the HVAC (Heating, Ventilation and Air Conditioning) systems. Regarding the demand of energy for heating, this is based only on Domestic Hot Water (DHW) because the study is carried out on an island with a tropical climate. Electricity refers to the energy needed for all lighting and for most equipment that needs it to operate [Chua, K.J, 2013].

For a better view, the average hourly values of energy consumption for the months considered are shown in table 2.

Table 2: Average Energy Consumption of the Two Consumption Profiles Used

Month	Average Hourly Electricity Consumption in each month [kWh]	Average Hourly Thermal Energy Consumption (Cooling) in each month [kWh]	Average Hourly Thermal Energy Consumption (Heating) in each month [kWh]
January	394,11	470,59	141,18
May	370,59	552,94	141,18

Table 3 shows the ratio between the January and May consumption values of the Table 2.

Table 3: Ratio between January and May

May/January (Electricity)	**0,94**
May/January (Cooling Energy)	**1,17**
May/January (Heating Energy)	**1,00**

The power profile for a typical day in May, was obtained from the data provided in article [Chua, K.J, 2013] (related to the power profile for a typical day in January) and the values in table 3. The values of power in each hour for a typical day of January were multiplied by the values of table 3, thus, it was obtained an approximation of the power profile for a typical day in May.

The power profiles for a typical day of January and May, are shown below in figures 3 and 4.

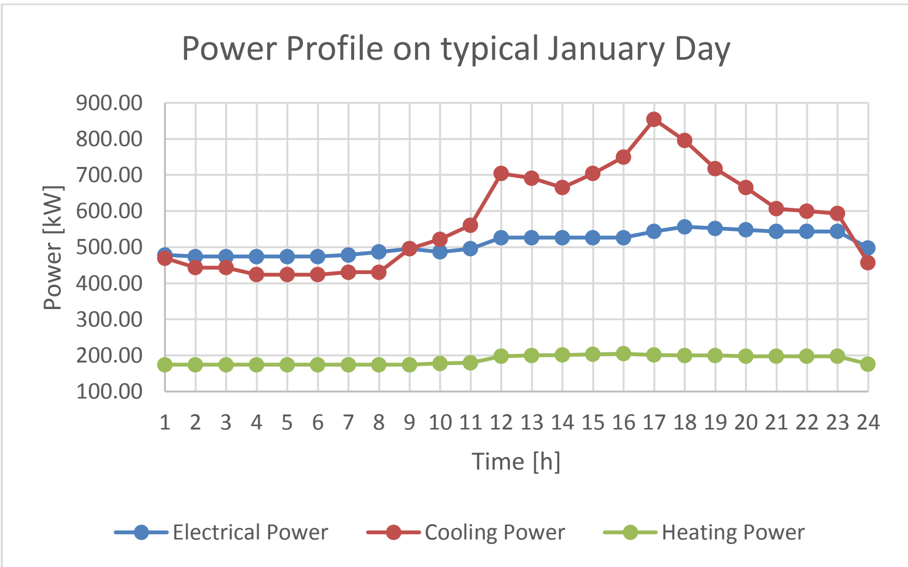

Figure 3: Power Profile on typical January Day

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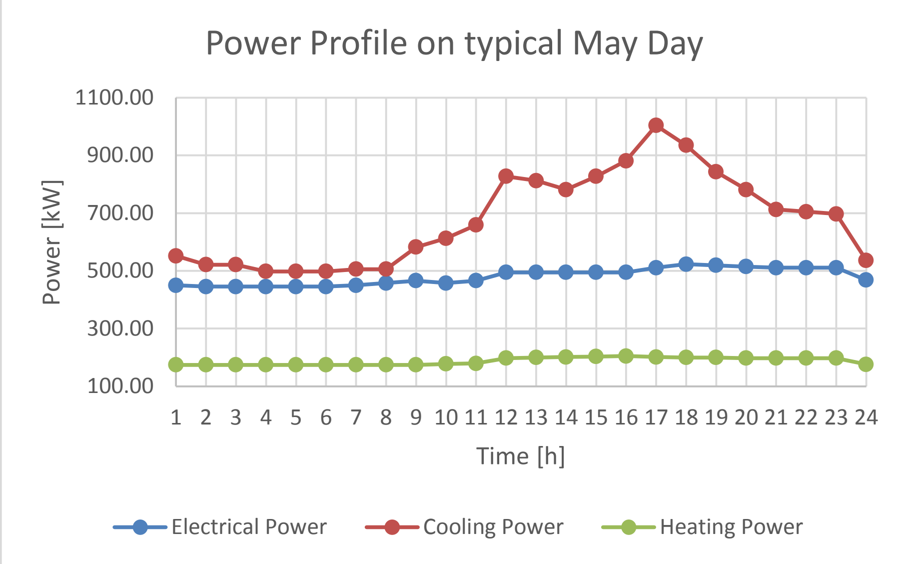

Figure 4: Power Profile on typical May Day

After having both power profiles, values for Dry Bulb Temperature (DBT) and Relative Humidity (RH) were collected for a typical day of each month (January and May) on the island Pulau Ubin. These values are important as they will influence the entire functioning of the systems. The values used correspond to the days chosen, January 1, 2019 and May 1, 2019 [timeanddate, 2020] .

Table 4 shows the maximum and minimum values for DBT and RH for these days.

Table 4: Maximum and Minimum Values of DBT and RH

Chosen days	DBT	RH
January 1, 2019	Máx: 34 °C ; Mín: 27 °C	Máx: 84 % ; Mín: 49 %
May 1, 2019	Máx: 33 °C ; Mín: 28 °C	Máx: 89 % ; Mín: 66 %

Reference Systems

The study of the technical-economic feasibility in the application of a trigeneration system on a tropical island, will be carried out, comparing two Reference Systems with a Trigeneration system. These reference systems, will be systems that can be used on the island and meets all energy needs.

According to article [Chua, K.J, 2013], the island uses diesel generators to meet the island's electrical load needs. Regarding thermal load, cooling and heating, no information was found on how it is produced. Since there is no information regarding the production of cold and heat, it was decided to contact several companies to see which would be the best solution. Mitsubishi Electric suggested the use of steam compression chillers for the production of cold and high temperature heat pumps for the production of DHW, through total heat recovery. This total heat recovery allows to recover the heat, that would normally be released by the condensers of the chillers to the atmosphere, thus increasing the efficiency of the system.

The daytime cooling energy storage system can be built from two different systems, Partial Storage System and Full Storage System. Thus, both of these systems were studied as reference systems, with a comparison at the end of the study with the trigeneration system.

Partial Storage System

In the Partial Storage System, the chiller(s) used in the system are operating throughout the day, however it is possible, if the cooling needs permit, to shut down one of the chillers for a few hours and thus reduce consumption of electricity. The excess energy produced throughout the day is stored in a thermal energy storage system (TESS) of cold water [Doty, S. *et al.*, 2010].

Full Storage System

In the Full Storage System, the chiller(s) operate(s) during a certain period of the day (enough to satisfy daily needs). During those hours, excess cold water is stored in a TESS and subsequently, in periods when the chiller(s) are shut down, needs are met through the energy stored in the cold water TESS [Doty, S. *et al.*, 2010].

Systems Operation Regime

In order to develop case studies like the one in this article, in which there is several equipment to

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operate, it is necessary to define the load that the equipment operates and the hours of operation of the plant. In order to have an efficient system, several calculations were performed for different operating loads of the equipment used. In this way, it is possible to know in which load cases, the equipment is able to satisfy the energy needs by consuming a smaller amount of energy. All results obtained with these calculations will be presented in the results chapter. The plant contains 4 workers and operates during all day (24 h).

Equipment's

In addition to the equipment already mentioned for energy production (diesel generators, steam compression chillers and heat pumps), energy storage equipment (DHW deposits and cold water storage systems), heat exchange equipment (heat exchangers) and water cooling equipment (cooling tower) were also dimensioned.

Now, all dimensioned equipments, constituents of these systems are presented: Steam Compression Chillers; Thermal Energy Storage System (TESS) - Cold Water; Heat Pumps; DHW accumulation deposits; Heat Exchangers (Grid Water – Heat Pump High Temperature Water); Diesel Generators; Electrical Energy Storage System (EESS) and Cooling Tower for Compression Chillers.

In order to implement the most efficient system, studies were carried out on various models of energy production equipments at various loads (table 5).

Table 5: Models and Loads studied of energy production equipments

Equipments	Brand	Studied Models	Studied Loads
Diesel Generators	FG Wilson	P400-3; P250-5; P110-3	100 %; 75 %; 50 %
Heat Pumps	Mitsubishi Eletric	EW-HT 0412; EW-HT 0302	100 %; 90 %; 80 %; 70 %; 60 %
Steam Compression Chillers	Mitsubishi Eletric	NECS/R/CA 1816	100 %; 90 %; 80 %; 70 %

The model and load choices are presented in the results chapter.

Reference Systems Installation Principle Scheme

In order to facilitate the visualization of the connection of all the equipments and systems, figure 5 shows the installation principle scheme for the reference systems. This scheme also shows all the temperatures of the system's water circuits.

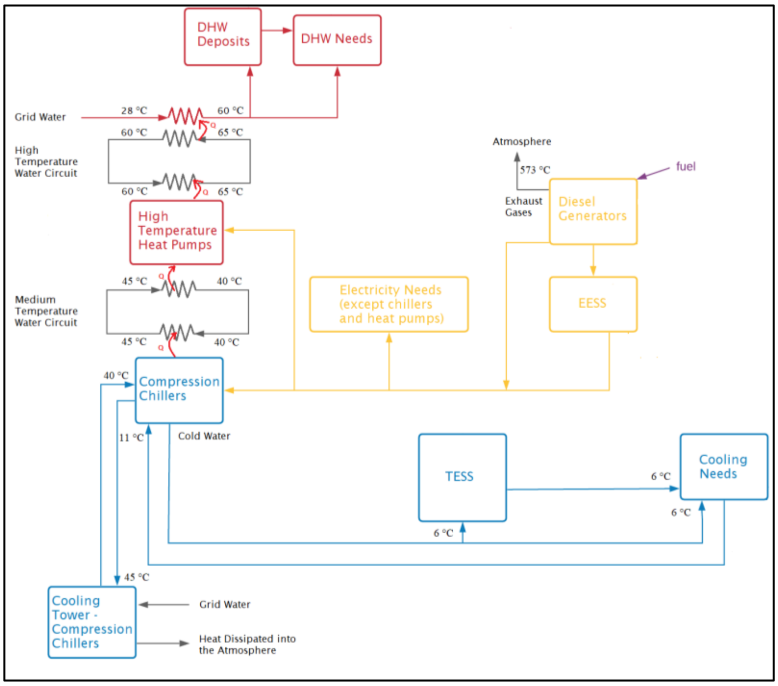

Figure 5: Reference Systems Installation Principle Scheme

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Trigeneration System

Contrary to reference systems, which there is no heat recovery in diesel generators, the trigeneration system will recover the heat released by the exhaust gases to produce cold, through an absorption chiller, and recover the heat released in the cooling systems of diesel generators for DHW production.

From what has been said, it is possible to reduce the number of hours of operation on compression chillers and heat pumps. With this reduction, the consumption of electricity will decrease, and, consequently, the fuel consumption of diesel generators will also decrease.

Equipment's

Absorption Chiller

In the selection of the absorption chiller to be used for the trigeneration system under study, it was considered whether it is simple or double effect, the heat source that allows the absorption chiller to be activated and the working fluid. The choice fell on a simple effect absorption chiller, driven by hot water with Lithium Bromide/Water as working fluid. This choice is justified by the fact that the use of hot water at low temperature, (simple effect allows the use of hot water at a lower temperature than double effect [Shirazi, A, 2018]) allows a potential use of renewable energy sources. Since the case study is located on a tropical island, with the option taken to use this type of chillers, an insertion in the future, of solar collectors in the system to heat the water (which would provide heat to the absorption chiller generator), it could be an option. The use of the Lithium Bromide/Water combination as working fluids allows to obtain a higher coefficient of performance (COP) than the Water/Ammonia combination, so it was this pair of working fluids that was used [Wang, R, 2006].

Cooling Tower for Absorption Chiller

In the absorption chiller it is necessary to cool the condenser and the absorber. The chiller cooling water will enter the system at 29 °C and exit at 35 °C (figure 6). Given the different temperature range values of this water, compared to the water used to cool the condenser of the steam compression chiller (water enters at 40 °C and leaves at 45 °C - figure 5), it was decided to use two cooling towers, one for the compression chillers and one for the absorption chiller.

One of the precautions to be taken in the water circuits of the cooling towers, is the survival and multiplication of the Legionella bacteria. This bacteria can survive and multiply at a temperature range between 20 °C and 45 °C [Petrochem, P, 2011].

In addition to absorption chiller and cooling tower, it was also necessary to design two more types of heat exchangers for the trigeneration system. These exchangers, are the ones that allow the energy recovery of the exhaust gases and the cooling circuits of the engines.

All equipment dimensioned for the trigeneration system was as follows: Steam Compression Chillers; Thermal Energy Storage System - Cold Water; DHW accumulation deposits; Heat Exchanger (Grid Water - Engine Cooling Circuit); Diesel Generators; Electric Energy Storage System; Cooling Tower for Compression Chillers; Heat Exchanger (Exhaust Gases - Hot Water Circuit that Activates the Absorption Chiller); Absorption Chiller and Cooling Tower for the Absorption Chiller.

Trigeneration System Installation Principle Scheme

In order to facilitate the visualization of the connection of all the equipments and systems, figure 6 shows the installation principle scheme for the trigeneration system. This scheme also shows all the temperatures of the system's water circuits.

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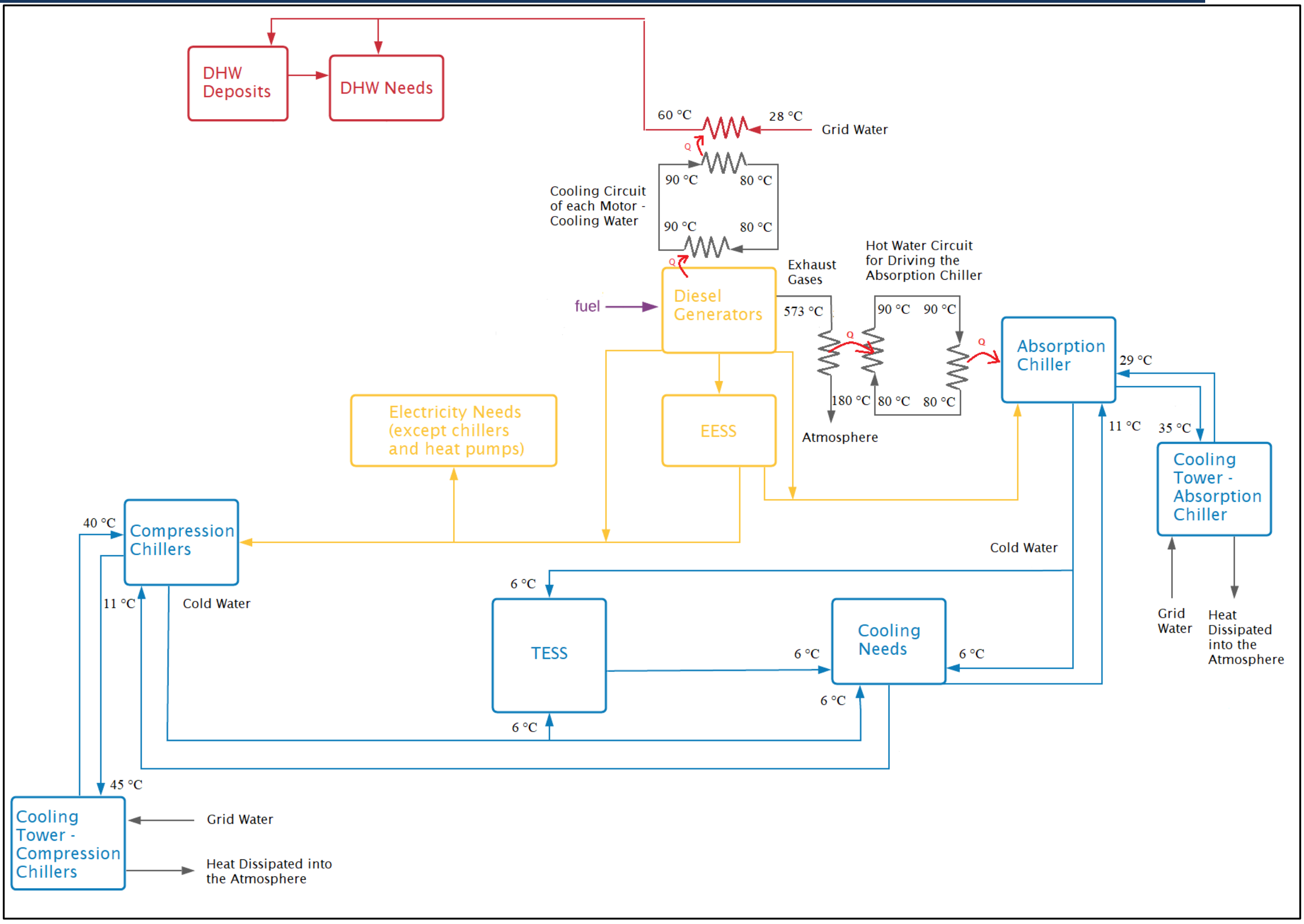

Figure 6: Trigeneration System Installation Principle Scheme

Economic Analysis

After the development of all systems, the technical-economic feasibility of implementing the trigeneration system in relation to the reference systems was studied. The realization of this type of studies becomes crucial, when an investor intends to invest in a project, as he is able to understand the financial behavior that his investment will have. To carry out the calculations pertaining to the economic analysis, it was necessary to take some considerations:

The life of the project is 20 years;
The prices used do not change during the analysis period;
The demand for electrical and thermal energy will be the same over the years; 10% refresh rate.

In the economic analysis, the energy and economic parameters of all systems were studied.

Energy Parameters

The energy parameters of the system, are based on the efficiency of the system (thermal and electrical efficiency) and the savings in fuel consumption, that is achieved with the use of trigeneration system.

The thermal efficiency (η_T) is defined as the quotient between the Daily Thermal Energy Produced (DTEP) and the Daily Energy Provided by Fuel (DEPF).

$$\eta_T = \frac{DTEP}{DEPF} \quad (1)$$

The electrical efficiency (η_E) is defined as the quotient between the Daily Electric Energy Produced (DEEP) and the Daily Energy Provided by Fuel (DEPF).

$$\eta_E = \frac{DEEP}{DEPF} \quad (2)$$

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Regarding savings in fuel consumption, it was stipulated that the objective with the implementation of the trigeneration system, was to reduce fuel consumption by 5% to 10% per day in relation to the reference systems. To calculate fuel consumption per year, it was necessary to know the consumption profiles for each month of the year. In the article [Chua, K.J, 2013] used to know the consumption profile in the month of January and to calculate the consumption profile in the month of May, it appears that the average hourly energy consumption in each month throughout the year, do not vary much (also those presented in figure 2 of this article). Given this little variation, an approximation of fuel consumption was made in the rest of the months. This approximation was carried out as follows:

The average hourly total energy consumption in each month was calculated.
The variation in consumption values between January and the rest of the months (except May) of the year was determined.
The variation in consumption values between May and the rest of the months (except January) of the year was determined.
For each month (except January and May), two absolute values are obtained. If the value of the variation with month of January is less than the value of the variation with month of May, the fuel consumption profile considered for that month is the profile of January. Otherwise, the fuel consumption profile to be considered is the profile of May.

After all the calculations, the January consumption profile was also associated with the months of February, September, November and December. The rest of the months of the year were associated with the consumption profile of May.

Economic Parameters

Economic parameters cover the project's Net Present Value (NPV), the Investment Return Period (IRP) and the Internal Rate of Return (IRR). Based on these values, it is possible to understand the behavior of the investment made in the present project. As previously mentioned, the useful life of the project is 20 years, so the investment will be amortized over these 20 years.

All the economic parameters mentioned, can only be calculated, when you know the costs associated to systems:

Costs of Main Equipments;
Costs of Equipment Accessories (examples; transformers, circuit breakers, water circulation pumps, valves, etc ...);
Transportation costs;
Fuel consumption costs (per year);
Equipment Maintenance Costs (per year);
Employee costs (per year);
Bank loan charges.

The NPV is based on the subtraction between the sum of the cash flows of all the years under analysis and the initial investment. An indicator for the project to be accepted, is that the net present value is greater than zero at the end of the project's useful life. One of the variables that influences the NPV calculation is the refresh rate. This rate allows the determination of the current value of future cash flows, contributing to the decision on the viability of a given investment. Thus, it is possible to know how much money the investor receives each year.

The calculation of the net present value is given by:

$$\text{NPV} = \sum_{i=0}^{n} \frac{CF_i}{(1+t)^i} - I_o \quad (3)$$

CFi – Cash Flow in year i [€]
t – Refresh Rate (10 % - considered)
Io – Initial Investment [€]

The IRP represents the period in which the accumulated net profit equals the value of the initial investment of the project.

The expression can be represented as follows:

$$I_o = \sum_{i=0}^{IRP} CF_i \quad (4)$$

The IRR is a parameter that allows to verify the profitability of the investment made. This rate assesses the percentage of return for a given project, and is usually compared to the refresh rate. If the IRR is bigger than the refresh rate, together with the NPV> 0, the project should be accepted. For the calculation of this value, the NPV is equal to 0.

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The equation that allows the calculation of the IRR is presented below.

$$0 = \sum_{i=0}^{n} \frac{CF_i}{(1+IRR)^i} - I_o \quad (5)$$

RESULTS

Equipments Loads and Operation Hours

A good operation management of the equipments, namely the load and the time of operation, is essential for achieving a more efficient system. Various loads and operating hours were studied for the different equipments. It was decided to use constant load regimes instead of variable regimes, because there is less wear on the equipments, consequently, there is a more efficient system.

Reference Systems

Steam Compression Chillers

The operating loads of the chillers were chosen, taking into account the minimum capacity of the thermal cold water storage system that would be used, and the daily consumption of electric energy from chillers. The load of the chillers that presents the set of these values lower, was the load chosen for the two consumption profiles.

The values obtained for all studied loads are shown in table 6 for the partial storage system and in table 7 for the full storage system.

Table 6: Comparison of Chillers Operation Loads in the Partial Storage System

Partial System Storage						
	January Profile			May Profile		
Load of Chillers	Min. TESS storage capacity [kWh]	Amount of Energy Stored in the tank at the end of the day [kWh]	Daily Consumption of Electric Energy [kWh]	Min. TESS storage capacity [kWh]	Amount of Energy Stored in the tank at the end of the day [kWh]	Daily Consumption of Electric Energy [kWh]
100%	1753,71	159,73	4525,80	2992,17	141,93	5476,20
90%	2252,22	404,93	4500,59	2830,93	69,61	5350,58
80%	2654,32	339,34	4439,55	2128,78	335,96	5210,45
70%	2015,00	76,43	4123,65	Insufficient capacity of chillers		

Chillers Operation Regime

January 1 Profile
Load 100%
1 Chiller in operation – 04:00h às 15:59h / 18:00h às 18:59h / 20:00h às 00:59h
2 Chillers in operation - 01:00h às 03:59h / 16:00h às 17:59h / 19:00h às 19:59h

May 1 Profile
Load 80%
1 Chiller in operation – 16:00h às 17:59h / 23:00h às 23:59h
2 Chillers in operation - 01:00h às 15:59h / 18:00h às 22:59h / 00:00h às 00:59h

Table 7: Comparison of Chillers Operation Loads in the Full Storage System

Full Storage System						
	January Profile			May Profile		
Load of Chillers	**Min. TESS storage capacity [kWh]**	**Amount of Energy Stored in the tank at the end of the day [kWh]**	**Daily Consumption of Electric Energy [kWh]**	**Min. TESS storage capacity [kWh]**	**Amount of Energy Stored in the tank at the end of the day [kWh]**	**Daily Consumption of Electric Energy [kWh]**
100%	2724,18	216,63	4824,40	3560,16	145,28	6421,40
90%	3480,29	496,49	5585,82	2830,93	238,79	5917,24

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80%	2734,38	158,93	4934,44	2128,78	236,63	5337,62
70%	2015,00	72,88	4342,50	Insufficient capacity of chillers		

Chillers Operation Regime

January 1 Profile
Load 70%
0 Chillers in operation - 00:00h às 00:59h
1 Chiller in operation – 23:00h às 23:59h
2 Chillers in operation - 01:00h às 22:59h

May 1 Profile
Load 80%
0 Chillers in operation - 00:00h às 00:59h
2 Chillers in operation - 01:00h às 23:59h

Heat Pumps
The choice of heat pumps (HPs) operation load, was based on the storage capacity of the DHW deposits and their daily consumption of electrical energy. The load that allows having these values lower was the load chosen, thus, the costs decrease due to the smaller size required for the DHW deposits and the lower consumption of electricity.

The results of the studies developed for the different operating loads of the HPs are shown in tables 8 and 9.

Table 8: Comparison of HPs Operation Loads in the Partial Storage System

Partial Storage System						
	January Profile			**May Profile**		
BC EW-HT 0412	Min. storage capacity of the DHW deposit [l]	Amount of Energy Stored in the deposits at the end of the day [kWh]	Daily Consumption of Electric Energy [kWh]	Min. storage capacity of the DHW deposit [l]	Amount of Energy Stored in the deposits at the end of the day [kWh]	Daily Consumption of Electric Energy [kWh]
100%	8896,10	83,74	931,50	8896,10	83,74	931,50
90%	10604,66	83,74	933,00	8847,56	83,74	933,00
80%	7865,17	-424,88	828,00	7256,06	253,28	966,00
70%	5125,68	-933,50	726,00	6564,65	15,92	919,00
60%	2386,18	-1442,12	624,00	8847,56	83,74	936,00

Heat Pumps Operation Regime

January 1 Profile
Chillers load - 100%
Heat Pumps load - 100%
0 HPs in operation - 17:00h às 17:59h
1 HP in operation – 03:00h às 15:59h / 18:00h às 18:59h / 20:00h às 00:59h
2 HPs in operation - 01:00h às 02:59h / 16:00h às 16:59h / 19:00h às 19h59

May 1 Profile
Chillers load - 80%
Heat Pumps load – 70%
0 HPs in operation - 04:00h às 04:59h / 08:00h às 08:59h
1 HP in operation - 12:00h às 12:59h / 16:00h às 17:59h / 22:00h às 00:59h
2 HPs in operation - 01:00h às 03:59h / 05:00h às 07:59h / 09:00h às 11:59h / 13:00h às 15:59h / 18:00h às 21:59h

Table 9: Comparision of HPs Operation Loads in the Full Storage System

Full Storage System						
	January Profile			**May Profile**		
BC EW-HT 0412	Min. storage capacity of the DHW deposit [l]	Amount of Energy Stored in the deposits at the end of the day [kWh]	Daily Consumption of Electric Energy [kWh]	Min. storage capacity of the DHW deposit [l]	Amount of Energy Stored in the deposits at the end of the day [kWh]	Daily Consumption of Electric Energy [kWh]
100%	10595,51	83,74	931,50	9243,54	83,74	931,50
90%	9455,96	83,74	933,00	7158,55	83,74	995,20
80%	9565,86	117,65	938,40	7900,69	117,65	938,40
70%	7282,95	15,92	919,60	6240,28	15,92	919,60
60%	9565,86	83,74	936,00	9565,86	83,74	936,00

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Heat Pumps Operation Regime

January 1 Profile
Chillers load - 70%
Heat Pumps load - 70%
0 HPs in operation - 04:00h às 04:59h / 08:00h às 08:59h / 12:00h às 12:59h / 00:00h às 00:59h
1 HP in operation – 19:00h às 19:59h / 23:00h às 23:59h
2 HPs in operation - 01:00h às 03:59h / 05:00h às 07:59h / 09:00h às 11:59h / 13:00h às 18:59h / 20:00h às 22:59h

Before using the EW-HT 0412 Heat Pump, the use of the EW-HT 0302 pump was studied and it was found that, for none operating load, in both profiles, it met the needs of DHW. All equipment was designed for the most unfavorable case between the two profiles under study.

May 1 Profile
Chillers load - 80%
Heat Pumps load – 70%
0 HPs in operation - 04:00h às 04:59h / 08:00h às 08:59h / 12:00h às 12:59h / 19:00h às 19:59h / 00:00h às 00:59h
2 HPs in operation - 01:00h às 03:59h / 05:00h às 07:59h / 09:00h às 11:59h / 13:00h às 18:59h / 20:00h às 23:59h

Diesel Generators
In relation to diesel generators, the use of the three generator models (P400-3, P250-5 and P110-3) without EESS was initially studied. The goal of this study, was to know which loads the generators provide a lesser consumption of fuel.

Tables 10 and 11 show the values obtained from the various studies related to the generators, for the reference systems.

Table 10: Comparison of Loads and Generators in the Partial Storage System

Partial Storage System							
	January Profile			May Profile			
Load	Daily Electric Energy Produced [kWh]	Max. Nº of generators used	Daily Fuel Consumption [l]	Daily Electric Energy Produced [kWh]	Max. Nº of generators used	Daily Fuel Consumption [l]	Model of Generator
100%	21000,00	4	5201,22	20160,00	3	5000,40	P400-3
75%	20790,00	5	5263,93	20160,00	4	5112,16	P400-3
50%	19320,00	7	5176,44	19460,00	6	5220,92	P400-3
100%	19136,00	6	4929,87	19872,00	5	5129,55	P250-5
75%	19320,00	7	5137,75	19182,00	6	5111,23	P250-5
50%	18860,00	11	5076,36	18676,00	9	5035,85	P250-5
100%	18960,00	12	5198,74	18560,00	11	5097,35	P110-3
75%	18540,00	16	5154,25	18420,00	14	5128,93	P110-3
50%	18200,00	24	5335,52	18120,00	21	5320,55	P110-3

Table 11: Comparison of Loads and Generators in the Full Storage System

Full Storage System							
	January Profile			May Profile			
Load	Daily Electric Energy Produced [kWh]	Max. Nº of generators used	Daily Fuel Consumption [l]	Daily Electric Energy Produced [kWh]	Max. Nº of generators used	Daily Fuel Consumption [l]	Model of Generator
100%	19880,00	3	4922,80	19880,00	3	4931,15	P400-3
75%	19950,00	4	5050,45	19950,00	4	5059,07	P400-3
50%	19460,00	6	5212,67	19600,00	6	5258,97	P400-3
100%	19504,00	5	5027,07	20240,00	5	5225,00	P250-5
75%	19182,00	6	5100,26	19320,00	6	5145,57	P250-5
50%	18492,00	9	4978,48	18860,00	9	5085,89	P250-5

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100%	18320,00	11	5023,66	18560,00	11	5097,71	P110-3
75%	18360,00	14	5104,67	18720,00	14	5212,94	P110-3
50%	17960,00	21	5265,54	18160,00	21	5332,64	P110-3

After the calculations, it was found that all models of the generators studied, have a lower fuel consumption when they are operating at 100%, so this was the load used. The model of the generators used was the P400-3. This choice was based on the lower consumption of fuel per day, and the smaller number of generators used when compared to the other models.

Then, fuel consumption was calculated again, but now with the use of EESS. The results obtained (tables 12 and 13) show that the implementation of EESS allows to reduce the consumption of daily fuel, in both profiles and systems.

Table 12: Partial Storage System with EESS

		Partial Storage System					
Profile	**Storage**	**Daily Electric Energy Produced [kWh]**	**Max. Nº of generators used**	**Daily Electric Energy Wasted [kWh]**	**Daily Fuel Consumption [l]**	**Fuel cost per day [€/dia]**	**Storage Capacity of EESS [kWh]**
January	Without EESS	21000,00	4	3292,70	5201,22	5320,84	-
	With EESS	18200,00	4	492,70	4507,83	4611,51	266,69
May	Without EESS	20160,00	3	2514,95	5000,40	5115,40	-
	With EESS	18200,00	3	554,95	4514,57	4618,41	260,51

Diesel Generators Operation Regime

January 1 Profile
Chillers load - 100%
Heat Pumps load - 100%
Diesel Generators load – 100%
2 Diesel Generators in operation - 05:00h às 06:59h / 08:00h às 08:59h / 10:00h às 10:59h / 12:00h às 12:59h / 15:00h às 15:59h / 21:00h às 21:59h / 00:00h às 00:59h

3 Diesel Generators in operation – 01:00h às 04:59h / 07:00h às 07:59h / 9:00h às 9:59h / 11:00h às 11:59h / 13:00h às 14:59h / 17:00h às 20:59h / 22:00h às 23:59h

4 Diesel Generators in operation - 16:00h às 16:59h

May 1 Profile
Chillers load - 80%
Heat Pumps load – 70%
Diesel Generators load – 100%
2 Diesel Generators in operation - 03:00h às 03:59h / 05:00h às 05:59h / 08:00 às 08:59h / 11:00h às 11:59h / 16:00h às 17:59h / 23:00h às 23:59h

3 Diesel Generators in operation - 00:00h às 02:59h / 04:00h às 04:59h / 06:00h às 07:59h / 09:00h às 10:59h / 12:00h às 15:59h / 18:00h às 22:59h

Table 13: Full Storage System with EESS

		Full Storage System					
Profile	Storage	Daily Electric Energy Produced [kWh]	Max. Nº of generators used	Daily Electric Energy Wasted [kWh]	Daily Fuel Consumption [l]	Fuel cost per day [€/dia]	Storage Capacity of EESS [kWh]
January	Without EESS	19880,00	3	2367,90	4922,80	5036,03	-
	With EESS	18200,00	3	687,90	4507,67	4611,34	272,25

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May	Without EESS	19880,00	3	2107,78	4931,15	5044,57	-
	With EESS	18200,00	3	427,78	4515,22	4619,07	272,61

Diesel Generators Operation Regime

January 1 Profile
Chillers load - 70%
Heat Pumps load - 70%
Diesel Generators load – 100%
2 Diesel Generators in operation - 03:00h às 03:59h / 05:00h às 05:59h / 07:00h às 07:59h / 10:00h às 10:59h / 13:00h às 13:59h / 21:00h às 21:59h / 00:00h às 00:59h

3 Diesel Generators in operation – 01:00h às 02:59h / 04:00h às 04:59h / 06:00h às 06:59h / 08:00h às 09:59h / 11:00h às 12:59h / 14:00h às 20:59h / 22:00h às 23:59h

May 1 Profile
Chillers load - 80%
Heat Pumps load – 70%
Diesel Generators load – 100%
1 Diesel Generator in operation - 00:00h às 00:59h
2 Diesel Generators in operation - 03:00h às 03:59h / 05:00h às 05:59h / 08:00h às 08:59h / 11:00h às 11:59h / 17:00h às 17:59h
3 Diesel Generators in operation - 01:00h às 02:59h/ 04:00h às 04:59h / 06:00h às 07:59h / 09:00h às 10:59h / 12:00h às 16:59h / 18:00h às 23:59h

Trigeneration System
When implementing the trigeneration system, it was found that it is possible to not use any heat pump. All DHW needs are met, by recover the heat released in the cooling circuit of the various engines. To be possible not to use HPs, it is necessary that the system has the operating regime presented below.

Diesel Generators and Chillers Operation Regime

January 1 Profile
Compression Chillers at 100% load
0 Chillers in operation – 04:00h às 05:59h / 09:00h às 09:59h / 23:00h às 23:59h
1 Chiller in operation – 06:00h às 08:59h / 10:00h às 15:59h / 17:00h às 22:59h / 00:00h às 00:59h
2 Chillers in operation - 01:00h às 03:59h / 16:00h às 16:59h

Generators at 100% load
1 Generator in operation – 05:00h às 05:59h / 10:00h às 10:59h / 00:00h às 00:59h
2 Generators in operation – 06:00h às 06:59h / 08:00h às 08:59h / 11:00h às 11:59h / 13:00h às 13:59h / 18:00h às 18:59h / 22:00h às 23:59h
3 Generators in operation - 01:00h às 04:59h / 07:00h às 07:59h / 09:00h às 09:59h / 12:00h às 12:59h / 14:00h às 17:59h / 21:00h às 21:59h
4 Generators in operation - 19:00h às 20:59h

Absorption Chillers at 100% load
In operation - 01:00h às 04:59h / 07:00h às 07:59h / 09:00h às 09:59h / 12:00h às 12:59h / 14:00h às 17:59h / 19:00h às 21:59h

May 1 Profile
Compression Chillers at 100% load
0 Chillers in operation – 04:00h às 04:59h / 09:00h às 09:59h / 20:00h às 20:59h
1 Chiller in operation - 08:00h às 08:59h / 16:00h às 17:59h / 23:00h às 23:59h
2 Chillers in operation - 00:00h às 03:59h / 05:00h às 07:59h / 10:00h às 15:59h / 18:00h às 19:59h / 21:00h às 22:59h

Generators at 100% load
1 Generator in operation – 05:00h às 05:59h / 11:00h às 11:59h
2 Generators in operation – 03:00h às 03:59h / 07:00h às 08:59h / 13:00h às 13:59h / 16:00h às 17:59h / 21:00h às 00:59h
3 Generators in operation - 01:00h às 02:59h / 04:00h às 04:59h / 06:00h às 06:59h / 10:00h às 10:59h / 12:00h às 12:59h / 14:00h às 15:59h / 18:00h às 19:59h
4 Generators in operation - 09:00h às 09:59h / 20:00h às 20:59h

Absorption Chillers at 100% load
In operation - 01:00h às 02:59h / 04:00h às 04:59h / 06:00h às 06:59h / 09:00h às 10:59h / 12:00h às 12:59h / 14:00h às 15:59h / 18:00h às 20:59h

After the development of the trigeneration system, the reduction in daily fuel consumption was calculated, and the three systems were compared, based on the minimum capacity of the energy storage systems and the water cooling systems. All values obtained are shown in table 14.

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Table 14: Comparison of Equipment Capacities for Different Types of Systems

Type of System	Full Storage		Partial Storage		Trigeneration	
Profile	**Jan**	**May**	**Jan**	**May**	**Jan**	**May**
Fuel Cons. [l/dia]	4507,67	4515,22	4507,83	4514,57	4230,86	4167,56
Fuel Reduction with the use of the Trigeneration System [%]	6,14	7,70	6,14	7,69	-	
Minimum DHW Deposit Capacity [l]	7282,95	6240,28	8896,10	6564,65	3969,84	2894,68
Minimum TESS Capacity of Cold Water [l]	346252,2	365804,0	301353,1	365804,0	424292,7	357486,2
Minimum EESS Capacity [kWh]	272,25	272,61	266,69	260,51	963,28	811,12
Minimum Cooling Tower Capacity for the Compression Chiller [kW]	953,08	1092,10	1340,40	1092,10	1386,60	1325,16
Minimum Cooling Tower Capacity for the Absorption Chiller [kW]	-				603,00	603,00

Used Equipment's

All equipment applied to the three systems are shown in table 15. This table lists the companies consulted, the price of each equipment and the number of equipment used in each system.

Table 15: Mark/Model/Quantity of Equipment used

Equipments		Mark and Model	Nº of Equip (Partial/Full/Trigeneration)	Price by unit [€]
Steam Compression Chiller		Mitsubishi Electric NECS/R/CA 1816	2/2/2	75 006,00
Cold Water TESS		-	1 (400 m^3)/ 1 (400 m^3)/1 (500 m^3)	120 000,00 (400 m^3) 130 000 (500 m^3)
Absorption Chiller		Carrier 16LJ-A11	0/0/1	100 000,00
Heat Pump		Mitsubishi Eletric EW – HT/0412	2/2/0	13 636,00
DHW deposits	4000 L Deposit	Reflex Winkelman HF4000/R	0/2/2	2 525,00
	4000 L deposit insulation	-	0/2/2	1 460,00
	5000 L Deposit	Reflex Winkelman HF5000/R	2/0/0	3 285,00
	5000 L deposit insulation	-	2/0/0	1 593,00
Plate Exchanger: Grid Water - High Temperature Water Circuit		Reflex Winkelmann RLB-110-120	2/2/0	2 188,00
Plate Exchanger: Grid Water - Engine Cooling Water Circuit		Reflex Winkelmann RMB-31-60	0/0/4	450,00
Diesel Generators		FG Wilson P400-3	4/3/4	37 950,00
Electric Energy Storage System (300 kVA/ 355 kWh)		Rolls-Royce MTU Energy Packs QS	1/1/3	142 000,00
Cooling Tower (Steam Compression Chiller)		Baltimore Aircoil Company FXVS 0809B-24T-K/P	1/1/1	44 209,00
Cooling Tower (Absorption Chiller)		Baltimore Aircoil Company FXVS 1212C-24D-O/X	0/0/1	72 299,00
Shell & Tube exchanger:		-	0/0/1	8 253,08

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Exhaust Gases - Water Circuit that drives the Absorption Chiller			
Equipments	**Mark and Model**	**Nº of Equip (Partial/Full/Trigeneration)**	**Price by unit [€]**

Regarding TESS and the Shell & Tube heat exchanger, it was not possible to contact manufacturers of this equipment.

The investment cost and TESS efficiency were estimated. When consulting several documents, it appears the range of efficiency values typical of these systems, with the highest value of 90% being used [Karim, M.A, 2009; G.S.T.E.S.S.B.E, 2016]. As for the investment cost, it was possible to obtain an approximate value, due to the minimum capacity of TESS. This value is taken from the graph in figure 7.

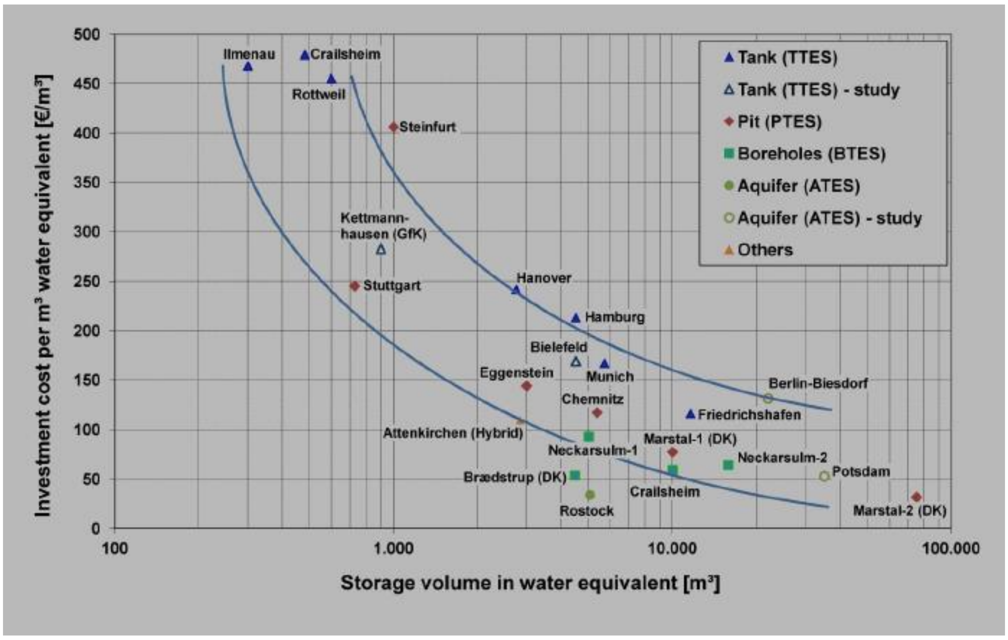

Figure 7: Estimated TESS investment [G.S.T.E.S.S.B.E, 2016]

In order to be able to select a Shell & Tube exchanger, the example of exchanger used in the final report Capture of Heat Energy from Diesel Engine Exhaust [Lin, C.S, 2008] was used. The temperature conditions of the final report are similar to the case under study, and the exchanger used by this report is also able to satisfy the needs shown in table 16.

Table 16: Minimum Conditions of Shell & Tube Heat Exchanger

Parameters	Exchanger for activating the absorption chiller
Min. Flow that has to pass through the exchanger [m^3/h]	2,70
Minimum heat transfer area of the exchanger [m^2]	4,65

Economic evaluation of the project

Efficiency and Fuel Consumption

The efficiency (table 17) and fuel consumption (table 18) present different values for each system. The efficiencies are presented for the two consumption profiles studied and the fuel consumption is calculated for one year.

Table 17: Electrical and Thermal Efficiency of each System

Type of System	Electrical Efficiency [%]		Thermal Efficiency [%]	
	January	May	January	May
Partial Storage System	40,34	40,28	45,65	52,22
Full Storage System	40,34	40,28	47,25	53,10
Trigeneration System	40,34	40,28	49,56	57,50

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Table 18: Fuel consumption per year in each system

Type of System	**Fuel consumption per year [l/ano]**
Partial Storage System	1 651 314,88
Full Storage System	1 651 430,47
Trigeneration System	1 534 885,26

Costs and Behaviors of Investments

Associated Costs

For the analysis of the economic parameters of project, it is necessary to take into account all associated costs. These costs were obtained in several ways:

Equipments Costs - Obtained by contacting the various companies for each equipment used.

Chillers and HPs Accessories Costs - Considered 20% of the main equipment costs (Chillers and HPs).

Diesel Generators Accessories Costs - Information retired from the Sustainable Energy Handbook (700 USD/kW installed ~ 591.88 €/kW installed) [Pirolli, M, 2016].

Transport Costs - Not counted, suppliers will be responsible for the cost of transportation and insurance of the cargo, until the place of installation.

Fuel Costs - Calculated by multiplying the fuel consumption values (table 18) and the cost of fuel per liter in Singapore (1,023 €/l - value from 14 December 2020) [Valev, N, 2020].

Equipments Maintenance Costs - Considered 0,015 €/kWh for Diesel Generators and through article [Biserni, C, 2019], 0,006 €/kWh - Steam Compression Chillers, 0,010 €/kWh - Heat Pumps and 0,002 €/kWh - Absorption Chiller.

Employees Costs - Consideration of using four employees (three in 8-hour shifts and one to cover other employees's vacations/periods of absence). Costs considered to be € 15,000/(employee.year).

Bank loan charges - Investors are responsible for all initial investment in the trigeneration system, they already have the necessary money to invest, so it is not necessary to include charges for loans to the bank to carry out the investment.

All costs associated with each system are shown in table 19. In addition to these costs, the additional investment that is made in the equipments of the trigeneration system and the cost reduction per year obtained by using the trigeneration system, both in relation to reference systems, are also shown in table 19.

Table 19: Associated Costs for all systems

Costs	**Partial Storage System**	**Full Storage System**	**Trigeneration System**
Equipments [€]	649 425,00	609 689,00	1 092 343,08
Diesel Generators Accessories [€]	662 900,22	497 175,17	662 900,22
Compression Chillers Acessories [€]	30 002,40	30 002,40	30 002,40
Heat Pumps Acessories [€]	5 454,40	5 454,40	0,00
Absorption Chillers Acessories [€]	0,00	0,00	20 000,00
Fuel [€/year]	1 689 295,12	1 689 413,37	1 570 187,62
Equipments Maintenence [€/year]	124 944,45	126 052,33	97 037,21
Employees [€/year]	60 000,00	60 000,00	60 000,00
Total Costs (wihtout Equipments and Acessories) [€/year]	1 874 239,57	1 875 465,70	1 727 224,83
Additional investment in equipments of the Trigeneration System in relation to Reference Systems [€]	457 463,68	662 924,74	-
Cost Reduction with the use of Trigeneration System instead of Reference Systems [€/year]	147 014,74	148 240,87	-

From all the costs associated with each system, it was possible to calculate the economic parameters of the investment made. Table 20 shows the values obtained for NPV, IRR and IRP, in relation to both reference systems.

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Table 20: Economic Parameters of the Case Study

Systems	NPV [€]	IRR [%]	IRP [Years and Moths]
In Relation to Partial Storage System	988 887,96	37,26	3 years and 4 months
In Relation to Full Storage System	881 325,93	27,27	4 years and 10 months

For a better visualization of the behavior of all the investment made in the trigeneration system, in figures 8 and 9, graphs of the updated cash flow accumulated in each project year are presented, for both reference systems studied.

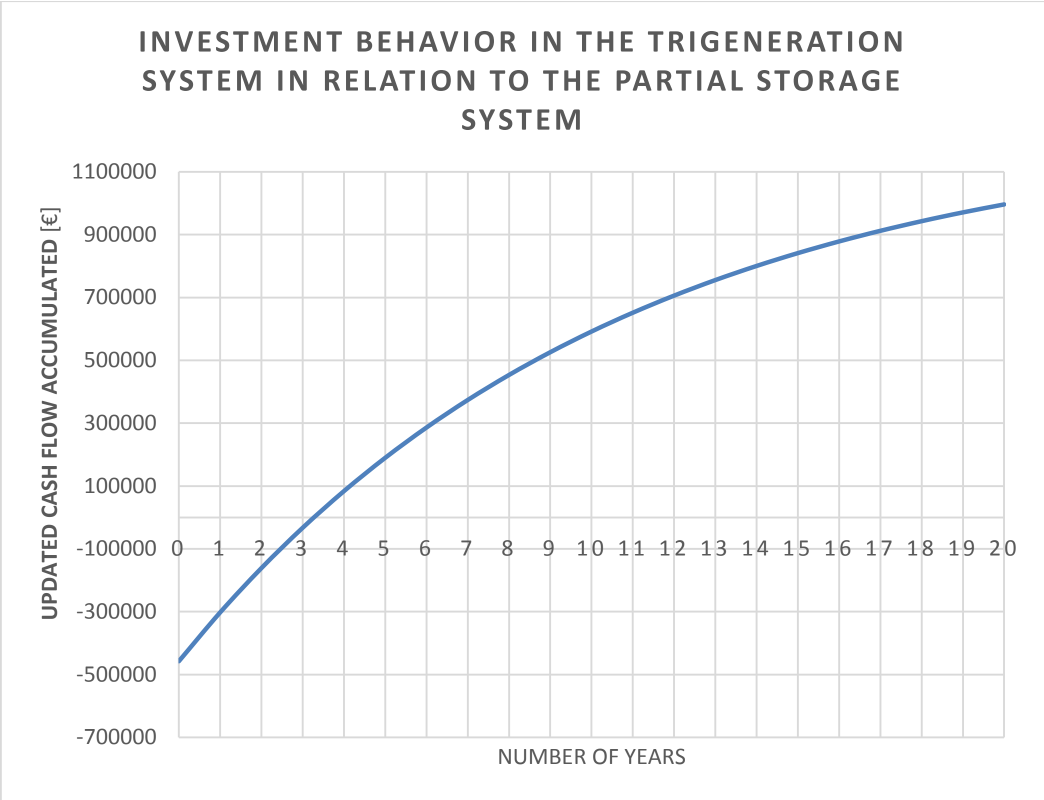

Figure 8: Investment Behavior in the Trigeneration System in relation to the Partial Storage System

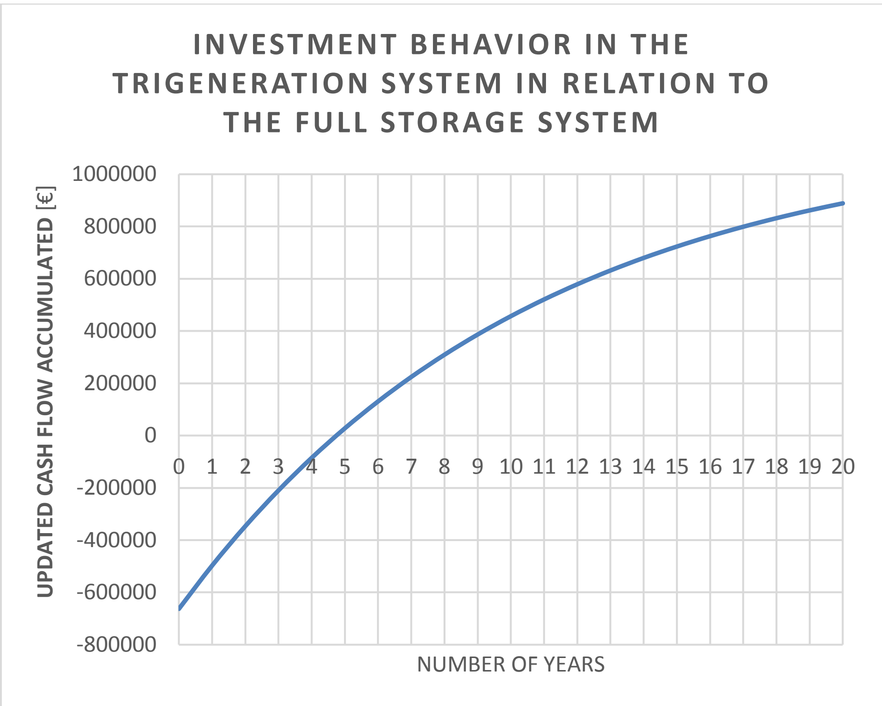

Figure 9: Investment Behavior in the Trigeneration System in relation to the Full Storage System

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DISCUSSION

Considering the results obtained in the present case study, it is possible to draw several conclusions that are presented in the following points:

In the optimization of the base systems, several studies of operating load and operating hours of the equipment were carried out. These studies made it possible to verify that the variation in the operating loads of the equipment and their operating hours, have a great influence on the entire system, namely in the energy consumption and in the minimum capacity of the energy storage systems.

The objective stipulated for the implementation of the trigeneration system was related to the reduction of 5% to 10% of fuel consumption per day, in relation to the base systems. The reduction in fuel consumption achieved was approximately 6.14% in the January consumption profile and 7.70% in the May profile, thus exceeding the stipulated objective.

Regarding the storage equipment, the chilled water storage systems are different, a 500 m^3 system was used for the Trigeneration System and a 400 m^3 system for each Base System. Regarding the hot water deposits used in the trigeneration systems, these are similar to those of the Full System. Finally, in the storage of electrical energy, it was necessary to use three battery systems (in the Trigeneration system) similar to the one used in the Base Systems.

When calculating the thermal and electrical efficiencies of all three systems, it was found that thermal efficiency of the trigeneration system has higher values (table 17), and electrical efficiency has equal values in all systems. It was already expected that the thermal efficiency would be higher in the trigeneration system, due to the use of heat from the refrigeration circuits of the engines to produce DHW, and the use of heat from the exhaust gases to produce cold water (through a absorption chiller). Thus, it is possible to take advantage of the energy that would be dissipated into the environment (in the base systems) to produce thermal energy.

The calculation of economic parameters (NPV,IRP,IRR), made it possible to study the technical and economic feasibility of using the trigeneration system on the island Pulau Ubin. In relation to the Partial System, the NPV is 988 887,96 €, the IRP is 3 years and 4 months, and finally the IRR is 37.26%. In relation to the Full System, the NPV is 881 325,93 €, the IRP is 4 years and 10 months, and finally the IRR is 27.27%. Given the results obtained, namely a NPV > 0 at the end of the project's useful life and an IRR > Refresh Rate, it can be concluded that the use of the trigeneration system in a remote isolated area (island), in substitution of Full/Partial System, presents a technically viable and economically efficient solution.

After making the conclusions, some suggestions for future research are presented:

The insertion of renewable energies in the systems may be a good suggestion to reduce fuel consumption, consequently, there would be a less harmed environment. Given that the study is carried out on a tropical island, the use of solar energy would be a good idea. The use of solar collectors for the production of DHW would allow the trigeneration system to be not only dependent on the engine's cooling circuits, to satisfy heating needs. In addition to the production of energy for heating, photovoltaic panels could also be used to produce electricity using solar energy. Thus, it would be possible to reduce the number of operation hours of diesel generators, and consequently, there will be a reduction in fuel consumption.

Another study that could be carried out, would be based on the comparison of trigeneration technologies. These technologies involve absorption chillers, adsorption chillers, desiccant cooling systems and ejector cooling systems. The objective would be, in the implemented trigeneration system, to replace the absorption chiller, with other types of technologies and to verify the differences in consumption and investment. Thus, it would be possible to see if, with the use of other technologies, there would be optimization of the trigeneration system.

Nomenclature

Abbreviations

CHP Combined Heat and Power

CCHP Combined Cooling, Heat and Power

COP Coefficient of Performance

DBT Dry Bulb Temperature

DEEP Daily Electric Energy Produced

DEPF Daily Energy Provided by Fuel

DHW Domestic Hot Water

DTEP Daily Thermal Energy Produced

EESS Electric Energy Storage System

HPs Heat Pumps

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HVAC Heating, Ventilation and Air Conditioning
IEA International Energy Agency
IRP Investment Return Period
IRR Internal Rate of Return
NPV Net Present Value
RH Relative Humidity
TESS Thermal Energy Storage System

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