International Journal of Energy Optimization and Engineering
Volume 11 • Issue 2

Technical-Economic Feasibility Study of a Tri-Generation System in an Isolated Tropical Island

Nuno Domingues, ISEL, Portugal*
Jorge Mendonça Costa, ISEL, Portugal
Rui Miguel Paulo, ISEL, Portugal

ABSTRACT

Over the years, and despite the energy efficiency measures and possibilities, there has been an increase in energy consumption worldwide. However, the resources and primary energies are limited and short stocked, and the energy production technologies have environmental and social impacts on production and exploration. One alternative is to reuse the energy waste in the processes. In this study, a trigeneration system in a large scale out of grid consumption is analyzed and a technical-economic feasibility is elaborated. The case study is based on an isolated tropical island. For the baseline scenario, two traditional energy production systems that does not contain energy recovery in the engines are assumed to be implemented. For the improved scenario, a trigeneration system absorption chiller is analyzed. An economic analysis of this project was given the indicators obtained, it was possible to conclude that the use of a trigeneration system on an isolated large scale out of grid energy consumption system, is feasible and preferable.

KEYWORDS

Absorption Chiller, Cogeneration, Economic Analysis, Energy efficiency, Technical-Economic Feasibility, Trigeneration

1. INTRODUCTION

The economic globalization has been wider over the years and is accompanied by an increase in energy demand and energy consumption. According to the International Energy Agency (IEA), energy consumption has increased dramatically (almost doubled) from 1975 to 2015 (Chen 2018). To traditional response to face the increase in consumption by producing more amount of energy is no longer environmentally, economic and social acceptable. Therefore, new ways to capture energy loses and reuse them in an efficient way is on focus. For example, the gases released in the energy generation processes in the thermoelectric plants, still 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, Dupont et al. 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

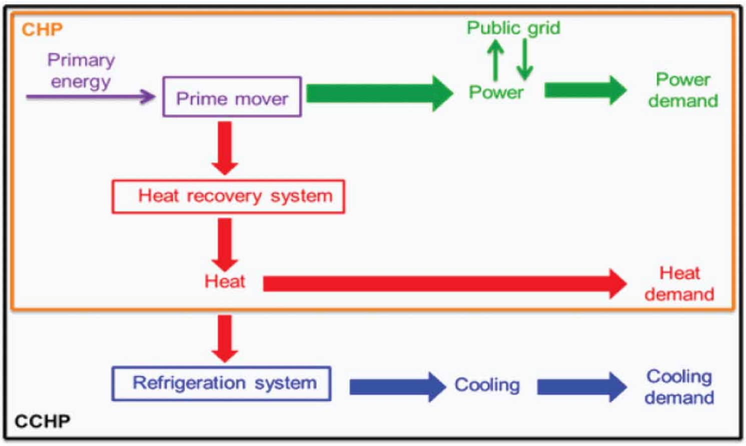
DOI: 10.4018/IJEOE.309416

*Corresponding Author

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). 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 (to satisfy a determined energy demand, Cogeneration uses a smaller amount of fossil fuels) (Consulting). 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 working of cogeneration, where exists the production of cold in addition to the production of heat and electricity. Trigeneration systems are implemented when there is a need for cooling equipment such as absorption chillers to produce cold (Baghernejad 2016, Feidt, Dupont et al. 2017). Figure 1 (Feidt, Dupont et al. 2017) presents a diagram referring to the connection of Trigeneration systems with Cogeneration systems.

Figure 1. Working of trigeneration



In Figure 1, the area enclosed by the acronym CHP (Combined Heat and Power) represents the constitution of Cogeneration systems, while the area enclosed by the acronym CCHP (Combined Cooling, Heat and Power) represents the composition 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 (Baghernejad 2016, Feidt, Dupont et al. 2017). By taking use of this energy, lower energy production is needed, thereby lower social and environmental impacts are present. 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 out of grid system (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 to produce energy on large scale consumption islands and remote areas.

2. SOLUTIONS AND ANALYSES

2.1. Background/Related Works

Some previous studies are interesting for the base study of the present papers fndings and applications.

(Uche, 2020) produces experimental tests of a small polygeneration plant unit based on hybrid renewable energy and desalination have been used to validate a novel model simulation of this plant. It provides electricity by coupling photovoltaic/thermal collectors and a micro-wind turbine, fresh water by means of hybrid desalination (membrane distillation, and reverse osmosis), and sanitary hot water coming from the photovoltaic/thermal collectors and an evacuated tubes collector. Plant was designed to operate in off-grid conditions and conventional energy storage systems were used (lead acid batteries and hot water tank). Simulation model was performed in TRNSYS environment and it was fully validated by comparing several key plant measurements. The analysis was focused on five typical days of summer, fall and winter. Some differences found in experimental and simulated values were analysed. To reduce those gaps, some modifications have been suggested to the model or the pilot unit respectively. As a result, a validated model in TRNSYS of the plant was obtained. This model can be used for the further scale up of new projects to cover any other scheduled demands of power and water in isolated areas, whenever is based on the combination of the abovementioned technologies.

(Chua, 2014) evaluates the potential of integrating renewable energy technological resources for tri-generation applications in an island. The integrated tri-generation system has to be self-sustaining in delivering cooling, heating and power. Several CCHP (combined cooling heating and power) systems at different penetration levels were proposed. The CCHP systems comprising key prime movers include microturbines, photovoltaic, solar Stirling dish, fuel cell system, biomass power generator and an absorption cooling technology. The systems are judiciously designed to provide the island's tri-generation needs. Three different operational schemes of varying renewable energy penetration were considered – peak shaving, 20% and 40% renewable energy penetration. Key results have suggested that reductions of approximately 20% in primary energy savings are realizable for all three cases. Additionally, a renewable energy penetration level of 40% yielded the largest reduction in terms of carbon dioxide emission. In terms of cost benefits for the proposed system combinations, peak shaving and 20% renewable energy penetration can realize savings of up to USD $150,000 per annum.

(Demir, 2021) designs and analyzes a novel integrated solar-driven system for ammonia synthesis, freshwater production and power generation. The trigeneration system contains a solar thermal subsystem, a thermal energy storage system where the molten salt is used as a heat transfer fluid and storage medium, a solar energy-driven Rankine cycle, a multistage flash distillation, a proton exchange membrane electrolyser array, and an ammonia synthesis unit. The proposed integrated system uses solar energy to charge the molten salt, which flows through a heat exchanger and generates steam for the topping cycle. The exhaust stream of the steam turbine provides heat for the multistage flash distillation (MFD) process. A 20 stage MFD unit is proposed where the seawater is utilized as the feedwater in this study. A portion of the produced freshwater is sent to the PEM electroylzer array for hydrogen production, which is used for ammonia production via the Haber-Bosch process. The thermodynamic analysis of the solar driven multigeneration system is analyzed through the Engineering Equation Solver (EES) and Aspen Plus software packages. The novelty of this study relies on the development of a new solar energy-based integrated system and its application for a selected community with over 10,000 residents to meet all of their needs to be self-sufficient and sustainable. Ammonia (for multiple purposes, such as fuel, energy carrier and feedstock), freshwater and electricity are the useful outputs as targeted in this paper. The study incorporates the phase change materials into the system for thermal energy storage purposes. The performance assessments based on energy and exergy efficiencies are carried out for the overall system and its components. Furthermore, the power, freshwater and ammonia production capacities are studied for better demand coverage. The overall exergy efficiency of the system is determined as 12.1%, where the ammonia synthesis, power generation, and freshwater production capacities are 0.85 kg/s, 17.6 MW, and 143.97 kg/h respectively.

Moreover, the study investigates the energy and exergy efficiencies with and without the presence of an air separation unit. The study results show that the air separation unit has less than 0.3% effect on the overall energy and exergy efficiencies.

(Polyzakis, 2010) is a demand led study taking into account changes in ambient conditions and power settings of a tri-generation power plant. Includes an economic evaluation tool for combined heat, cooling and power generation plant. The thesis is based on an overall technical-economic analysis of the tri-generation system, including: 1. Energy demand analysis and evaluation of actual tri-generation case studies. 2. Economic analysis and evaluation of the entire tri-generation plant. Initially, the main effort is to carry out research concerning the energy demands of different actual cases. The research includes sourcing, collecting, classification and evaluation of the available information. The cases cover a wide range of economic life and the resulting data specifies the energy needs, which the purposed tri-generation power plant needs to cover. The second part deals with the prime mover (namely the Gas Turbine, GT) modelling and simulation. The technical part of the assessment includes the Design Point (DP) and Off Design (OD) analysis of the GT. In other words, the performance analysis simulates different thermodynamic cycles (Simple, or with Heat Exchanger), and different configurations (one or two shafts). Also, includes the simulation of the absorption cooling system alone and/or in co-operation with the prime mover. The simulation is based upon the premise that the original prime mover is replaceable. Finally, an evaluation methodology of tri-generation plants, is introduced taking into account, both technical facts and economic data -based on certain cases from Greek realityhelping the potential users to decide whether it is profitable to use such technology or not. The economic scene will include the basic economic facts such as initial cost, handling and operational cost (fuel prices, maintenance etc), using methodology based on Net Present Value (NPV). This thesis suggests several tri-generation technology modes. The more economic favourable than the conventional technology is the 2-shaft simple cycle mode for the isolated island (120MW), while the 1-shaft simple cycle mode is the more economic favourable in the case of hotel (1MW). The main contribution of the thesis is that it provides an intergraded realistic tool, which simulates the future of a trigeneration plant, capable of helping the potential investor decide if it is profitable to proceed with the investment.

2.2. Definition of the Case Study and Energy Needs

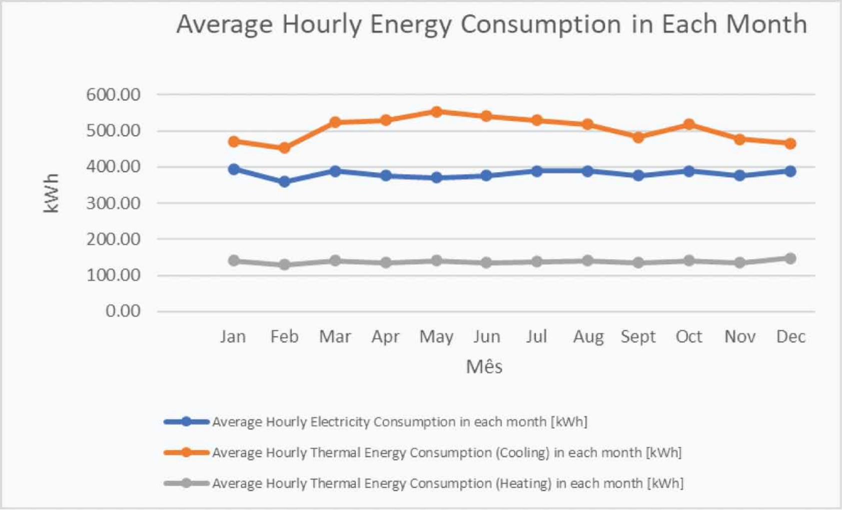
For the development of the work, it was defined as the location of study case, the island Pulau Ubin. This island contains about 200 people, is located northeast of Singapore and has an area of approximately 1020 hectares (10,2 km^2). The energy simulations were performed using the eQuest analysis tool (Chua 2013). 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 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

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 (Chua 2013) and the other profile studied was the power profile of May. The month of May was chosen because it is the month with greater in average hourly energy consumption variation in comparison to the profile of January. Figure 2 illustrates the Average Hourly Values of Energy Consumption in Each Month.

Figure 2. Average hourly values of energy consumption in each month



The demand of energy for cooling, refers to the thermal energy harvested 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 2013). The average hourly values of energy consumption for the several months considered are shown in Table 2. Table 3 shows the ratio between the January and May consumption, related to the values of Table 2.

Table 2. Average energy consumption of the two consumption profiles used

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

Table 3. Ratio between January and May

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

The power profile for a typical day in May, was obtained from the data available in (Chua 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 profile for a typical day of January is shown in Figure 3 and for May in Figure 4.

Figure 3. Power profile on typical January day

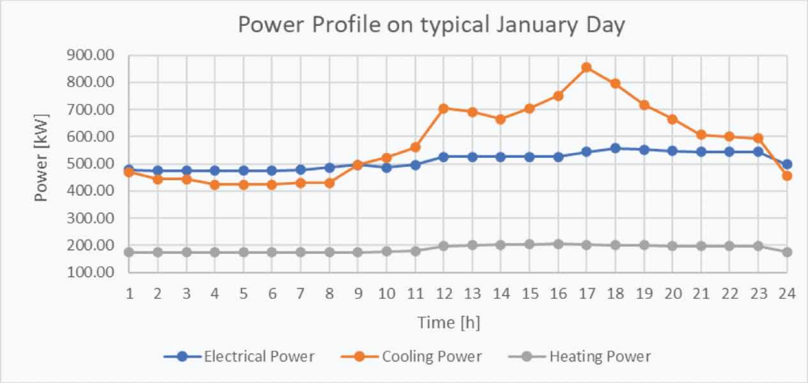
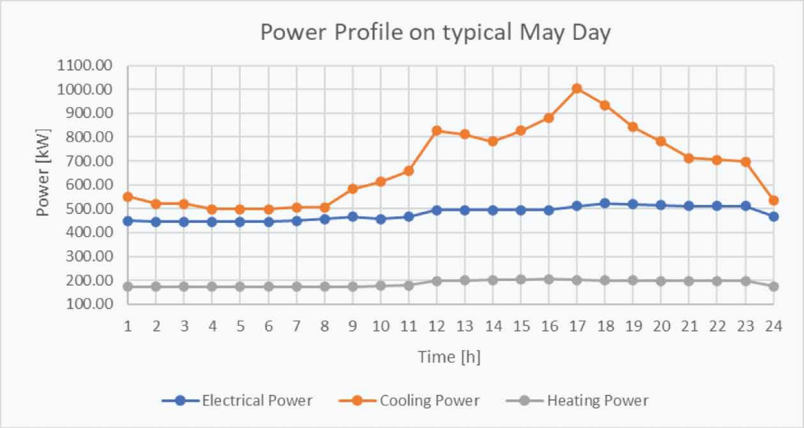


Figure 4. Power profile on typical May day



In complement to the typical daily power profiles, the 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 assumed, 1st of January of 2019 and 1st of May 1 of 2019 (timeanddate). 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
1st of January of 2019	Máx: 34 °C ; Min: 27 °C	Máx: 84% ; Min: 49%
1st of May 1 of 2019	Máx: 33 °C ; Min: 28 °C	Máx: 89% ; Min: 66%

2.3. Baseline Scenario 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 Baseline scenario Systems with a Trigeneration system. These Baseline scenario Systems will be systems that can be used on the island and meets all energy needs.

The island uses diesel generator(s) (DG) to meet the island's electrical load needs (Chua 2013). 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 chiller(s) (CC) to produce cold and high temperature heat pump(s) (HP) 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 CC 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 systems were studied as Baseline scenario Systems, with a comparison at the end of the study with the Trigeneration System.

2.3.1 Partial Storage System and Full Storage System

In the Partial Storage System, the CC used in the system are operating throughout the day. However, it is possible, if the cooling needs allow, to shut down one of the CC for a few hours leading the other to a more efficient load regimes, thus reducing consumption of energy. The excess energy produced throughout the day is stored in a Thermal Energy Storage System (TESS) of cold water (Doty and Turner 2010).

In the Full Storage System, the CC operate 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 chillers are shut down, needs are met through the energy stored in the cold water TESS (Doty and Turner 2010).

2.2.2 Systems Operation Regime

To develop case studies like the one in this article, in which there is several equipments to operate, it is necessary to define the load that the equipments operates and the hours of operation of the plant. To have an efficient system, several calculations were performed for different operating loads of the equipments used. In this way, it is possible to know in which load cases, the equipments can satisfy the energy needs by consuming a smaller amount of energy. The plant contains 4 workers and operates during all day (24 h).

2.3.3. Equipments

In addition to the equipment already mentioned for energy production (DG, steam CC and HP), energy storage equipment (DHW deposits and cold-water storage systems), heat exchange equipment (heat exchangers) and water cooling equipment (cooling tower) were also dimensioned. To implement the most efficient system, studies were carried out on various models of energy production equipment at various loads, as shown in Table 5.

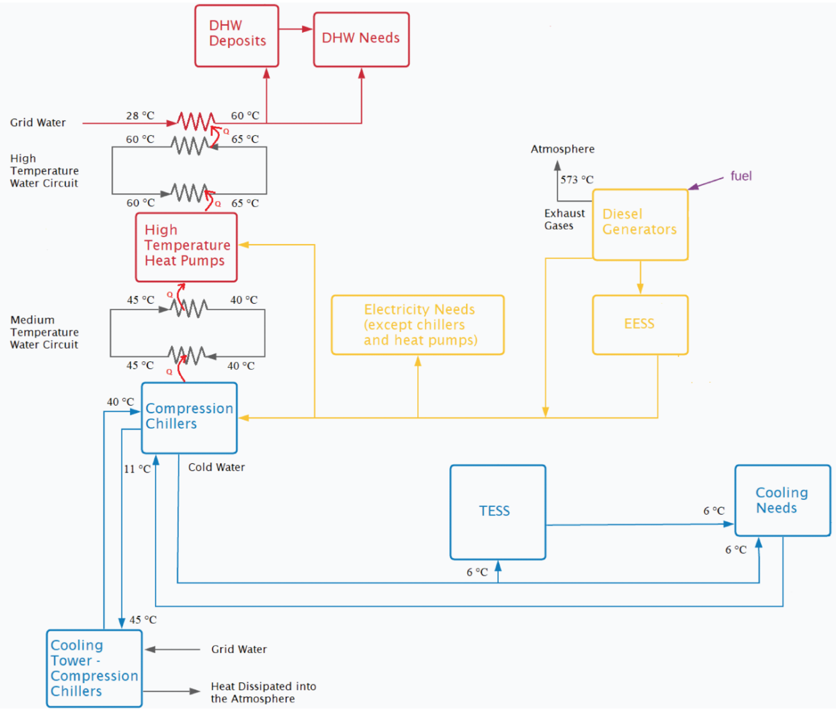
Table 5. Models and loads studied of energy production equipments

Equipments	Brand	Studied Models	Studied Loads
DG	FG Wilson	P400-3; P250-5; P110-3	100%; 75%; 50%
HP	Mitsubishi Eletric	EW-HT 0412; EW-HT 0302	100%; 90%; 80%; 70%; 60%
Steam CC	Mitsubishi Eletric	NECS/R/CA 1816	100%; 90%; 80%; 70%

2.3.4 Baseline Scenario Systems Installation Working Diagram

To facilitate the visualization of the connection of all the equipments and systems, Figure 5 shows the installation working diagram for the Baseline scenario Systems. This Diagram also shows all the temperatures of the system's water circuits.

Figure 5. Baseline scenario systems installation working diagram



2.4. Trigeneration System

Opposing to Baseline scenario Systems, which there is no heat recovery in DG, 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 DG for DHW production. From what has been said, it is possible to reduce the number of operation hours of on CC and HP. With this reduction, the consumption of electricity will decrease, and, consequently, the fuel consumption of DG will also decrease.

2.4.1 Equipment

- Absorption Chiller

The selection of the absorption chiller to be used for the trigeneration took into account whether it is simple or double effect, the heat source that allows the absorption chiller to be activated and the working fluid. The option was taken 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 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 2006).

- Cooling Tower for Absorption Chiller

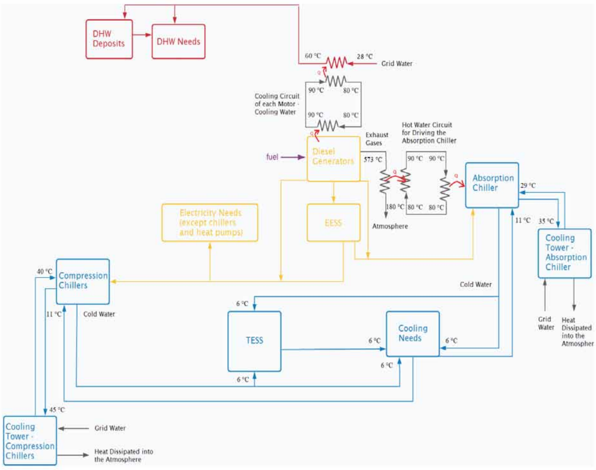
In the absorption chiller it is necessary to cool the condenser and the absorber. The chiller cooling water will enter the system at 29 °C and exit at 35 °C (Figure 6). Given the different temperature range values of this water, compared to the water used to cool the condenser of the steam CC (water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

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.

2.4.2 Trigeneration System Installation Working Diagram

In order to facilitate the visualization of the connection of all the equipments and systems, Figure 6 shows the Installation Working Diagram for the Trigeneration System. This Diagram also shows all the temperatures of the system's water circuits.

Figure 6. Trigeneration system installation working diagram



2.5 Economic Analysis

After the development of all systems, the technical-economic feasibility of implementing the Trigeneration System in relation to the Baseline scenario Systems was studied. The realization of this type of studies becomes crucial for any investor that wonders to invest in a project and wants to understand the financial behavior that the investment will have. To carry out the calculations pertaining to the economic analysis, it was assumed that:

- 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% resfresh rate.

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

2.5.1 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):

$$\eta_T = \frac{DTEP}{DEPF} \tag{1}$$

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):

$$\eta_E = \frac{DEEP}{DEPF} \tag{2}$$

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 Baseline scenario 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 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.

2.5.2 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 Equipment;
- Costs of Equipment Accessories (e.g. transformers, circuit breakers, 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 NPV 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 NPV is given by:

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

CFi – Cash Flow in year i [€]
t – Refresh Rate (10% - considered)
I_o – 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:

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

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

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

3. RESULTS AND ASSUMPTIONS

3.1 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.

3.1.1 Baseline Scenario Systems

- Steam Compression Chillers

The operating loads of the CC 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 CC. The load of the CC 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 8 for the Full Storage System. Table 7 and Table 9 represent the CC operation regime for Partial Storage System and Full Storage System, respectively.

Table 6. Comparison of compression chillers operation loads in the partial storage system

Partial System Storage						
Load of CC	**January Profile**			**May Profile**		
	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%	1 753,7	159,7	4 525,8	2 992,2	141,9	5 476,2
90%	2 252,2	404,9	4 500,6	2 830,9	69,6	5 350,6
80%	2 654,3	339,3	4 439,6	2 128,8	335,9	5 210,5
70%	2 015,0	76,4	4 123,7	Insufficient capacity of chillers		

Table 7. Compression chillers operation regime in the partial storage system

CC Operation Regime		
Profile	**January**	**May**
Load	**100%**	**80%**
1 CC in operation	04:00h às 15:59h / 18:00h às 18:59h / 20:00h às 00:59h	16:00h às 17:59h / 23:00h às 23:59h
2 CC in operation	01:00h às 03:59h / 16:00h às 17:59h / 19:00h às 19:59h	01:00h às 15:59h / 18:00h às 22:59h / 00:00h às 00:59h

Table 8. Comparison of compression chillers operation loads in the full storage system

Full Storage System						
Load of CC	**January Profile**			**May Profile**		
	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%	2 724,2	216,6	4824,4	3 560,2	145,3	6 421,4
90%	3 480,3	496,5	5585,8	2 830,9	238,8	5 917,2
80%	2 734,4	158,9	4934,4	2 128,8	236,6	5 337,6
70%	2 015,0	72,9	4342,5	Insufficient capacity of chillers		

Table 9. Compression chillers operation regime in the full storage system

CC Operation Regime		
Profile	**January**	**May**
Load	**70%**	**80%**
0 CC in operation	00:00h às 00:59h	00:00h às 00:59h
1 CC in operation	23:00h às 23:59h	-
2 CC in operation	01:00h às 22:59h	01:00h às 23:59h

- Heat Pumps

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

The results of the studies developed for the different operating loads of the HP are shown in Tables 10 for Partial Storage System and in Table 12 for Full Storage System. Table 11 and Table 13 represent the HP operation regime for Partial Storage System and Full Storage System, respectively.

Table 10. Comparison of heat pumps operation loads in the partial storage system

Partial Storage System						
BC EW-HT 0412	**January Profile**			**May Profile**		
	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%	8 896,1	83,7	931,5	8 896,1	83,7	931,5
90%	10604,7	83,7	933,0	8 847,6	83,7	933,0
80%	7 865,2	-424,9	828,0	7 256,1	253,3	966,0
70%	5 125,7	-933,5	726,0	6 564,7	15,9	919,0
60%	2 386,2	-1 442,1	624,0	8 847,6	83,7	936,0

Table 11. Heat pumps operation regime in the partial storage system

HP Operation Regime		
Profile	**January**	**May**
Load	**100%**	**70%**
0 HP in operation	17:00h às 17:59h	04:00h às 04:59h / 08:00h às 08:59h
1 HP in operation	03:00h às 15:59h / 18:00h às 18:59h / 20:00h às 00:59h	12:00h às 12:59h / 16:00h às 17:59h / 22:00h às 00:59h
2 HP in operation	01:00h às 02:59h / 16:00h às 16:59h / 19:00h às 19h59	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 12. Comparison of heat pumps operation loads in the full storage system

Full Storage System						
BC EW-HT 0412	**January Profile**			**May Profile**		
	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%	10 595,5	83,7	931,5	9 243,5	83,7	931,5
90%	9 455,9	83,7	933,0	7 158,6	83,7	995,2
80%	9 565,9	117,7	938,4	7 900,7	117,7	938,4
70%	7 282,9	15,9	919,6	6 240,3	15,9	919,6
60%	9 565,9	83,7	936,0	9 565,9	83,7	936,0

Table 13. Heat pumps operation regime in the full storage system

HP Operation Regime		
Profile	**January**	**May**
Load	**70%**	**70%**
0 HP in operation	04:00h às 04:59h / 08:00h às 08:59h / 12:00h às 12:59h / 00:00h às 00:59h	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
1 HP in operation	19:00h às 19:59h / 23:00h às 23:59h	-
2 HP 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	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

Before using the EW-HT 0412 HP, the use of the EW-HT 0302 HP 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.

- Diesel Generators

In relation to DG, the use of the three generator models (P400-3, P250-5 and P110-3) without Electric Energy Storage System (EESS) was initially studied. The goal of this study, was to know which loads the generators provide a lesser consumption of fuel. After the calculations, it was found that all models of the DG studied, have a lower fuel consumption when they are operating at 100%, so this was the load used. The model of the DG used was the P400-3. This choice was based on the lower consumption of fuel per day, and the smaller number of DG used when compared to other models. Then, fuel consumption was calculated again, but now with the use of EESS.

The results obtained (Tables 16 and 18 for both Storage Systems) show that the implementation of EESS allows to reduce the consumption of daily fuel, in both profiles and systems. Table 17 and Table 19 represent the DG operation regime for Partial Storage System and Full Storage System, respectively.

Table 14. Partial storage system with EESS

Partial Storage System							
Profile	**Storage**	**Daily Electric Energy Produced [kWh]**	**Max. Nº of DG**	**Daily Electric Energy Wasted [kWh]**	**Daily Fuel Consumption [l]**	**Fuel cost per day [€/dia]**	**Storage Capacity of EESS [kWh]**
January	Without EESS	21 000,0	4	3 292,7	5 201,2	5 320,8	-
	With EESS	18 200,0	4	492,7	4 507,8	4 611,5	266,7
May	Without EESS	20 160,0	3	2 514,9	5 000,4	5 115,4	-
	With EESS	18 200,0	3	554,9	4 514,6	4 618,4	260,5

Table 15. Diesel generators operation regime in the partial storage system

DG Operation Regime		
Profile	**January**	**May**
Load	**100%**	**100%**
2 DG 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	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 DG 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	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
4 DG in operation	16:00h às 16:59h	-

Table 16. Full storage system with EESS

Full Storage System							
Profile	**Storage**	**Daily Electric Energy Produced [kWh]**	**Max. Nº of DG**	**Daily Electric Energy Wasted [kWh]**	**Daily Fuel Consumption [l]**	**Fuel cost per day [€/dia]**	**Storage Capacity of EESS [kWh]**
January	Without EESS	19 880,0	3	2 367,9	4 922,8	5 036,0	-
	With EESS	18 200,0	3	687,9	4 507,7	4 611,3	272,25
May	Without EESS	19 880,0	3	2 107,8	4 931,2	5 044,6	-
	With EESS	18 200,0	3	427,8	4 515,2	4 619,1	272,61

Table 17. Diesel generators operation regime in the full storage system

DG Operation Regime		
Profile	**January**	**May**
Load	**100%**	**100%**
1 DG in operation	-	00:00h às 00:59h
2 DG 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	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 DG 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	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

3.1.2 Trigeneration System

When implementing the Trigeneration System, it was found that it is possible to not use any HP. All DHW needs are met, by recover the heat released in the cooling circuit of the various engines.

To be possible not to use HP, it is necessary that the system has the operating regime presented in Tables 18-20.

Table 18. Compression chillers operation regime in the trigeneration system

CC Operation Regime		
Profile	**January**	**May**
Load	**100%**	**100%**
0 CC in operation	04:00h às 05:59h / 09:00h às 09:59h / 23:00h às 23:59h	04:00h às 04:59h / 09:00h às 09:59h / 20:00h às 20:59h
1 CC in operation	06:00h às 08:59h / 10:00h às 15:59h / 17:00h às 22:59h / 00:00h às 00:59h	08:00h às 08:59h / 16:00h às 17:59h / 23:00h às 23:59h
2 CC in operation	01:00h às 03:59h / 16:00h às 16:59h	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

Table 19. Diesel generators operation regime in the trigeneration system

DG Operation Regime		
Profile	**January**	**May**
Load	**100%**	**100%**
1 DG in operation	05:00h às 05:59h / 10:00h às 10:59h / 00:00h às 00:59h	05:00h às 05:59h / 11:00h às 11:59h
2 DG 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	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 DG 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	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 DG in operation	19:00h às 20:59h	09:00h às 09:59h / 20:00h às 20:59h

Table 20. Absorption chillers operation regime in the trigeneration system

Absorption Chillers Operation Regime		
Profile	**January**	**May**
Load	**100%**	**100%**
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	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 23.

Table 21. 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]	4 507,7	4 515,2	4 507,8	4 514,6	4 230,9	4 167,6
Fuel Reduction with the use of the Trigeneration System [%]	6,14	7,70	6,14	7,69	-	
Min. DHW Deposit Capacity [l]	7 282,9	6 240,3	8 896,1	6 564,7	3 969,8	2 894,7
Min. TESS Capacity of Cold Water [l]	346 252,2	365 804,0	301 353,1	365 804,0	424 292,7	357 486,2
Min. EESS Capacity [kWh]	272,3	272,6	266,7	260,5	963,3	811,1
Min. Cooling Tower Capacity for the CC [kW]	953,1	1 092,1	1 340,4	1 092,1	1 386,6	1 325,2
Min. Cooling Tower Capacity for the Absorption Chiller [kW]	-				603,0	603,0

3.1.3 Used Equipment

All equipment applied to the three systems are shown in Table 24. This table lists the companies consulted, the price of each equipment and the number of equipment used in each system.

Table 22. Mark/Model/Quantity of equipment used

Equipments		Mark and Model	Nº of Equip (Partial/Full/ Trigeneration)	Price by unit [€]
Steam CC		Mitsubishi Electric NECS/R/CA 1816	2/2/2	75 006,0
Cold Water TESS		-	1 (400 m3)/ 1 (400 m3)/1 (500 m3)	120 000 (400 m3) 130 000 (500 m3)
Absorption Chiller		Carrier 16LJ-A11	0/0/1	100 000,0
HP		Mitsubishi Eletric EW – HT/0412	2/2/0	13 636,0
DHW deposits	4000 L Deposit	Reflex Winkelman HF4000/R	0/2/2	2 525,0
	4000 L Deposit insulation	-	0/2/2	1 460,0
	5000 L Deposit	Reflex Winkelman HF5000/R	2/0/0	3 285,0
	5000 L Deposit insulation	-	2/0/0	1 593,0
Plate Exchanger: Grid Water - High Temperature Water Circuit		Reflex Winkelmann RLB-110-120	2/2/0	2 188,0

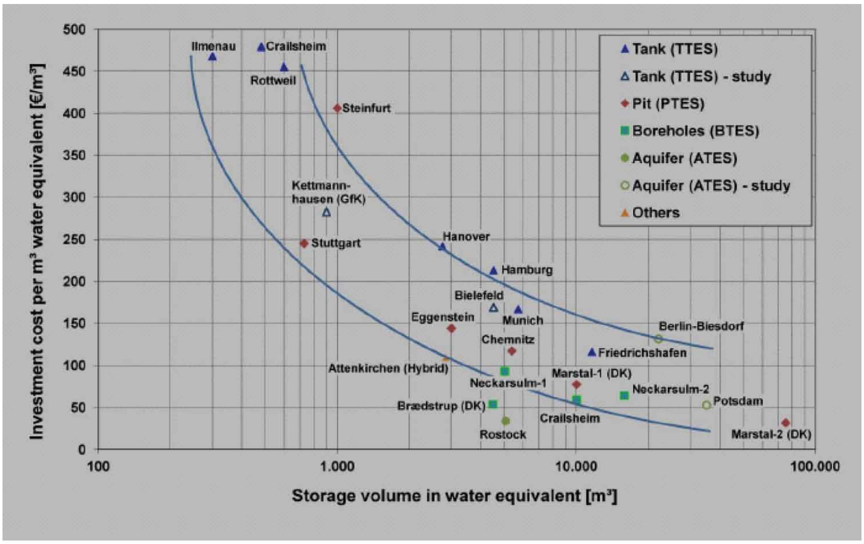
Table 22 continued on next page

Table 22 continued

Equipments	Mark and Model	Nº of Equip (Partial/Full/ Trigeneration)	Price by unit [€]
Plate Exchanger: Grid Water - Engine Cooling Water Circuit	Reflex Winkelmann RMB-31-60	0/0/4	450,0
DG	FG Wilson P400-3	4/3/4	37 950,0
Electric Energy Storage System (300 kVA/ 355 kWh)	Rolls-Royce MTU Energy Packs QS	1/1/3	142 000,0
Cooling Tower (Steam CC)	Baltimore Aircoil Company FXVS 0809B-24T-K/P	1/1/1	44 209,0
Cooling Tower (Absorption Chiller)	Baltimore Aircoil Company FXVS 1212C-24D-O/X	0/0/1	72 299,0
Shell & Tube exchanger: Exhaust Gases - Water Circuit that drives the Absorption Chiller	-	0/0/1	8 253,1

Regarding TESS and the Shell & Tube heat exchanger, it was not possible to contact manufacturers of this equipments. 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 2009, 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 (2016).

Figure 7. Estimated TESS investment



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 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 25.

Table 23. Minimum conditions of shell and tube heat exchanger

Parameters	Exchanger for activating the absorption chiller
Minimum flow that has to pass through the exchanger [m3/h]	2,70
Minimum heat transfer area of the exchanger [m2]	4,65

3.2 Economic Evaluation of the Project

3.2.1 Efficiency and Fuel Consumption

The efficiency (Table 26) and fuel consumption (Table 27) 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 24. 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

Table 25. 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

3.2.2 Costs and Behaviours of Investments

- **Associated Costs:** For the economic parameters analysis, all associated costs were considered that were obtained in several ways:
    - **Equipments Costs:** Obtained by contacting the various companies for each equipment used.
    - **Chillers and HP Accessories Costs:** Considered 20% of the main equipment costs (Chillers and HP).

- **DG Accessories Costs:** Information retired from the Sustainable Energy Handbook (700 USD/kW installed ~ 591.88 €/kW installed) (Pirolli 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 27) and the cost of fuel per liter in Singapore (1,023 €/l - value from 14 December 2020) (Valev 2020).
- **Equipments Maintenance Costs:** Considered 0,015 €/kWh for DG and through article (C.Biserni 2019), 0,006 €/kWh - Steam CC, 0,010 €/kWh - HP 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 28. 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 Baseline scenario Systems, are also shown in Table 28.

Table 26. Associated costs for all systems

Costs	Partial Storage System	Full Storage System	Trigeneration System
Equipments [€]	649 425,0	609 689,0	1 092 343,1
DG Accessories [€]	662 900,2	497 175,2	662 900,2
CC Acessories [€]	30 002,4	30 002,4	30 002,4
HP Acessories [€]	5 454,4	5 454,4	0,0
Absorption Chillers Acessories [€]	0,0	0,0	20 000,0
Fuel [€/year]	1 689 295,1	1 689 413,4	1 570 187,6
Equipments Maintenence [€/year]	124 944,5	126 052,3	97 037,2
Employees [€/year]	60 000,0	60 000,0	60 000,0
Total Costs (wihtout Equipments and Acessories) [€/year]	1 874 239,6	1 875 465,7	1 727 224,8
Additional investment in equipments of the Trigeneration System in relation to Baseline scenario Systems [€]	457 463,7	662 924,7	-
Cost Reduction with the use of Trigeneration System instead of Baseline scenario Systems [€/year]	147 014,7	148 240,9	-

From all the costs associated with each system, it was possible to calculate the economic parameters of the investment made. Table 29 shows the values obtained for NPV, IRR and IRP, in relation to both Baseline scenario Systems.

Table 27. 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

4. DISCUSSION, LIMITATIONS AND FUTURE WORK

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 Baseline scenario 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 Baseline scenario 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 equipments, 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 Baseline scenario System. Regarding the hot water deposits used in the Trigeneration System, these are similar to those of the Full Storage 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 Baseline Scenario 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, 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 Baseline scenario 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 Storage 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 Storage 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 Storage 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 DG, 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.
- The insertion of renewable energies affects the systems and the conclusions are based on a study carried out on a tropical island. With other climates, the results would be expected to be different, namely the reduction of solar PV and thermal contribution and the increase of wind and biomass renewables energies.
- Solar thermal collectors are a special kind of heat exchangers that convert solar radiation into thermal energy through a transport medium or a heat transfer fluid (HTF). The positive effect can solar collectors have to produce DHW are in the reduction of primary energy consumption and lower capacity investments.
- On-site trigeneration plants are much more efficient, economically sound, and environmentally friendly than typical central power plants. Because of this, customers' energy expenses are significantly lower, and the associated pollution is also much less than if the customer had an energy system supplied with electricity from the grid, along with water heaters and boiler systems on-site. Trigeneration's superior efficiencies surpass even the latest state-of-the-art combined cycle cogeneration power plants by up to 50 percent. Coupled with a four-pipe system, hot water/steam and chilled water can be produced simultaneously for circulation throughout the building or campus (which would be referred to as a district energy system).
- Size is not an impediment, since trigeneration systems can even be installed in small commercial settings, restaurants, hotels, schools, office buildings, and shopping centers, and not only for large plants.

4.1 Abbreviations

CC Compression Chiller(s)
CCHP Combined Cooling, Heat and Power
CHP Combined Heat and Power
COP Coefficient of Performance
DBT Dry Bulb Temperature
DEEP Daily Electric Energy Produced
DEPF Daily Energy Provided by Fuel
DG Diesel Generator(s)
DHW Domestic Hot Water
DTEP Daily Thermal Energy Produced
EESS Electric Energy Storage System
HP Heat Pump(s)
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

4.2 Symbols

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

REFERENCES

Baghernejad, A. (2016) Exergoeconomic optimization and environmental analysis of a novel solar-trigeneration system for heating, cooling and power production purpose. 1

Bellos, E., & Tzivanidis, C. (2020). Concentrating solar collectors for a trigeneration system-A comparative study. *Applied Sciences*, *10*(13). 10.3390/app10134492

Biserni, C. (2019) Optimum sizing of cogeneration plants by means of a genetic algorithm optimization: A case study. 7

Cannistraro, G., Cannistraro, M., Cannistraro, A., Galvagno, A., & Trovato, G. (2016). Technical and economic evaluations about the integration of co-Trigeneration systems in the dairy industry. *International Journal of Heat and Technology*, *34(*2), S332 – S336. 10.18280/ijht.34S220

Chen, G. Q. (2018) *Energy use in world economy from household-consumption-based perspective*. 1

Chitsaz, A., Hosseinpour, J., & Assadi, M. (2017). Effect of recycling on the thermodynamic and thermoeconomic performances of SOFC based on trigeneration systems; A comparative study. *Energy*, *124*, 613–624. https://doi.org/10.1016/j.energy.2017.02.019

Chua, K. J. (2013) *Sustainable energy systems for a remote island community*. 3-4

Chua, K. J., Yang, W. M., Er, S. S., & Ho, C. A. (2014). Sustainable energy systems for a remote island community. *Applied Energy*, *113*, 1752–1763.

Doty, S., & Turner, W. C. (2010). Energy Management Handbook. Capitulo 19 - Thermal Energy Storage. I. *The Fairmont Press*, *485*, 486.

Feidt, M., et al. (2017) *Cogeneration/Trigeneration*. 2-3

ECTP(2016Guideline for Seasonal Thermal Energy Storage Systems in the Built Environment. 8;43. Solites.

Jamaluddin, K., Wan Alwi, S. R., Hamzah, K., & Klemeš, J. J. (2020). A numerical pinch analysis methodology for optimal sizing of a centralized trigeneration system with variable energy demands. *Energies*, *13*(8). https://doi.org/10.3390/en

Jradi, M., & Riffat, S. B. (2019). Performance Analysis of an Innovative ORC-based Micro-scale CCHP System under Lebanese Conditions. *International Journal of Thermodynamics*, *22*(2), 96–103. https://doi.org/10.5541/ijot.494481

Karim, M. A. (2009) Performance Evaluation of A Stratified Chilled - Water Thermal Storage System. 3, 1

Lin, C.-S. (2008). Capture of Heat Energy from Diesel Engine Exhaust, Institute of Northern Engineering, 18-20.

Murat Emre Demir, M. Emre Demir, & Ibrahim Dincer, I. Dincer. (2021). Development and assessment of a solar driven trigeneration system with storage for electricity, ammonia and fresh water production. *Energy conversion and management*, 245, 114585. doi: 10.1016/j.enconman.2021.114585.

Pirolli, M. (2016). *Sustainable Energy Handbook: 13 of Module 16.11*. Simplified Financial Models.

Polyzakis, A. (2010). Economic evaluation of an energy investement based on trigeneration technology [Doctoral dissertation]. Πανεπιστήμιο Μακεδονίας Οικονομικών και Κοινωνικών Επιστημών.

Shirazi, A. (2018) Solar-powered absorption chillers: A comprehensive and critical review. 4 timeanddate. https://www.timeanddate.com/weather/@1880162/historic

Tzivanidis, C., & Bellos, E. (2020). A comparative study of solar-driven trigeneration systems for the building sector. *Energies*, *13*(8). https://doi.org/10.3390/en13082074

Uche, J., Muzás, A., Acevedo, L. E., Usón, S., Martínez, A., & Bayod, A. A. (2020). Experimental tests to validate the simulation model of a Domestic Trigeneration Scheme with hybrid RESs and Desalting Techniques. Renewable Energy, *155*, 407-419. https://www.globalpetrolprices.com/Singapore/diesel_prices/

Wang, R. (2006) Combined cooling, heating and power: a review. 12

Nuno A. S. Domingues, Pós Doc in Science Communication from FCSH-UNL (2021), Pós Doc in Electrical Engineering and Computer Science from IST (2020), PhD in Electrical Engineering and Computer Science from FCT-UNL (2015), Master in Electrical Engineering and Computer Science from IST (2008), Undergraduate (5-year) degree in Electrical Engineering from ISEL (2005). His topics of research include electricity markets modelling and simulation, energy systems, SCADA and DSS, decision making, intelligent optimization, evolutionary algorithms, machine learning, sustainability, efficiency, clean technologies, mobility and transport, sustainable consumption, e-learning, science communication, education and regulation. He is a Professor in ISEL. Among other certifications, he has the diploma on Problem Based Learning and Excelence on Teaching and Learning by UNESCO. https://publons.com/researcher/1176435/nuno-domingues/metrics/https://www.isel.pt/docentes/nuno-alexandre-soares-domingues https://scholar.google.pt/citations?user=-mtxKk8AAAAJ&hl=pt-PT https://www.linkedin.com/in/nuno-domingues-a1401916/https://orcid.org/0000-0003-0763-8106

Jorge Mendonça e Costa is Executive Director at the Portuguese Association for Industrial High Electrical Energy Consumers (APIGCEE) and is presently Coordinating Professor at the Mechanical Engineering Department (ADEM) of Instituto Superior de Engenharia de Lisboa (ISEL).