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Water saving in electric power generation facilities using the hygroscopic cycle in the subtropical climate

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Abstract:

The sustainability of the electric power generation system worldwide is undoubtedly one of the main challenges of our era. This will be achieved through the massive incorporation of renewable energy sources, but also using highly efficient non-renewable sources. These latest technologies are still necessary today to guarantee the supply of electricity. To optimize its operation in a sustainable way, it is required to minimize both the consumption of primary energy and the water necessary for cooling. In this work, the Hygroscopic Cycle Technology is presented as an alternative to traditional thermal cycles and that allowing to minimize the use of water in refrigeration processes. Thus, assuming the incorporation of this technology to existing thermal power plants in the Canary Islands, cooling water savings were calculated. In this way, the total savings achieved in this subtropical climate amounted to 1.6 Mm^3 annually. A very high value that reinforces the interest of this technological improvement in the thermal processes of thermoelectric plants avoiding the consumption of water.

Keywords:

Hygroscopic Cycle Technology; Energy; Savings in Water Consumption; Sustainability; Thermodynamic Cycles.

1. Introduction

The interest in the use of renewable energies as sources of electricity generation has been strongly increased in recent years. The policies against climate change [1,2] agreed by the main producing and consuming countries of energy, as well as the increase in the price of these raw materials have been decisive. However, electricity production with these "clean" sources has not yet succeeded in displacing traditional energy production using fossil fuels such as coal or gas. Furthermore, in developing countries the use of these traditional energy sources has increased significantly in recent years. According to the Global Electricity Review 2022 [3], the world supply of energy through "clean" sources reached 38%, but nevertheless, there was an unprecedented growth in the level of polluting emissions linked to electricity generation and the energy production with coal. Therefore, the need to improve the efficiency of processes and reduce the environmental impact of power generation with non-renewable sources is paramount. In this direction, the investigations presented in this article are directed and that present an improvement of the thermal cycles used in thermoelectric plants fed with hydrocarbons or coal. The Rankine cycle (RC) used in these plants operates with steam, and despite being a mature technology, due to its wide and extensive use in various industrial processes over time, it still has an improvement rate in its performance. Because of its widespread use, the improvement in efficiency derived from RC constitutes an important global impact in the improvement of energy production processes and in the reduction of related polluting emissions, and also, in the economic viability or increased financial profitability of power plants that use it [4]. In Figure 1 [5], an RC used in thermoelectric installations is represented.

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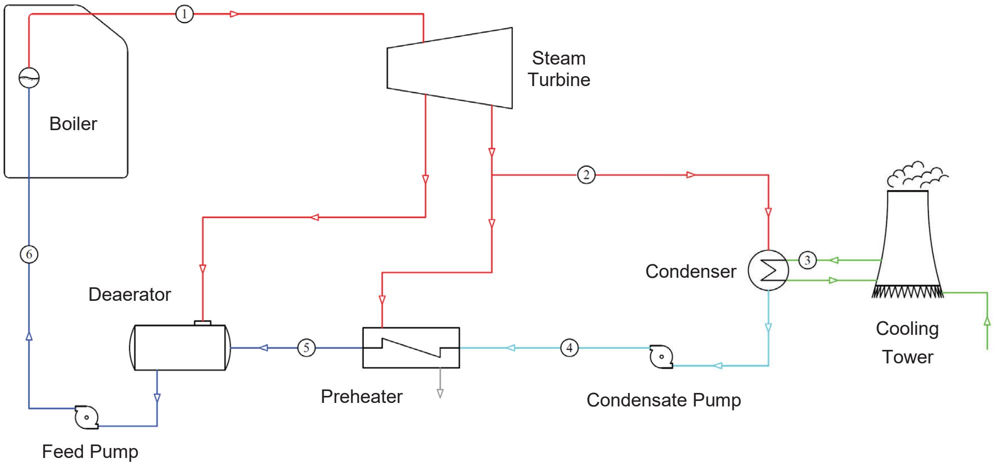

Figure. 1. Diagram of the Rankine Cycle in a thermoelectric power plant.

In this line of cycle improvement [6,7], recent research has focused on reducing irreversibilities and their associated losses, proposing improvements in supercritical, regenerative, superheated, and binary steam cycles. In addition to trying to maintain the quality of the steam above 90% at the outlet of the steam turbine and avoid the entry of steam into the process pumps. Other lines of research have worked on improving efficiency, substituting the pure water used in the cycle with other fluids entering the turbine. Thus, the Organic Rankine Cycle (ORC) appeared [8], which shares its configuration with the traditional RC but is designed to generate work with low-energy heat, with temperatures between 80 and 400 ºC. The ORC [9] uses so-called pure organic fluids, which can be different types of refrigerants and organic compounds. The use of "dry" fluids avoids the need to overheat the steam [10], as is done in the Rankine Cycle Technology (RCT), making the working temperatures and evaporation pressures much lower and increasing the efficiency of the cycle.

Zeotropic mixtures or fluids with different boiling points have also been used in the ORC, but to a lesser extent. The investigations [11,12] carried out comparing the efficiency obtained in the cycle with the use of zeotropic mixtures or dry fluids, have concluded that the use of the former only presents improvements in the efficiency of the process when the operating circumstances are very specific, for example, when the Cooling of water is done at fixed temperatures. However, its use may be interesting based on the growing concern for the environment. An interesting case of zeotropic mixtures is the one formed by ammonia and water and used in the so-called Kalina cycle (KC). This KC presents greater freedom in terms of the composition of the mixture, but its configuration is more complex. However, it is an important alternative [13] to pure ORC due to the use of low heat sources and achieves higher efficiency values due in part to its lower level of irreversibilities. On the other hand [14-18], it also presents limiting factors such as the optimization of the process, the working fluid and the heat sources.

Other cycles [19] that take advantage of the energy from low-medium heat sources are the Goswami cycles (GC), which use binary mixtures. In addition [20], they incorporate mixtures of ammonia and water as a fluid, combined with a RC and an absorption cycle (AC). Other investigations [21] carried out with different zootropic mixtures and working conditions of the RC, have achieved improvements of up to 15% in the performance of the ORC.

Additionally [22], it should be borne in mind the fact that environmental conditions significantly influence the viability of the different types of thermodynamic cycle. From this point of view, the situations of scarcity of water used both in the power generation and cooling processes of the last stages of the cycle, together with high ambient temperatures, can make the application of thermodynamic cycles impossible. This situation of rising temperatures and water scarcity is being aggravated by the current situation caused by climate change. Therefore [23], power generation must be carried out with the least possible use of water, since worldwide electricity generation consumes 10% of the available water, mainly in its cooling stage.

Thus, the so-called Hygroscopic Cycle Technology (HCT) [7,24] arises as an improvement to the traditional thermoelectric generation cycles, improving the thermal efficiency of the cycle, reducing the consumption of cooling water and enabling the implementation of thermal cycles in areas that, due to their high ambient temperatures would make electricity generation very difficult or impossible. In Figure 2 [5], the HCT, which is based on a RC but incorporating improvements in the refrigeration zone to use absorption physicochemical processes, is represented.

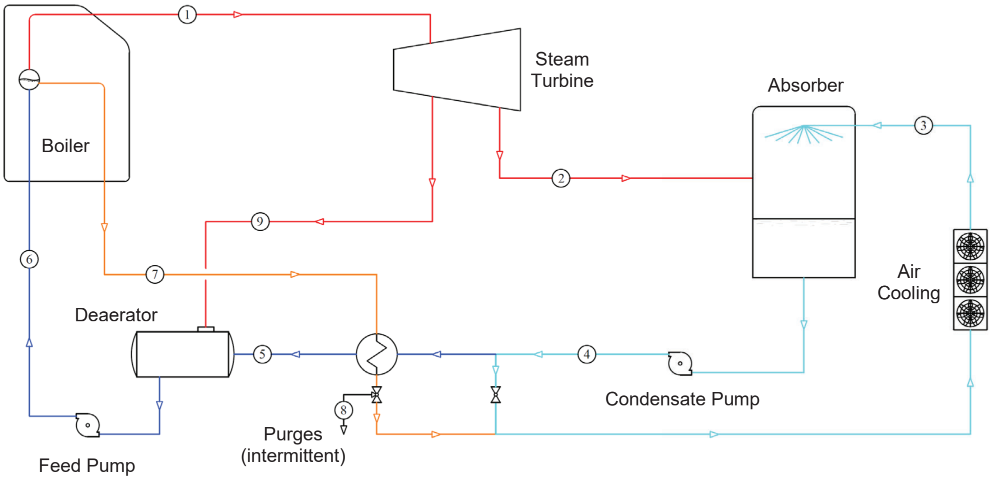

Figure. 2. Diagram of the Hygroscopic Cycle Technology in a thermoelectric power plant.

The HCT [25] uses hygroscopic compounds as part of the working fluids to optimize steam condensation at the turbine outlet through absorption processes. The hygroscopic substances [26] used must meet a series of characteristics to be used in the HCT. They must be non-flammable, have a lower vapor pressure than pure water and therefore less volatile than water, attract surrounding water vapor, and be easily separable to facilitate subsequent vapor desorption (reversible retention). In addition, these substances must be non-toxic and chemically stable under the working conditions of the HCT. The mixtures proposed by [27] consisted of LiBr-H2O as a suitable working fluid for the HCT. This hygroscopic and soluble salt in all stages of the HCT allowed to achieve the best results in the cycle. LiBr [28] increased its solubility considerably with increasing solution temperature. Additionally [26], the separation of the vapor and the hygroscopic compound did not require the use of special desorption technology or additional heat sources. The HCT [29] has already been successfully used in real installations with generated powers between 12.5 MW and 50 MW.

The direct steam condensation process is achieved in the HCT inside the absorber where the pure steam exhaust stream from the turbine (state 2 in Figure 1) is mixed with a solution of hygroscopic compounds in water (state 3 in Figure 1). The improvements [7,30] achieved by this direct condensation are the following:

- Due to the lower condensing pressure necessary at each cooling temperature, the electrical power at the turbine outlet is increased with reference to RC and therefore the general electrical performance of the cycle.
- For a given condensing pressure, the condensing temperature and therefore the cooling temperature are increased. In this way [31], a thermal dissipation of the condensation energy is possible only with air and therefore without the need for the use of water. By not using traditional water-cooling processes in cooling towers, the use of water is avoided and savings are made in cooling tower maintenance.
- At the same time, since the use of cooling water is not necessary, it allows the generation of energy with thermoelectric processes in areas with little water availability.
- Less demand for electrical energy [32] by the cooling system, made up of dry-coolers, since the increase in condensation temperature requires less dissipated thermal energy.

With all these features, the HCT allows improving the traditional RC and increasing electrical efficiency by approximately 2.5%, saving up to 50% in the consumption of demineralized water and additives, reducing investment costs by 5% and 25 % the costs of Operation and Maintenance (O&M) and increase the availability of the technology and its useful life [6]. These characteristics and improvements achieved with HCT technology are of special interest in areas with subtropical climates and possible water scarcity, as is the case in certain areas of the Canary Islands. It must be taken into account that in the Canary Islands the aquifers have been over-exploited, which is why the water table has dropped. As a result [33-36], numerous springs have dried up, wells and galleries have had to be deepened, and the danger of desertification has increased.

Currently [37], the Canary Islands are highly dependent on fossil fuels. According to data from the energy yearbook of the Canary Islands for the year 2021, renewable energies only represent 19.5% of electricity production. The energy is obtained in hundreds of units distributed in gas-fired power plants, diesel engines or steam turbines. Figure 3 shows the dispersion of plants along the islands.

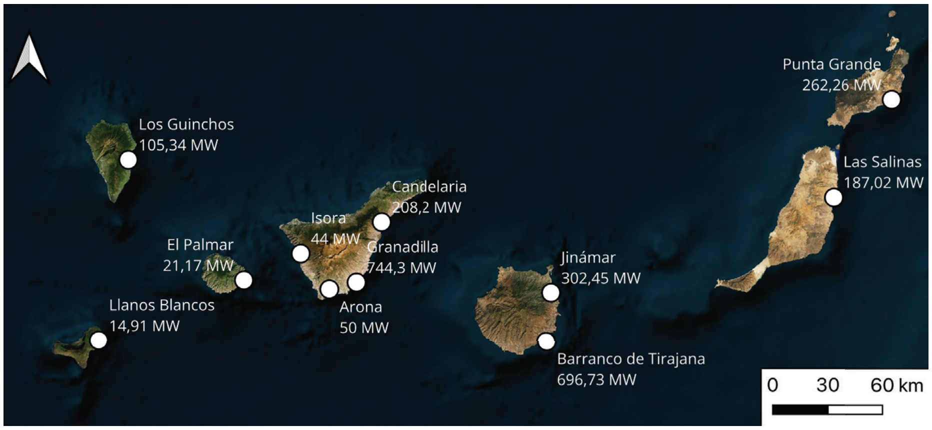

Figure 3. Thermoelectrical power plants and installed capacity in the Canary Islands.

Additionally, a detailed list of these Canarian thermoelectric plants ordered by island with their group type, cooling system, number of units and their power capacity can be found in Table 1.

Table 1. The Canarian thermoelectric plants.

Island	Power Plant	Group Type	Cooling System	Units	Power Capacity (MW)
El Hierro	Llanos Blancos	Diesel	Close cycle desalinated water	10	14.91
Fuerteventura	Las Salinas	Diesel	Open cycle seawater	9	107.92
	Las Salinas	Gas	Adiabatic cooling	3	79.1
Gran Canaria	Jinámar	Diesel	Open cycle seawater	5	84
	Jinámar	Gas	Adiabatic cooling	3	98.45
	Barranco Tirajana	Gas	Adiabatic cooling	6	376
	Jinámar	Steam	Open cycle seawater	2	120
	Barranco Tirajana	Steam	Open cycle seawater	4	320.73
La Gomera	El Palmar	Diesel	Open cycle seawater	6	13.38
	El Palmar	Diesel	Adiabatic cooling	3	7.79
La Palma	Los Guinchos	Diesel	Open cycle seawater	10	82.84
	Los Guinchos	Gas	Adiabatic cooling	1	22.5
Lanzarote	Punta Grande	Diesel	Open cycle seawater	11	199.76
	Punta Grande	Gas	Adiabatic cooling	2	62.5
Tenerife	Candelaria	Diesel	Open cycle seawater	3	36
	Granadilla	Diesel	Open cycle seawater	2	48
	Candelaria	Gas	Adiabatic cooling	3	92.2
	Granadilla	Gas	Adiabatic cooling	6	382.9
	Arona	Gas	Adiabatic cooling	2	50
	Isora	Gas	Adiabatic cooling	1	44
	Candelaria	Steam	Open cycle seawater	2	80
	Granadilla	Steam	Open cycle seawater	4	313.4

For all these reasons, in the present investigation the implementation of HCT in the existing thermoelectric plants and in operation in the different Canary Islands is simulated in order to obtain the potential of water savings for each installation. The application of the HCT is assessed according to the characteristics of each thermal power plant and the specific hydrological needs of the different island areas. All of this would translate into significant environmental savings and would allow the consideration of the use of HCT in areas where the viability of traditional thermoelectric cycles is not feasible or not convenient due to water scarcity.

2. Methodology

The methodology used to calculate the savings obtained with the application of the HCT in the Canary Islands thermoelectric plants consisted of:

1º.The refrigeration system data [38] and the power of the different units were obtained from the environmental declaration of each power generation plant and from the State Registry of Emissions and Polluting Sources [39]. It was also necessary to know the equivalent operating hours. These hours were calculated from the annual production data for each type of plant and island, which are included in the 2021 Canary Islands energy yearbook [37]. These data are shown in Table 2.

Table 2. Equivalent hours and annual production of the Canary thermoelectric plants.

Island	Power Plant	Group Type	Power Capacity (MW)	Annual production (MWh)	Equivalent hours (h)
El Hierro	Llanos Blancos	Diesel	14.91	26 133	1 752.7
Fuerteventura	Las Salinas	Diesel	107.92	477 165	4 421.5
	Las Salinas	Gas	79.1	31.563	399
Gran Canaria	Jinámar	Diesel	84	199 206	2 371.5
	Jinámar	Gas	474.45	1 814 728	3 824.9
	Barranco Tirajana	Gas			
	Jinámar	Steam	440.73	647 519	1 469.2
	Barranco Tirajana	Steam			
La Gomera	El Palmar	Diesel	21.17	71 022	3 354.8
	El Palmar	Diesel			
La Palma	Los Guinchos	Diesel	82.84	238 590	2 880.1
	Los Guinchos	Gas	22.5	499	22.2
Lanzarote	Punta Grande	Diesel	199.76	632 746	3 167.5
	Punta Grande	Gas	62.5	12 581	201.3
Tenerife	Candelaria	Diesel	84	177 029	2 107.5
	Granadilla	Diesel			
	Candelaria	Gas	569.1	1 905 502	3 348.3
	Granadilla	Gas			
	Arona	Gas			
	Isora	Gas			
	Candelaria	Steam	393.4	595 497	1 513.7
	Granadilla	Steam			

2º. In order to obtain the performance of power plants, research developed by [40-43] were considered. In this way, the performances were 34% for the groups with steam, 38% for the groups with gas and 45% for the groups with diesel.

3º. The heat that would have to be dissipated by the cooling system of each plant was obtained by applying equations (1) and (2).

$$\dot{Q}_C = \frac{\dot{W}}{\eta} \quad (1)$$

$$\dot{Q}_F = \dot{Q}_C - \dot{W} \quad (2)$$

Being:

$\dot{Q}_C$: thermal power supplied to the cycle of the plant.

$\dot{Q}_F$: heat rejected by thermal cycle of the plant.

$\dot{W}$: plant power capacity (Table 2).

η: power plant performance. Obtained in previous point 2º.

4º. The necessary water flow for the cooling process was calculated using the following equations and technical data:

$$\dot{Q}_F = \dot{m} \cdot (h_{out} - h_{in}) \tag{3}$$

$$T_{out} = T_{in} + \Delta T \tag{4}$$

Being:

h_{out}: cooling water outlet enthalpy.

h_{in}: cooling water inlet enthalpy.

$\dot{m}$: cooling water mass flow.

T_{in}: cooling water inlet temperature.

T_{out}: cooling water outlet temperature.

ΔT: Temperature difference of the cooling water between the inlet and outlet of the adiabatic cooling equipment. A value of 14 ºC has been taken according to the common industrial values [6].

4º According to [45-46], for processes with open cycle the average consumption of water in thermal power plants such as existing in the Canary Islands (Gas, Diesel or Steam group type) is 0.38 m^3/MWh.

3. Results and conclusions

In this way, the current annual water needs or cooling water consumption (m^3/year) per MWh of each thermoelectric plant in the Canary Islands were obtained and represented in Table 3. For processes with adiabatic coolers, it has been considered that the water consumption was 0.1 percent of the water used in the cooling system [47].

Table 3. Annual water consumption for the cooling system in thermoelectric plants from the Canary Islands.

Island	Power Plant	Water Consumption for the Cooling System (m^3/h)	Equivalent hours (h/year)	Annual Water Consumption for the Cooling System (m^3/year)
El Hierro	Llanos Blancos	5.67	1 752.7	9 930.45
Fuerteventura	Las Salinas	41	4 421.5	181 323.95
	Las Salinas	7.94	399	3 167.78
Gran Canaria	Jinámar	31.92	2 371.5	75 698.28
	Jinámar Barranco Tirajana	47.62	3 824.9	182 144.81
	Jinámar	45.60	1 469.2	246 057.80
	Barranco Tirajana	121.88		
La Gomera	El Palmar	5.08	3 354.8	19 022.10
	El Palmar	0.59		
La Palma	Los Guinchos	31.48	2 880.1	90 663.24
	Los Guinchos	2.26	22.2	50.14
Lanzarote	Punta Grande	75.91	3 167.5	240 441.12
	Punta Grande	6.27	201.3	1 262.79
Tenerife	Candelaria	13.68	2 107.5	127 883.10
	Granadilla	18.24		
	Candelaria Granadilla Arona Isora	57.12	3 348.3	191 257.83
	Candelaria	30.4	1 513.7	226 286.04
	Granadilla	119.1		

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Therefore, the minimum potential for savings in water consumption by refrigeration systems would be 1.6 Mm^3 per year. It means that the average minimum water consumption is 0.23 m^3/MWh in thermoelectric plants of the Canary Islands.

All this use of water can be avoided by using the HCT. In this way, the environmental problems associated with the consumption of water for industrial processes or returning water at high temperatures to ecosystems that can be seriously affected, as occurs in open refrigeration systems, would be avoided.

Currently, the total energy generation of the thermoelectric plants of the Canary Islands is 6 829 780 MWh/year. The efficiency is increased by 2.35% when HCT is used instead of traditional Rankine cycle [6]. Therefore, the increment of the total energy generation would be of 160 499.80 MWh/year. In addition to the increase in the efficiency, the application of HCT technology would reduce the costs associated with the maintenance of the cooling systems existing in the current thermoelectric plants in the Canary Islands. On the other hand, the reduction of installation costs would also have been achieved in the new built systems. This economic improvement would reduce the price of energy associated with its generation. Definitely, in the current economic context of high electricity prices it would be very interesting from both a social and a business point of view.

As future work, it is proposed to analyse the economic cost of the incorporation of the HCT in the different plants of the Canary Islands as well as the necessary time to recover the investment.

Nomenclature

$\dot{Q}_C$	heat supplied to the thermal cycle of the plant, kW
$\dot{Q}_F$	heat rejected by thermal cycle of the plant, kW
$\dot{W}$	plant power capacity, kW
h_{out}	cooling water outlet enthalpy, kJ/kg
h_{in}	cooling water inlet enthalpy, kJ/kg
$\dot{m}$	cooling water mass flow, kg/s
T_{in}	cooling water inlet temperature, ºC
T_{out}	cooling water outlet temperature, ºC
ΔT	temperature difference of the cooling water in the dry-cooler, ºC
Greek symbols	
η	power plant performance.

Acknowledgments

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