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Waste heat recovery from ship diesel generators for water-energy dual purpose plants

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ABSTRACT

Although, the recent efforts in the field of sustainable shipping, the energy efficiency is still limited at a half of the fuel calorific value, whereas the spare input energy is discharged in the environment as exhausted gas and jacket water. It is possible to increase the overall engine efficiency virtually up to 80% by introducing a Combined Rankine cycle to recover the enthalpy of the exhausted gases, and Multi-Stage Flash (MSF) or Multiple-Effect Distillation (MED) to recover the waste heat from the hot temperature cooling water system. In this paper we propose the process analysis of dual purpose plants for the on-ship desalination and compare different alternatives with respect to the process energy duty. In the proposed solution, an additional 1–2 MW of electrical power and around 1,400 m^3/d of freshwater can be produced by recovering the waste heat of a 19 MW diesel engine (at 85% load). MSF allows to recover a higher percentage of waste heat, highly increasing the HTW efficiency. On the other hand, when compared to MED, the distillate production by MSF is lower at the same number of stages/effects and, due of the higher quality of the steam, the MSF integration reduces the additional production of electrical energy.

Keywords: Diesel engine; Waste heat; MSF; MED; Process analysis

1. Introduction

It is mandatory to step in the shipping sector to cut CO_2 emissions, since approximately 90% of the world's goods are transported through sea. Currently, most of cargos and cruising passenger ships are equipped with diesel-electric engines. Carbon emissions from the marine sector are increasing day by day and, if no specific policies will be implemented and the patterns of social and economic behaviour will not change, future CO_2 emissions in shipping could increase of 400% by 2050 [1]. Among the primary objectives for the ship-owners there is the fuel consumption reduction (with relative operational costs and CO_2 emissions) in agreement with the regulation framework of the International Maritime Organization (IMO) [1–3]. Following the trend of the higher overall ship efficiency (required since the first oil crisis in 70 s) the efficiency of main engines reaches 50%. The most attractive source of waste from the engine is the exhausted gas, whose heat dissipation accounts for the half of the total waste heat, i.e., about 25% of the total chemical energy of the fuel [1–3]. At the state of the art, it is possible to generate an electrical output of up to the 10% of the main engine power by converting waste heat in steam and/or power turbine cycles and/or by heating the boiler feed-water with scavenge air [4].

On the other hand, a ship sailing in sea requires high quantities of fresh water for civil and industrial duties on ship, which are provided by conventional desalination processes (mainly RO), fed by energy produced on-board.

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Moreover, cruise ships, submarines and military war ships have been using desalination for decades and recently have supplied water in case of humanitarian emergency (i.e., the aircraft carrier U.S.S. Carl Vinson that provided half of its own freshwater of 1,500 m^3/d to aid disaster relief in Haiti) [3].

The most widespread desalination technology is the Reverse Osmosis (RO). Its thermodynamic supremacy derives from separation without change of state, albeit showing reliability issues due to the availability, pretreatment and maintenance, which are virtually absent in distillation and which can be crucial for the on-board applications [5,6]. Availability is reduced by arrests due to mechanical failures and/or the presence of suspended solids in the feed water and biofouling resulting into a fast membrane failure. Hence, accurate pre-treatment and maintenance are required, also because RO systems are also more sensible to water composition, proner to fouling and scaling than a distillation system; therefore, RO typically involves the frequent costly replacement of hardware and consumables [6]. Moreover, the organoleptic quality of water is susceptible to bacterial contamination; to overcome this issue, it necessary to implement additional stages and a strict management in order to avoid bad taste and odour. A continuous maintenance results into a membrane lifetime of the membranes of 3–5 years.

On the other hand, evaporative desalination techniques are more efficient, albeit with higher energy duties, since they exploit a low temperature energy source, which would be of no use for other applications and thus, simply discharged to the environment [4,7]. Furthermore, the thermal desalination normally can be operated by less skilled personnel and require simple standard filtration and dosing with a single anti-scaling agent to avoid scaling formation on the heat transfer surfaces. For all these reasons, thermal distillation is more compatible with on-ship application, in which spare parts, chemicals and skilled personnel must be avoided as much as possible. In the Multi-Stage Flash (MSF) plants, the saline solution circulates while storing the heat of condensation in the form of sensible heat and then expands in one or more stages, at decreasing pressures. The mediation between evaporation and condensation is a typical element of irreversibility in MSF, so it is necessary to operate with high flow rates of saline solution per m^3 of distillate product, the higher the smaller the maximum cycle temperature. In the typical working area of the MSF processes, both in simple crossing (~90°C) and recirculating (~115°C), this ratio varies between 8% and 12% which corresponds on averate to a flow rate of saline solution 10 times the distillate flow. The driving force varies in each stage, affecting both the evaporator surface and the pumping energy, as well as the external input of thermal energy in the brine heater [5,8]. The efficiency supremacy of the MED process depends on the heat transfer mode, since so the driving force is constant across the stages; more, the heat of condensation is directly transformed into the heat of evaporation. The circulating seawater is independent from the maximum temperature of the cycle and is linked exclusively to the degree of vaporization, assumed at the design stage (generally equal to one third) with a related seawater to distilled product equal 3–3.5 (at 70°C, typical of the MED, this ratio would rise to prohibitive values around 25–30 for MSF) [5].

The Forward Osmosis (FO) implementing thermolytic draw solutions can be used for the recovery of waste heat but it is still at the preindustrial development stage [4]. Similar considerations are valid also for the Membrane Distillation (MD) that has not been considered yet for this purpose, although greatly promising at its industrial development stage. Operation temperatures allow for an efficient use of waste-heat streams and the use of polymeric membrane modules reduces the corrosion and the weight of the mechanical parts. Compared with RO, the MD applies when high permeate recovery is required [5,9]. Humidification-dehumidification techniques have not been included in this preliminary feasibility study since, due to the high quantities of incondensable gases, the energy efficiency and the potentiality are far from the reference cases of industrial thermal desalination under our analysis [10].

In this context, the most convenient solution is to reclaim waste heat from the engine for fresh water production by thermal desalination processes [7]. In order to increase the overall energy performance of the ships, companies such as MAN and Wartsila, who construct diesel engines for the propulsion of large ships, have developed energy recovering systems exploiting both the hot temperature jacket water and the high temperature exhausted gases [11–13].

Alfa Laval developed a multiple effect plate (MEP) distillation through several units (1,500 m^3/d) claiming that distillation methods are preferable to the most common alternative (RO) in terms of distillate purity (2–10 ppm TDS) and availability (more than 90%). In the single effect of the Alfa Laval for on board applications, the engine cooling seawater is distilled in a plate-type (titanium) evaporator (40°C–60°C corresponding to a vacuum of 85%–95% maintained by the brine/air ejector). Vapours pass through a demister and continue to the plate condenser, which preheats the seawater feed [11].

The biggest commercial example for marine applications is the multiple stages flash evaporator (SERK COMO) realized by Wartsila with a maximum capacity of 1,500 t/d [12]. Although, the topic seems to be promising from the industrial point of view, at the best of our knowledge in the literature there are few papers regarding the on-ship seawater desalination and water reuse [14] and no one gives a complete theoretical analysis.

This paper describes the processes and technologies behind waste heat recovery by on-ship desalination and proposes a comparison between different alternatives by analysing the water-energy dual purpose plant, defines the optimal conditions to exploit the hot temperature cooling water (HTW) to produce desalted water and the potential for ship-owners to produce freshwater. The starting point is that, in order to produce fresh water, the brine heater of on-ship desalination should be coupled to the HTW cooling system (transferring the heat from the engine air cooler and jacket water cooler). Although, the most interesting heat source is the exhausted gas, we believe that this source (with high exegetic content) should be designated for the electrical power production. This approach presents two main advantages: firstly, it disengages the high-exergy waste heat (of exhausted gases) useful for electricity generation. In many of the standard high-efficiency engine version, the exhausted gas temperature is relatively low after the turbocharger, and just high enough to produce the necessary steam for the heating purposes of the ship by means of a standard exhausted gas fired boiler of the smoke tube design. Secondly, this approach exploits a very low quality (exergy) heat source. Commonly, heat of a central high temperature (90°C) cooling system is rejected into the sea with box heaters.

2. Case study

To perform the comparison calculations, the case of the 4-stroke turbocharged and intercooled WARTSILA 16V46F diesel engine with direct fuel injection has been taken into consideration. The engine is made of 16 cylinders and generate a total output of 19,200 kW [15]. The fresh water cooling system (internal cooling system) is divided into high (HTW at 74°C–94°C) and a low temperature water (LTW at 30°C–45°C) circuits. The HT water circulates through cylinder jackets and heads as well as into the first stage of the air cooler. The LT water circulates in the second stage air cooler and the lubricating oil cooler. The cooling water temperature after the cylinder heads is controlled in the HT circuit, while the inlet air temperature is kept constant with the arrangement of the LT circuit. The LT water partially bypasses the charge air cooler depending on the operating conditions to maintain a constant air temperature after the cooler. A sea water cooling system (external cooling system) controls the inlet temperature of the HT and LT water in the engine. Therefore, the heat duty generated by the fuel combustion is distributed in: shaft power output, lubricating oil cooler, jacket water cooler, exhausted gas, air cooler and heat radiation. The reference case comprises a combination of the Rankine cycle (RC), as suggested by Shu et al. [2], along with a Heat Recovery Steam Generator (HRSG) to produce steam at two pressure levels. Table 1 reports the main energy flow of both the standalone diesel engine and the combined system, while the overall process scheme of diesel engine combined plant is depicted in Fig. 1. All the process streams (HTW, LTW, exhausted gases) and their contribution to the overall energy balance have been evaluated as showed in the Sankey diagram of Fig. 2. The power distribution is evaluated at an engine load of 85%.

Table 1
Wartsila 16V46F; Engine driving propeller (maximum engine speed: 600 rpm); Ambient conditions: ISO standard reference conditions; Load: 85%

Engine output (kW)	16320	
Fuel consumption (g/kWh)	172	
PCI fuel (kJ/kg)	43950	
Total heat duty (kW)	34278	
	Without RC	With RC
Shaft power output	16320	16320
Lubricating oil cooler (LT-circuit)	1637	1637
Jacket water cooler (HT-circuit)	1839	1839
Exhausted gas	8939	2950
Rankine cycle	–	5989
Air cooler (HT-circuit)	3439	3439
Air cooler (LT-circuit)	1631	1631
Heat radiation	470	470

2.1. On ship desalination

The reference case for on-ship desalination is a RO plant consuming 2 kWh/m^3 (without auxiliary treatments) for the production of 10–60 m^3/h of fresh water from seawater of 35 mg/L TDS (1–4 no. of vessels with 4–6 elements of SWC5-1,640 Hydranautics). As aforementioned, the RO plant requires additional equipment as pre-filtration (multimedia filter with automatic backwash removes large particles), chemical pre-treatment (anti-scalant dosing), 5-micron

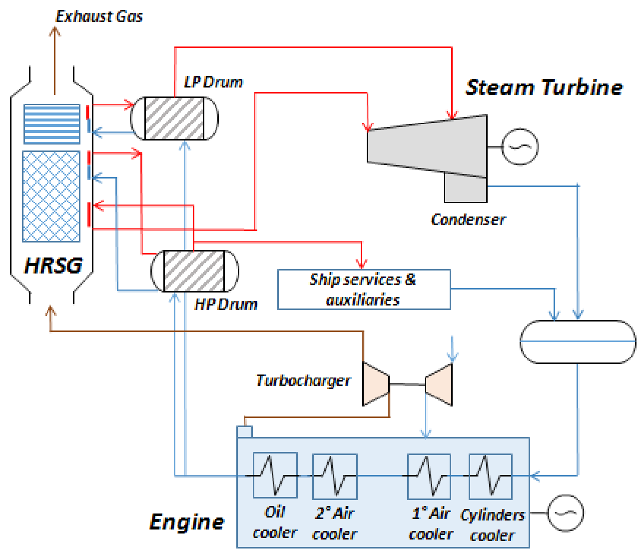

Fig. 1. Diesel Engine with HRSG and Steam Turbine for additional power generation.

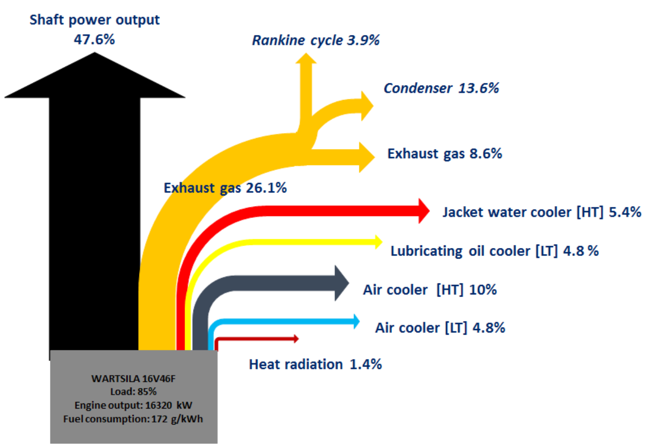

Fig. 2. Sankey diagram of the diesel engine with HRSG and additional power generation in steam cycle (see Fig. 1) (1.3 MW, η = 0.22).

cartridge filtration removes residual solids, colloids, and organic material, chemical post-treatment and re-hardening.

This paper reports results of simulations of possible schemes of thermal desalination, coupled with the recovery of waste heat from diesel engine propulsion, so to compare the overall energy performances. A schematic representation of the dual purpose water/energy plant with two pressure levels is given in Fig. 3. The HRGS duty-temperature diagram (two pressures, 10 and 4 bar) has been fixed according to the optimization pinch-analysis. In this case study, a preheater-deaerator is fed with the low pressure steam. The effect of the HRGS back pressure on the output of the diesel generator has been neglected. An extraction is used for the thermal desalination. It is not convenient to use HTW to preheat water in the power plant considering the structural complexity and the limited benefits in terms of yield, therefore, according to the actual thermal levels, the desalination process is designed so to maximize the recovered HTW part.

Fig. 4 reports the simplified process schemes for the MED and the MSF arrangement. In compliance with the process requirement, HTW preheats the seawater in the thermal desalination. We simulated the MSF and MED processes [5], along with the power plant, by performing the heat and material balances related to the different process schemes, implemented by means of a commercial software (Aspen Plus simulator), adopting the ELEC-NRTL thermodynamic model. The temperature of the condensing steam, extracted to feed the thermal process, is 70°C and 90°C, respectively for MED and MSF. The seawater total salinity is fixed at 35,000 ppm. The hot side temperature profile in the MED is realized from 70°C (0.31 bar) to 45°C (0.096 bar). The number of alternated feed preheaters (with HTW) vary with the number of effects, e.g., 3 preheaters for 6 effects, 4 preheaters for 8 effects, and 5 preheaters for 10 effects. The MSF maximum temperature of the seawater is 80°C, the brine preheating stage is divided into two parallel heat exchangers, one working with steam and the other with HTW. The hot side temperature profile is realized from 90°C (0.31 bar) to 45°C (0.096 bar) (temperature and pressure of the condensing steam).

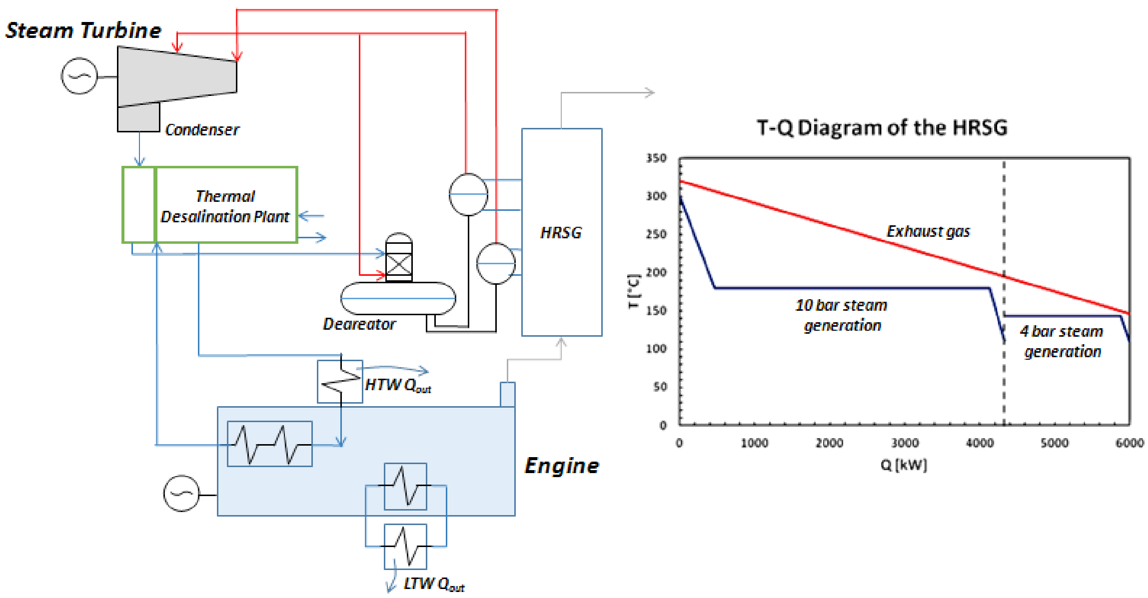

Fig. 3. Dual Purpose plant for on-ship desalination and electrical power production with temperature-duty diagram of the HRSG.

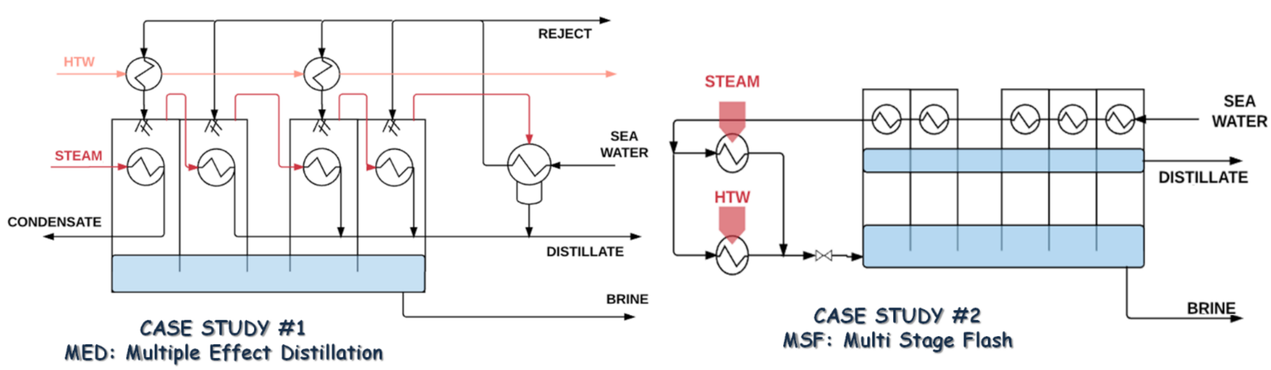

Fig. 4. Process schemes of the two thermal desalination plants analysed in the case studies.

3. Results

Fig. 5 depicts the required input energy (energy consumption EC in kWh/m^3) and the HTW for the Waste-heat recovery vs. the number of effects and the number of stages, respectively for MED and MSF. Fig. 6 shows the GOR (kg_{st}/kg_D) and the Distillate production at increasing effects and stages number, respectively for MED and MSF. As mentioned in the Introduction, the MED shows the highest energy efficiency. Moreover, the HTW recovery increases with the number of effects, because of the increasing preheating. In addition, at the MED low temperature, the energy losses are negligible and the distillate production increases with a quasi-linear equation of the number of stages. The recovery of HTW for MSF Desalination does not vary with the number of stages because this process works at higher temperatures, while the increase of the distillate with the number of stages is exponential. This points gives over an number of stages, the MSF process is more efficient than MED.

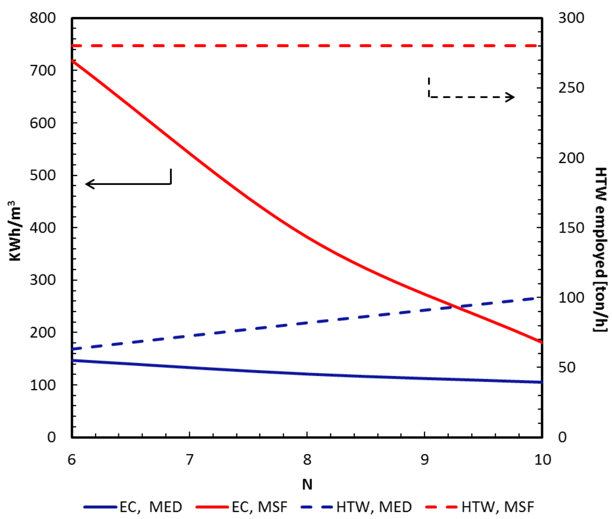

Fig. 5. Energy consumption (EC) and HTW reclaimed in MED and MSF application.

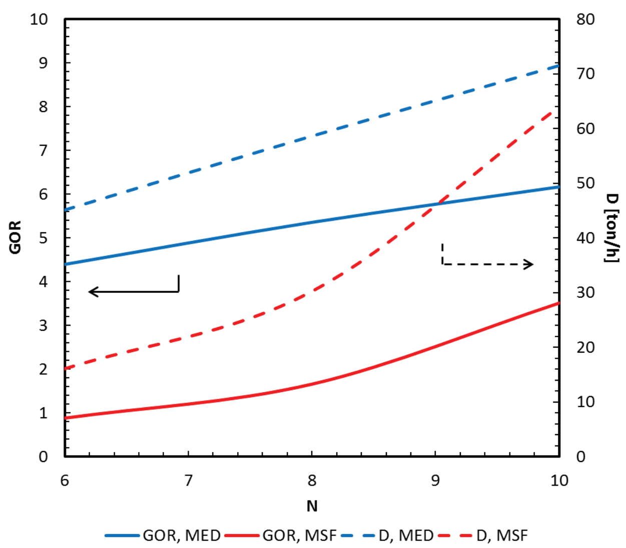

Fig. 6. GOR and Distillate for MED and MSF on-board application.

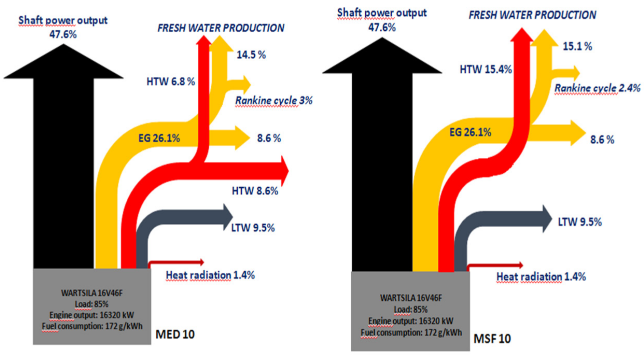

Fig. 7. Sankey Diagram of the dual purpose water/energy plant in case of MED and MSF.

Although, these indicators are useful to quantify the efficiency of processes, in the waste heat recovery it is more important to identify the percentage of energy extracted from the production of electricity and/or recovered from the waste streams. In Fig. 7 the Sankey diagrams for the dual-purpose plants (of the two thermal desalination schemes) are reported in order to quantify the overall recovery made possible from the desalination processes. The freshwater production is in the range 50–70 ton/h. The energy recovered is 24.9% and 32.9% for the dual purpose plant, respectively in the case of MED and MSF. Although, the overall heat recovery is larger for MSF, it is noteworthy that the use of a best quality steam in the MSF reduces the additional electrical output generated (RC) of the 17%. In the case of MED, the power output of the RC is 1.045 MW (η = 0.17) while in case of MSF, the turbine produces an additional 0.83 MW (η = 0.14).

4. Conclusion

Waste heat is a relevant by-product of the ship environment and can be used for thermal desalination, to provide freshwater for on-board civil and wastewaters treatment. Although, Reverse Osmosis is the benchmark in this field, thermal desalination can improve the global energy efficiency of the ship recovering the waste heat, mainly from cooling water and exhausted gases of the diesel engine. In this paper, we have presented some preliminary results of the process analysis of dual-purpose (water-energy) plants for large cargo or cruise ships. The overall engine efficiency raises up to 80% by implementing a Combined RC (to recover the enthalpy of the exhausted gases) with MSF or MED, to recover the waste heat from the HTW system. In this case, it is also possible to convert the waste heat of a 19 MW diesel engine into an additional 1–2 MW of electrical power, while producing around 1,400 m^3/d of freshwater.

MSF allows higher percentages of waste heat recovery, although, due to lower GORs than MED, the distillate production is lower keeping the same number of stages/effects. On the other hand, for on ship installation, the size of the plant as well as operative elements (of pre-treatment, maintenance, chemical dosing, personnel skills) provide additional elements to assess the reliability of different solutions not only in terms of energy efficiency. Further improvements can be achieved by considering the LTW and a power plant with deaerating condenser and the mentioned hybrid desalination methods, not included in these preliminary calculations.

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