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# Exergo-environmental analysis of a reverse osmosis desalination plant in Gran Canaria

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ABSTRACT

In this paper an exergo-environmental analysis of a reverse osmosis desalination plant in Gran Canaria (Canary Islands, Spain) has been performed using real plant operation data. The plant has a nominal capacity of 82,000 $m^3$/day. Different configurations are possible depending on the energy recovery, the reverse osmosis stages, the filtration technology or the feed water pressurization.

The exergo-environmental analysis combines an exergy analysis and a Life cycle assessment in order to determine the environmental impact associated with the process. The analysis is conducted at the component level. The primary locations of exergy destruction are the first stage reverse osmosis membrane module and the high pressure pump. Based on the value of the component-related environmental impact, these components are also the major candidates for improvement. The environmental impact associated with the exergy destruction is the largest contributor to the total environmental impact. This means that the overall environmental impact can be reduced by reducing the exergy destruction within specific components, which are identified for potential performance improvement.



## 1. Introduction to energy/exergo/environmental improvement of desalination plants

The Canary Islands (Spain) represent a world reference in seawater desalination, because of the high number of desalination plants and the use of different technologies. For many decades water desalination has contributed to the progress and development of the islands, providing a continuous supply of water for domestic, industrial and agricultural consumption. Nowadays, the mostly used desalination technology is RO (reverse osmosis). In the 7 islands, there exist more than 255 reverse osmosis desalination plants with a total nominal production higher than 486,000 $m^3$/day [1,2]. Although reverse osmosis processes represent great cost savings in comparison with thermal desalination processes, their energy requirements are still considerably high and they are accompanied by adverse environmental effects.

In order to evaluate the environmental impact of a reverse osmosis desalination plant an exergy based approach has been considered, the exergo-environmental analysis. The objective is to introduce in the field of desalination a method capable of providing a quantitative evaluation of sustainability, and to identify sections/components of the plant which offer the largest potential for the improvement of environmental performance. Exergy-based methods are widely recognized as powerful tools for developing, evaluating and improving an energy conversion system. An exergo-environmental analysis is a combination of exergy analysis and environmental assessment, conducted at the component level, to identify the location, the magnitude and the causes of environmental impacts due to thermodynamic inefficiencies within the system components [3].

There are no previous studies in literature applying the exergo-environmental analysis methodology to real reverse osmosis plants. Several previous studies have evaluated the environmental impact of reverse osmosis desalination plants. Among others, Sadhwani et al. [4] analyzed the environmental problems of seawater reverse osmosis desalination plants, focusing on some case studies located in Canary Islands, and describing the major impacts identified. Tarnacki et al. [5] compare the conventional desalination technology in Europe, reverse osmosis, to the newly developed membrane based technology Memstill® by means of LCA (life cycle assessment). Their objective is to define clearly conditions when the environmental impacts are lowest. The results reveal not only the strong dependency of the energy supply and

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**Nomenclature**

| | |
|---|---|
| $b$ | specific environmental impact per exergy unit, mPt/kJ |
| $\dot{B}$ | environmental impact rate, mPt/s |
| $e$ | specific exergy, kJ/kg |
| $\dot{E}$ | exergy flow rate, kW |
| $f_b$ | exergo-environmental factor, dimensionless |
| $n$ | number of inlet streams |
| $m$ | number of outlet streams |
| $\dot{m}$ | mass flow rate, kg/s |
| $p$ | pressure, kPa |
| $r_b$ | relative difference of exergy-related environmental impacts, dimensionless |
| $\dot{V}$ | volumetric flow, $m^3/h$ |
| $\dot{W}$ | electric power, kW |
| $y$ | exergy destruction ratio, % |
| $\dot{Y}$ | component-related environmental impact rate, mPt/s |

*Greek symbols*

| | |
|---|---|
| $\varepsilon$ | exergetic efficiency |

*Subscripts*

| | |
|---|---|
| $D$ | destruction |
| $F$ | fuel |
| in | inlet |
| $j$ | $j$-th material stream |
| $k$ | $k$-th component |
| out | outlet |
| $P$ | product |
| $L$ | loss |
| tot | total system |

*Superscripts*

| | |
|---|---|
| CH | chemical |
| CO | construction |
| DI | disposal |
| OM | operation and maintenance |
| PH | physical |
| TOT | total |

*Abbreviations*

| | |
|---|---|
| BP | Booster pump |
| DWEER | Dual work exchange energy recovery |
| ERI | pressure exchanger energy recovery system - Energy Recovery Inc. |
| GRP | glass reinforced plastic |
| HPP | high pressure pump |
| LCA | Life cycle assessment |
| PVC | Polyvinyl chloride |
| RO | reverse osmosis |
| TDS | total dissolved solids |
| TFC | Thin Film Composite |

demand but also the potential to reduce the environmental impacts while combining with alternative renewable energy supply. Vince et al. [6] developed an impact assessment tool for the environmental evaluation of potable water production using the LCA (life cycle assessment) method. They determine the weak points of potable water production processes (ground water treatment, ultrafiltration, nanofiltration, seawater reverse osmosis and thermal distillation associated to water transfer) or the best suited treatment in a specific context. As a result, the main source of impacts is shown to be electricity production for plant operation. They also presented improvement levers for impact reduction and for the objective comparison between alternative and conventional water treatment processes. Raluy et al. [7,8] analyzed the influence of different electricity and heat supply on the impacts of several desalination plants and showed that the impacts of the desalination plants could be significantly reduced with an energy supply from renewable sources, waste heat or cogeneration units.

The literature also reports various papers related with the performance of reverse osmosis desalination plants in terms of Second Law analysis. Among them, the recent studies of Lienhard et al. at the Center for Clean Water and Clean Energy at MIT (Massachusetts Institute of Technology) are of special relevance [9–11]. In their work [9], entropy generation mechanisms present in a wide range of desalination processes (reverse osmosis among them) are analyzed in order to evaluate the Second Law efficiency. Within each technology, the relative importance of each source of entropy generation are examined, in order to determine which should be the target of entropy generation minimization. A consistent basis for comparing the energy consumption of desalination and other chemical separation processes using Second Law efficiency is thus developed (the Second Law efficiency for a desalination process is defined as the minimum least work of separation for producing 1 kg of product water from feed of a given salinity) [10]. In Ref. [11] a method for defining and evaluating an economics-based Second Law efficiency is introduced, in analogy to the exergy-based Second Law efficiency. The Second Law efficiency is defined as the ratio of the cost of the minimum least (primary) energy of separation to the actual cost of separation. Of special interest is adopting a reliable formulation for the exergy of seawater [12,13]. In fact, the common model in literature that represents seawater as an ideal mixture of liquid water and solid sodium chloride gives seawater thermodynamic properties that are far from the correct ones. The ideal mixture model also has serious shortcomings, particularly with regard to calculation of the seawater flow exergy, the minimum work of separation, and the second law efficiency. It is thus necessary to use appropriate correlations in order to calculate the thermophysical properties of seawater [13], in order to perform the seawater flow exergy analysis for desalination plants. The methodology developed in Refs. [12,13] is applied to perform the analysis using reverse osmosis desalination plant data, comparing the results with those previously published using the ideal mixture model [12].

Other interesting papers dealing with exergy analysis of reverse osmosis desalination plants are present in the technical literature: Koroneos et al. [14] analyzed reverse osmosis, distillation, and heat desalination processes using the first and second laws of thermodynamics with particular attention to the minimum separation work requirement and the flow exergy. Spiegler [15] set the foundation of the optimal design of most systems that use or produce heat and/or power including desalination. Both the energetic and the economics of the separation process are based on a quantitative formulation of the second law of thermodynamics in terms of the concept of exergy and its destruction. Sorin [16] considers the application of finite time thermodynamics to reverse osmosis processes. They also show the existence of a maximum value for the power of separation which corresponds to the maximum conversion rate of mechanical exergy into chemical exergy. El-Emam and Dincer [17] investigated the performance of a RO (reverse osmosis) desalination plant at different seawater salinity values. Thermodynamic analysis, based on the first and second laws of thermodynamics, as well as a thermo-based economic analysis is performed for the proposed system. Bhutani et al. [18] developed a generic technology based tool for energy assessment and benchmarking of desalination plants. This tool facilitates a systematic and quick identification of energy improvements along with cost-benefit estimation in typical multi-stage flash and reverse osmosis based desalination plants.

There exist several exergy analysis of reverse osmosis desalination plants carried out with plant operation data: Cerci [19] conducted the exergy analysis of a 7250 $m^3$/d reverse osmosis desalination plant in California and an alternative design was investigated to improve its performance. The exergy analysis of a seawater reverse osmosis desalination plant with 21,000 $m^3$/d of nominal capacity located in Tenerife (Canary Islands, Spain) was studied by Romero-Ternero et al. [20]. The reverse osmosis plant of Al-Hussein thermal power station (552.7 $m^3$/d), was analyzed thermodynamically in order to evaluate the rates of exergy destruction and to identify the locations of highest exergy destruction [21]. The work of Gasmi et al. [22] studied the optimization of energy consumption in a reverse osmosis desalination unit with a capacity of 30,000 $m^3$/day. The simulation was validated by an exergy analysis which made it possible to evaluate the contribution of the equipments in energy degradation. Kahraman et al. [23] analyzed a brackish water desalination plant (12,270 $m^3$/d) in California that incorporates reverse osmosis, nanofiltration, and electrodialysis units. Exergetic, economic and environmental aspects have been considered, simultaneously, by Hosseini (2012) et al. [24] in order to provide optimization for designing a combined gas turbine and multi-stage flash desalination plant. A technical and Thermoeconomic assessment is carried out by Peñate and García-Rodríguez [25] in order to reduce energy costs in reverse osmosis desalination plants. They focused their study on the replacement of Pelton turbines by systems based on isobaric-chamber devices.

In this paper, an exergo-environmental analysis of a seawater reverse osmosis desalination plant in Gran Canaria has been carried out. The plant has a nominal production of 82,000 $m^3$/d and presents ten lines with different configurations depending on the energy recovery procedure, the reverse osmosis stages (double or single), the filtration technology or the feed water pressurization procedure (high pressure pump, pressure exchanger, booster pump). The thermodynamic analysis was performed using actual plant operation data. A real mixture model [13] is applied for the calculation of thermophysical properties of seawater. In the exergy analysis, physical and chemical exergies of the material streams are considered; correct exergy balances for the reverse osmosis membranes are then formulated. LCA (Life cycle assessmentLCA) of each significant system component and of all relevant input streams is carried out. The results section provides a detailed analysis of irreversibilities and of the environmental impacts of the system components, obtained through an exergo-environmental evaluation; consequently, ideas for performance improvement are formulated in the conclusions.

## 2. Description of the plant

The desalination station – Las Palmas III- was brought into service in October 1989. Since then, it has been retrofitted several times. The plant has a nominal production of 82,000 $m^3$/day using ten production lines. Each line consists of two RO (reverse osmosis) stages with the concentrate solution of the first one feeding the second through a BP (Booster pump). Reverse osmosis modules are accommodated in six-element pressure vessels. The energy recovery is performed either with Pelton turbines or with pressure exchanger energy recovery systems, according to the choices applied originally by the plant designers to specific sections (lanes) of the plant.

Feed water is pumped from a pond, where a first physical pre-treatment is achieved due to the natural driven filtration of the seawater through the porous walls of the pond. The feed water is characterized by an annual mean salinity of about 37,000 ppm. Feed water temperature varies during the year between 19 °C and 26 °C.

The main processes of a RO system are pre-treatment and filtration; high pressure pump; membranes; post-treatment. The pre-treatment and filtration procedure is similar in all ten lines. Filtration consists of sand filters, followed by precoat filters and finally by cartridge filters. Between precoat and cartridge filters, an antifouling/antiscaling agent (Hypersperse MDC220) is added. The total pressure losses are normally in the range of 2.3% and 4.0%, depending on the fouling of the filters: the higher the fouling the higher the pressure losses.

The desalination process comprises reverse osmosis, in all lines, in two stages. The brine from the first stage to the second stage feed by increasing the pressure via a booster pump or inter-stage pump. The permeate from both stages are mixed and sent to a regulation tank. The second stage brine is sent to an energy recovery device, which is a turbine Pelton (frame B, C, I, K and L) or an exchanger pressure device: ERI (Energy Recovery Inc.) (for frame E, F, G and H) or DWEER (Dual work exchange energy recovery) (for frame A).

The reverse osmosis racks are formed by a set of pressure pipes (GRP (glass reinforced plastic) cylindrical structures) inside which are arranged in six series of membrane modules. All membrane modules used are spiral wound configuration. These modules are consisted by two sheets of membrane folded and wrapped around an inner tube of PVC (polyvinyl chloride), together constituting a "package". All membranes are TFC (Thin Film Composite), i.e., mixed membranes are formed by a thin polyamide active layer adhered to a porous support of another material.

A common post-treatment for permeate of all ten lines consists of continual dosing of calcite and $CO_2$ for re-mineralization and pH adjustment. The osmotised and re-mineralized water is collected in a regulator tank. Lastly, the drinking water is pumped from the desalination plant to either a regulator storage tank or to the municipal storage tanks. Four transfer pumps, are used for this propose. From there, the water is distributed to the water supply network. The brine rejected from the membranes is returned to the sea.

In the following, the principal differences between the ten lines are described:

- The first seven lines (frames A, B, C, E, F, G and H) share intake and filtration process. Water pressurization is initially achieved using six pumps. One of them leads the seawater to a pressure filter, the rest are followed by sand filters. Feed water leaving the filters is collected in one tank at atmospheric pressure. Next, water is conducted to the precoat and cartridge filters through seven transfer pumps. Following, seawater is splitted in seven lines operating in parallel. In each line and before entering the reverse osmosis units, the inlet water is pressurized by a HPP (high pressure pump) which brings it to a pressure higher than 60 bar. Each line has its own HPP, except frames F and G that share the same HPP. Figs. 1–3 represent a schematic of a line with three different possible energy recovery configurations.
- Line 8 (frame I) has its own captation and filtration seawater system. It has no collection tank and the first filtration takes place through pressure filters.
- Lines 9 and 10 (frames K and L) operate in parallel sharing the captation and filtration procedure. Captation consists of three water intake pumps, of which only two are in operation at the same time. Filtration procedure is similar to that of line 8. Two

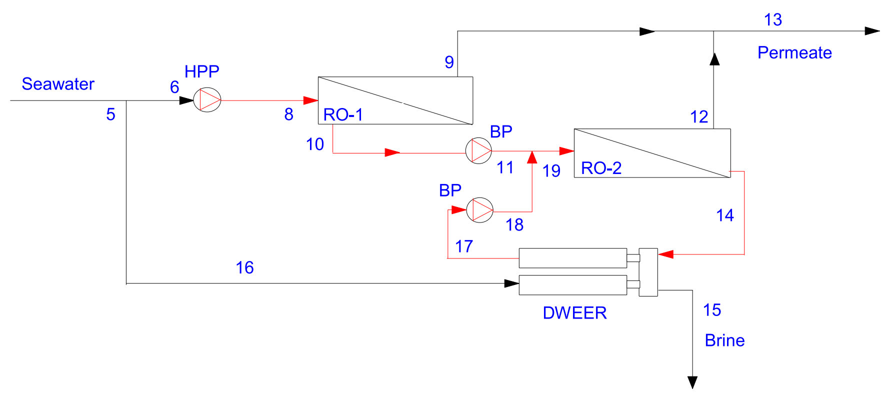


**Fig. 1.** Line with a Dual Work Exchange Energy Recovery (DWEER™) system.

HPP lead the seawater to the frames, an extra pump is reserved for maintenance purposes.

## 3. Methodology

An exergo-environmental analysis is an exergy-based method proposed to evaluate energy conversion processes from an environmental point of view. With this evaluation, it is possible to identify the location and magnitude of environmental impacts at the system component level. A detailed description of the analysis can be found in Refs. [3] and [26].

The method consists of three steps: 1) Detailed exergy analysis at the component level; 2) LCA (Life cycle assessment) of each significant system component and of all relevant input streams (in this step, the environmental impact obtained from the LCA is assigned to the exergy streams in the system); 3) Exergo-environmental evaluation and calculation of proper exergo-environmental variables.

This methodology provides relevant information about the environmental performance of each system component taking into account the influence of the thermodynamic inefficiencies within the system components in the formation of environmental impacts.

### 3.1. Exergy analysis

In an exergy analysis, an exergy balance is formulated for each component at steady state conditions; considering for example the $k$-th component:

$$\dot{E}_{F,k} = \dot{E}_{P,k} + \dot{E}_{D,k} + \dot{E}_{L,k} \tag{1}$$

Here it is assumed that the system boundaries used for all exergy balances are at the temperature $T_0$ of the reference environment and thus that the exergy losses due to heat transfer to the environment associated with one component are negligible, $\dot{E}_{L,k} = 0$ [27]. Therefore, the exergy destruction in the $k$-th component is

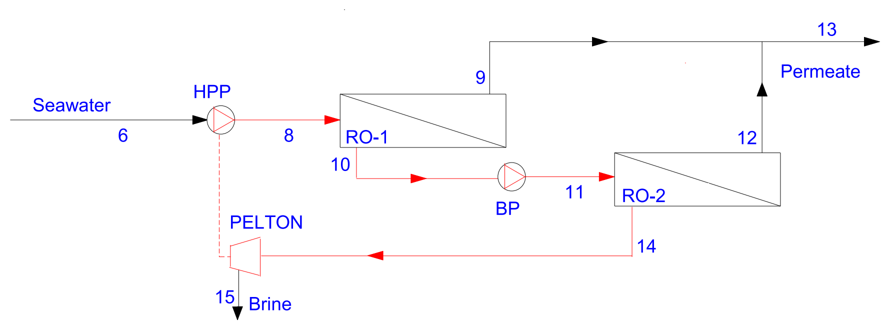


**Fig. 2.** Line with a Pelton turbine.

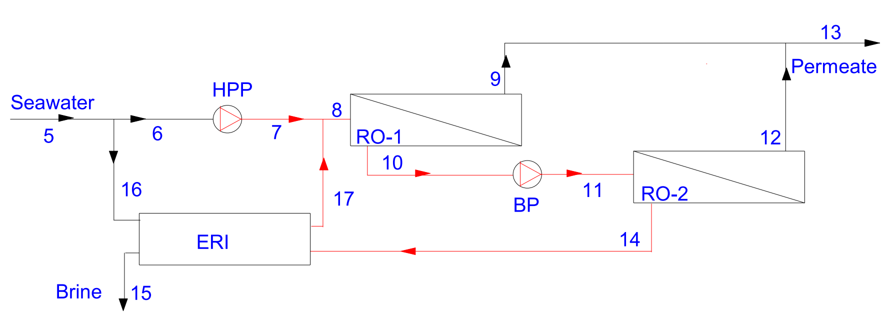


**Fig. 3.** Line with a pressure exchanger energy recovery (ERI) system.

calculated as the difference between the fuel and the product for the component. Exergy losses appear only at the level of the overall system, for which the exergy balance becomes:

$$\dot{E}_{F,\text{tot}} = \dot{E}_{P,\text{tot}} + \sum_k \dot{E}_{D,k} + \dot{E}_{L,\text{tot}} \tag{2}$$

The exergetic efficiency of the $k$-th component is:

$$\varepsilon = \frac{\dot{E}_{P,k}}{\dot{E}_{F,k}} = 1 - \frac{\dot{E}_{D,k}}{\dot{E}_{F,k}} \tag{3}$$

In addition to the exergy destruction rate, $\dot{E}_{D,k}$, and the exergetic efficiency, the thermodynamic evaluation of a system component is based on the exergy destruction ratio, $y_{D,k}$, which compares the exergy destruction in the $k$-th component with the fuel exergy supplied to the overall system, $\dot{E}_{F,\text{tot}}$:

$$y_{D,k} = \frac{\dot{E}_{D,k}}{\dot{E}_{F,\text{tot}}} \tag{4}$$

This ratio expresses the percentage of the decrease in the overall system efficiency due to the exergy destruction in the $k$-th system component:

$$\varepsilon_{\text{tot}} = \frac{\dot{E}_{P,\text{tot}}}{\dot{E}_{F,\text{tot}}} = 1 - \sum_k y_{D,k} - \frac{\dot{E}_{L,\text{tot}}}{\dot{E}_{F,k}} \tag{5}$$

Alternatively, the component exergy destruction rate can be compared with the total exergy destruction rate within the system, $\dot{E}_{D,\text{tot}}$, giving the ratio:

$$y^*_{D,k} = \frac{\dot{E}_{D,k}}{\dot{E}_{D,\text{tot}}} \tag{6}$$

$\dot{E}_{D,k}$ is an absolute measure of the inefficiencies in the $k$-th component whereas $\varepsilon_k$, $y_{D,k}$ and $y^*_{D,k}$ are relative measures of the same inefficiencies. In $\varepsilon_k$ the exergy destruction within a component is related to the fuel for the same component whereas in $y_{D,k}$ the exergy destruction within a component is related to the fuel for the overall system. In $y^*_{D,k}$ the exergy destruction within a component is related to the exergy destruction in the overall system.

The characterization of fuel and product for a component is of capital importance in order to give an appropriate definition of the exergetic efficiency. The product is determined by considering the desired result produced by the component and fuel by the resources expended to generate the result [27]. In this study, fuel and product were calculated considering physical and chemical exergies of the material stream separately following widely accepted guidelines [27,28]. The exergy balance is then applied for the different devices as follows:

Pump:

$$\dot{E}_{F,\text{PUMP}} = \dot{W}_{\text{PUMP}} \tag{7}$$

$$\dot{E}_{P,\text{PUMP}} = \dot{E}_{\text{outlet}} - \dot{E}_{\text{inlet}} \tag{8}$$

Peltron turbine:

$$\dot{E}_{F,\text{PELTON}} = \dot{E}_{\text{inlet}} - \dot{E}_{\text{outlet}} \tag{9}$$

$$\dot{E}_{P,\text{PELTON}} = \dot{W}_{\text{PELTON}} \tag{10}$$

ERI and DWEER:

$$\dot{E}_F = \dot{E}_{\text{brine,inlet}} - \dot{E}_{\text{brine,outlet}} \tag{11}$$

$$\dot{E}_P = \dot{E}_{\text{feed,outlet}} - \dot{E}_{\text{feed,inlet}} \tag{12}$$

Reverse Osmosis:

$$\dot{E}_{F,\text{RO}} = \dot{E}^{\text{PH}}_{\text{feed}} - \left(\dot{E}^{\text{PH}}_{\text{permeate}} + \dot{E}^{\text{PH}}_{\text{brine}}\right) \tag{13}$$

$$\dot{E}_{P,\text{RO}} = \left(\dot{E}^{\text{CH}}_{\text{permeate}} + \dot{E}^{\text{CH}}_{\text{brine}}\right) - \dot{E}^{\text{CH}}_{\text{feed}} \tag{14}$$

No exergetic product can be defined for the dissipative components, like filters. They just decrease the exergy content of a stream without generating an immediate useful effect.

Herein, the exergies of the flow streams (Table 1) were calculated according to the definitions given in Ref. [27]. The physical and chemical exergy of seawater, permeate and brine were obtained based on the thermodynamic properties calculated with the correlations given by Sharqawy et al. [13]. EES Thermodynamic software [29] was used to perform all the calculations. An average seawater temperature, 21.5 °C, was considered.

### 3.2. Life cycle assessment

LCA is a systematic method for assessing the environmental impacts of a product over its life cycle. It is carried out following

**Table 1**
Thermodynamic and exergetic values of selected streams of lanes A, C and E.

| Stream | $P$ (kPa) | TDS (ppm) | $\dot{V}$ (m$^3$/h) | $e^{CH}$ (kJ/kg) | $e^{PH}$ (kJ/kg) | $e^{TOT}$ (kJ/kg) | $\dot{E}^{CH}$ (kW) | $\dot{E}^{PH}$ (kW) | $\dot{E}^{TOT}$ (kW) |
|---|---|---|---|---|---|---|---|---|---|
| *Lane A* | | | | | | | | | |
| 5 | 320 | 37,000 | 804 | 0.00 | 0.21 | 0.21 | 0 | 49 | 49 |
| 6 | 320 | 37,000 | 398 | 0.00 | 0.21 | 0.21 | 0 | 24 | 24 |
| 8 | 4870 | 37,000 | 398 | 0.00 | 4.65 | 4.65 | 0 | 527 | 527 |
| 9 | 110 | 166 | 79 | 2.85 | 0.01 | 2.86 | 62 | 0 | 63 |
| 10 | 4540 | 46122 | 319 | 0.10 | 4.30 | 4.40 | 9 | 393 | 403 |
| 11 | 6360 | 46,122 | 318 | 0.10 | 6.06 | 6.16 | 9 | 553 | 562 |
| 12 | 110 | 342 | 322 | 2.81 | 0.01 | 2.82 | 251 | 1 | 252 |
| 13 | 110 | 307 | 401 | 2.82 | 0.01 | 2.83 | 314 | 1 | 315 |
| 14 | 6240 | 73,396 | 403 | 1.19 | 5.83 | 7.01 | 140 | 687 | 827 |
| 15 | 240 | 73,396 | 403 | 1.19 | 0.13 | 1.32 | 140 | 16 | 155 |
| 16 | 300 | 37,000 | 406 | 0.00 | 0.19 | 0.19 | 0 | 23 | 23 |
| 17 | 6170 | 37,000 | 406 | 0.00 | 5.92 | 5.92 | 0 | 685 | 685 |
| 18 | 6360 | 37,000 | 406 | 0.00 | 6.10 | 6.10 | 0 | 706 | 706 |
| 19 | 6360 | 41,007 | 724 | 0.02 | 6.08 | 6.10 | 4 | 1259 | 1263 |
| *Lane C* | | | | | | | | | |
| 6 | 320 | 37,000 | 683 | 0.00 | 0.21 | 0.21 | 0 | 42 | 42 |
| 8 | 6230 | 37,000 | 683 | 0.00 | 5.97 | 5.97 | 0 | 1163 | 1163 |
| 9 | 110 | 121 | 246 | 2.85 | 0.01 | 2.87 | 195 | 1 | 195 |
| 10 | 5940 | 57,760 | 437 | 0.46 | 5.60 | 6.06 | 58 | 709 | 767 |
| 11 | 7050 | 57,760 | 437 | 0.46 | 6.67 | 7.13 | 58 | 844 | 901 |
| 12 | 110 | 230 | 101 | 2.84 | 0.01 | 2.84 | 79 | 0 | 80 |
| 13 | 110 | 152 | 347 | 2.85 | 0.01 | 2.86 | 274 | 1 | 275 |
| 14 | 6850 | 75,054 | 336 | 1.28 | 6.40 | 7.67 | 126 | 630. | 756 |
| 15 | 150 | 75,054 | 336 | 1.28 | 0.05 | 1.33 | 126 | 5 | 130 |
| *Lane E* | | | | | | | | | |
| 5 | 320 | 37,000 | 759 | 0.00 | 0.21 | 0.21 | 0 | 46 | 46 |
| 6 | 320 | 37,000 | 446 | 0.00 | 0.21 | 0.21 | 0 | 27 | 27 |
| 7 | 6790 | 37,000 | 446 | 0.00 | 6.52 | 6.52 | 0 | 829 | 829 |
| 8 | 6790 | 37,000 | 759 | 0.00 | 6.52 | 6.52 | 0 | 1410 | 1410 |
| 9 | 110 | 135 | 335 | 2.85 | 0.01 | 2.86 | 265 | 1 | 266 |
| 10 | 6500 | 66,127 | 424 | 0.82 | 6.10 | 6.92 | 101 | 753 | 855 |
| 11 | 7170 | 66,127 | 424 | 0.82 | 6.74 | 7.56 | 101 | 833 | 934 |
| 12 | 110 | 349.2 | 114 | 2.81 | 0.01 | 2.82 | 89 | 0 | 89 |
| 13 | 110 | 268.8 | 449 | 2.83 | 0.01 | 2.84 | 352 | 1 | 353 |
| 14 | 7050 | 90,316 | 310 | 2.22 | 6.51 | 8.73 | 204 | 599 | 802 |
| 15 | 240 | 90,316 | 310 | 2.22 | 0.13 | 2.35 | 204 | 12 | 216 |
| 16 | 320 | 37,000 | 310 | 0.00 | 0.21 | 0.21 | 0 | 19 | 19 |
| 17 | 6790 | 37,000 | 310 | 0.00 | 6.52 | 6.52 | 0 | 576 | 576 |

international standard approaches [30] in four steps: 1) Goal and scope definition; 2) Inventory analysis (identification and quantification of the consumption and release of materials); 3) Impact assessment and 4) Interpretation of the results.

The application of an LCA is supported by:

a) A software to perform the calculations of the analysis. Here the software Package SimaPro 7.1 [31] was used. It has the fundamental features necessary for this process, and it has already been used by other authors to analyze desalination and water treatment processes [7,8].
b) A database with the required information about materials processes and wastes. Among the database sources available with the SimaPro software package, EcoInvent v2.0 has been considered the most suitable for this analysis [32].
c) A method of evaluation of the impact. Eco-indicator 99 [33] has been selected because it considers many environmental aspects and uses average European data.

A detailed description of the design, materials and corresponding weights of the equipment items of the reverse osmosis desalination plant has been provided by the operators of the plant. Table 2 shows the materials and weights of the equipments for just lanes A, C and E, which have been chosen as representatives for lanes with DWEER, Pelton, and ERI energy recovery systems respectively.

A life time of 25 years and 8250 working hours per year were assumed. The specific 2011 Canary Islands energy mix was considered during operation phase (steam turbines: 23%; gas turbines: 20%; diesel motors: 18%; combined cycles: 29%; cogeneration: 1%; wind: 4.6%; solar photovoltaic: 4.22% small hydro: 0.05%). Chemicals used for cleaning and maintenance tasks were also taken into account.

Through the LCA, environmental impacts, $\dot{B}_j$, are assigned to each exergy stream, $j$, of the plant. Also the component-related environmental impact of a component $k$,$\dot{Y}_k$, is calculated with the contribution of the specific Life cycle phases for each component, that is: construction (CO), operation and maintenance (OM), and disposal (DI):

$$\dot{Y}_k = \dot{Y}_k^{CO} + \dot{Y}_k^{OM} + \dot{Y}_k^{DI} \quad (15)$$

The major contribution to the overall environmental impact of the system occurs during the operation phase, mainly because of the use of fossil fuels for electricity production and the emission of pollutants as a consequence of combustion.

**Table 2**
Weights and materials for the main components of lanes A, C and E.

| Component | Weight (kg) | | |
|---|---|---|---|
| | Lane A | Lane C | Lane E |
| HPP | 6206 | 5472 | 6420 |
| RO1 | 7872 | 5096 | 4950 |
| RO2 | 6692 | 864 | 5707 |
| BP1 | 3959 | 3683 | 3471 |
| BP2 | 373 | – | – |
| DWEER | 5460 | – | – |
| PELTON | – | 810 | – |
| ERI | – | – | 872 |

HPP, BP1 and BP2: stainless steel, 27.3%; copper, 8.3%; iron, 21.7%; silicon, 0.67%; casting, 41.7%; aluminum 0.26%.
RO1 and RO2 membranes: polyamide.
DWEER: super duplex stainless steel, 50%; glass reinforced plastic, 50%.
PELTON: stainless steel 316, 15%; duplex stainless steel, 40%; super duplex stainless steel, 40%; epoxi, 5%.
ERI: ceramics, 30%; glass reinforced plastic, 60%; stainless steel, 10%.

### 3.3. Exergo-environmental evaluation

In an exergo-environmental evaluation the environmental impact associated with a component and its fuel streams are assigned to its product exergy streams by means of an exergo-environmental model. Exergo-environmental variables are calculated and consequently the environmental performance of each system component can be evaluated.

The exergo-environmental model consists of two steps [26]:

1. Environmental impact balances for each component:

For a component with $n$ inlet streams and $m$ outlet streams the environmental balance is formulated by:

$$\sum_{j=1}^{m} \dot{B}_{j,k,\text{out}} = \sum_{j=1}^{n} \dot{B}_{j,k,\text{in}} + \dot{Y}_k \quad (16)$$

$$\sum_{j=1}^{m} \left(b\cdot\dot{E}\right)_{j,k,\text{out}} = \sum_{j=1}^{n} \left(b\cdot\dot{E}\right)_{j,k,\text{in}} + \dot{Y}_k \quad (17)$$

In the membranes, due to the change of the chemical exergy, it is necessary to split the physical and chemical contributions:

$$\dot{B}_{j,k} = \dot{B}_{j,k}^{PH} + \dot{B}_{j,k}^{CH} = \left(b\cdot\dot{E}\right)_{j,k}^{PH} + \left(b\cdot\dot{E}\right)_{j,k}^{CH} \quad (18)$$

The environmental balance can also be formulated following the already well-known fuel and product definitions [3,28]:

$$\dot{B}_{P,k} = \dot{B}_{F,k} + \dot{Y}_k \quad (19)$$

$$b_{P,k}\dot{E}_{P,k} = b_{F,k}\dot{E}_{F,k} + \dot{Y}_k \quad (20)$$

where $\dot{B}_{P,k}$ and $\dot{B}_{F,k}$ are the environmental impact rates associated with product and fuel respectively, expressed in Eco-indicator 99 millipoints per time unit (mPt/s), and, $b_{P,k}$ and $b_{F,k}$ are the corresponding environmental impacts per unit of exergy for product and fuel in millipoints per exergy unit (mPt/GJ).

2. Auxiliary environmental impact equations based on the P and F rules [27,28], analog to the standard rules of exergoeconomic analysis, where F and P refers to the exergy of fuel and product for a component.

Additionally, exergo-environmental variables can be defined to evaluate the environmental performance of the single components of the energy conversion system:

a) The environmental impact rate associated with the exergy destruction within the $k$-th component:

$$\dot{B}_{D,k} = b_{F,k}\dot{E}_{D,k} \quad (21)$$

b) The relative difference between the average specific environmental impact of the product and the fuel, which represents an indicator of the potential for reducing the environmental impact associated with a component:

$$r_{b,k} = \frac{b_{P,k} - b_{F,k}}{b_{F,k}} \quad (22)$$

c) The exergo-environmental factor, which expresses the relative contribution of the component-related environmental impact, $\dot{Y}_k$, to the sum of environmental impacts associated with the $k$-th component.

$$f_{b,k} = \frac{\dot{Y}_k}{\dot{Y}_k + \dot{B}_{D,k}} \quad (23)$$

The exergo-environmental model calculates the total environmental impact associated with the $k$-th component$\dot{B}_k$, by calculating the environmental impact of exergy destruction, $\dot{B}_{D,k}$, and the component-related environmental impact, $\dot{Y}_k$. With this approach, the total environmental impact associated with the $k$-th component of the $k$-th component within the system is identified:

$$\dot{B}_k = \dot{Y}_k + \dot{B}_{D,k} \quad (24)$$

The exergo-environmental balances and their respective auxiliary environmental impact equations for the different devices of the desalination plant are:

Pump:

$$\dot{B}_{F,\mathrm{PUMP}} = \dot{B}_{\mathrm{elctricity,PUMP}} \quad (25)$$

$$\dot{B}_{P,\mathrm{PUMP}} = \dot{B}_{\mathrm{outlet}} - \dot{B}_{\mathrm{inlet}} \quad (26)$$

Peltron turbine:

$$\dot{B}_{F,\mathrm{PELTON}} = \dot{B}_{\mathrm{inlet}} - \dot{B}_{\mathrm{outlet}} \quad (27)$$

$$\dot{B}_{P,\mathrm{PELTON}} = \dot{B}_{\mathrm{electricity\ \ PELTON}} \quad (28)$$

$$b_{\mathrm{inlet}} = b_{\mathrm{outlet}} \quad (29)$$

ERI and DWEER:

$$\dot{B}_F = \dot{B}_{\mathrm{brine,inlet}} - \dot{B}_{\mathrm{brine,outlet}} \quad (30)$$

$$\dot{B}_P = \dot{B}_{\mathrm{feed,outlet}} - \dot{B}_{\mathrm{feed,inlet}} \quad (31)$$

$$b_{\mathrm{brine,inlet}} = b_{\mathrm{brine,outlet}} \quad (32)$$

Reverse Osmosis:

$$\dot{B}_{F,\mathrm{RO}} = \dot{B}^{\mathrm{PH}}_{\mathrm{feed}} - \left(\dot{B}^{\mathrm{PH}}_{\mathrm{permeate}} + \dot{B}^{\mathrm{PH}}_{\mathrm{brine}}\right) \quad (33)$$

$$\dot{B}_{P,\mathrm{RO}} = \left(\dot{B}^{\mathrm{CH}}_{\mathrm{permeate}} + \dot{B}^{\mathrm{CH}}_{\mathrm{brine}}\right) - \dot{B}^{\mathrm{CH}}_{\mathrm{feed}} \quad (34)$$

$$b^{\mathrm{PH}}_{\mathrm{feed}} = b^{\mathrm{PH}}_{\mathrm{permeate}} = b^{\mathrm{PH}}_{\mathrm{brine}} \quad (35)$$

$$\frac{\dot{m}_{\mathrm{permeate}} b^{\mathrm{CH}}_{\mathrm{permeate}} e^{\mathrm{CH}}_{\mathrm{permeate}} - \dot{m}_{\mathrm{feed}} b^{\mathrm{CH}}_{\mathrm{feed}} e^{\mathrm{CH}}_{\mathrm{feed}}}{\dot{m}_{\mathrm{permeate}} e^{\mathrm{CH}}_{\mathrm{permeate}} - \dot{m}_{\mathrm{feed}} e^{\mathrm{CH}}_{\mathrm{feed}}} = \frac{\dot{m}_{\mathrm{brine}} b^{\mathrm{CH}}_{\mathrm{brine}} e^{\mathrm{CH}}_{\mathrm{brine}} - \dot{m}_{\mathrm{feed}} b^{\mathrm{CH}}_{\mathrm{feed}} e^{\mathrm{CH}}_{\mathrm{feed}}}{\dot{m}_{\mathrm{brine}} e^{\mathrm{CH}}_{\mathrm{brine}} - \dot{m}_{\mathrm{feed}} e^{\mathrm{CH}}_{\mathrm{feed}}} \quad (36)$$

*Methodological limitations and uncertainties*. The LCA method used here is just one of the possible methods for assessing the environmental impact. As all methods, it has limitations and uncertainties: on one hand, it is not possible to account for all environmental impacts and, on the other, the definition of the boundaries is subject to some arbitrariness. This limitations lead to inaccuracies [3]. However, among the existing methods, LCA considers the different environmental aspects in a comprehensive quantitative way. Consequently, the results obtained from an exergo-environmental analysis are very useful: the components with the highest potential for improvement are identified. At the same time, the method shows whether improvement can be obtained primarily by reducing the thermodynamic inefficiencies or by reducing consumption of materials during construction or operation of the component.

## 4. Results and discussion

In this section, the results of the exergetic and exergo-environmental analysis for just lanes A, C and E are analyzed. Lanes A, C and E have been chosen as representatives for lanes with DWEER, Pelton, and ERI energy recovery systems respectively.

The results of the exergetic analysis are shown in Table 1. Thermodynamic and exergetic data for the main streams of lanes A, C and E are presented.

Considering Table 1, it is worth mentioning that the chemical exergy of some streams (permeate and brine) is not negligible and, therefore, it would not be correct to ignore its value in the exergy analysis of desalination processes.

Table 3 shows the exergy of the fuel, the exergy of the product, the exergy destruction and the exergy destruction ratios for each main component of lanes A, C and E. The Pelton turbine, the high pressure pumps and the first stage of reverse osmosis are the devices responsible for the largest exergy destructions. The exergy destruction in HPP of lane A is considerably lower than in HPP of the other lanes because a large amount of the inlet seawater flow is sent to the DWEER instead of being pumped to the RO1. In lane A (equipped with a DWEER), the second stage of reverse osmosis is less efficient than the first one, because this second stage receives a greater amount of inlet flow. The conversion of physical exergy into chemical exergy taking place in the membranes is more efficient for lane A working with DWEER than for lane C (Pelton turbine) or E (ERI energy recovery device). This fact suggests the convenience of an advanced exergy analysis, where the interactions between the different devices could be pointed out in terms of endogenous/exogenous exergy destruction calculations [34].

Fig. 4 shows the exergetic efficiency of the main devices composing the different lanes. Most of the components show an

**Table 3**
Exergetic variables of the main components of lanes A, C and E.

| Component | $\dot{E}_{F,k}$ (kW) | $\dot{E}_{P,k}$ (kW) | $\dot{E}_{D,k}$ (kW) | $y^*_{D,k}$ (%) |
|---|---|---|---|---|
| *Lane A* | | | | |
| $RO2_A$ | 572 | 387 | 185 | 39.5 |
| $HPP_A$ | 640 | 503 | 137 | 29.2 |
| $BP1_A$ | 235 | 160 | 76 | 16.1 |
| $RO1_A$ | 134 | 72 | 62 | 13.2 |
| $BP2_A$ | 35 | 21 | 14 | 3.0 |
| $DWEER_A$ | 672 | 662 | 10 | 2.1 |
| *Lane C* | | | | |
| $PELTON_C$ | 625 | 379 | 246 | 30.5 |
| $HPP_C$ | 1350 | 1121 | 229 | 28.3 |
| $RO1_C$ | 453 | 252 | 201 | 24.9 |
| $RO2_C$ | 213 | 147 | 66 | 8.2 |
| $BP_C$ | 201 | 135 | 66 | 8.2 |
| *Lane E* | | | | |
| $HPP_E$ | 1095 | 802 | 293 | 39.0 |
| $RO1_E$ | 656 | 366 | 290 | 38.5 |
| $BP_E$ | 176 | 79 | 97 | 12.9 |
| $RO2_E$ | 234 | 192 | 42 | 56.4 |
| $ERI_E$ | 586 | 557 | 29 | 38.9 |

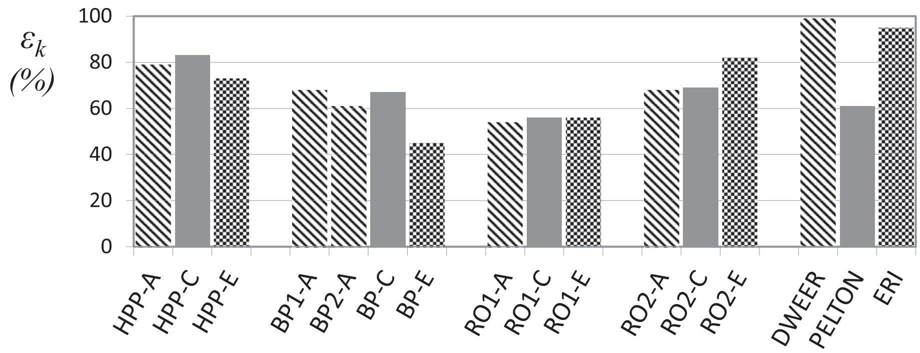


**Fig. 4.** Exergetic efficiency of main devices of lanes A, C and E.

exergetic efficiency higher than 50%. DWEER and ERI present an exergetic efficiency higher than 95%. As expected, the exergetic efficiency of the Pelton turbine is lower: 61%. The low exergetic efficiency of the booster pump in frame E is remarkable. An urgent intervention in order to improve it is highly recommended. The exergetic efficiency of HPP and BP could be improved by adjusting their operation to nominal conditions. The exergetic efficiency of the reverse osmosis stages could be improved by replacing the oldest and dirtiest membranes. Nevertheless, most of the exergy destruction is unavoidable due to the irreversibilities in processes involving chemical separation.

Using data shown in Fig. 4, it is possible to calculate the total exergetic efficiency of the lane as:

$$\varepsilon_{\text{tot}} = \frac{\dot{E}_{P,\text{tot}}}{\dot{E}_{F,\text{tot}}} = \frac{\dot{E}_{\text{total produced water}}}{\dot{E}_{\text{total seawater inlet}} + \dot{W}_{\text{pumps}} - \dot{W}_{\text{turbines}}} \tag{37}$$

The total exergetic efficiencies of lanes A, C and E are quite low: 32.8%, 28.4% and 26.8% respectively. These values are not surprising, taking into account that the exergy of produced water is very low. Nevertheless, this total exergetic efficiency values are much higher than the ones reported by other authors [19,23], which are in the range of 4%. The reason for this is that they used an ideal mixture model of pure water and sodium chloride salt to present and calculate the thermodynamic properties of seawater. This model was initially suggested by Cerci [19] and has been discussed by Sharqawy et al. [12,13]. In this ideal mixture model, the chemical exergy part was neglected. As a result, the flow exergy of that model always decreases with salt concentration and has negative values at salinities higher than the dead state salinity. In addition, some flow exergy values calculated by that ideal mixture model have negative values at pressure equal to or higher than the dead state pressure. However, by using the formulation presented by Sharqawy et al. [12,13], for the flow exergy together with the seawater thermodynamic properties correlations, correct trends for the flow exergy, always positive, are obtained, as shown in Table 1. The lower value of the total exergetic efficiency for lane E (with ERI) than that for lane C (with Pelton) is caused by the inefficient operation of its HPP.

The total exergy losses associated with the brine discharge amount between 130 and 215 kW, corresponding to 8–16% of the fuel exergy of the respective lane.

Table 4 presents the values of the exergo-environmental magnitudes obtained in the analysis: the environmental impacts per unit of exergy for product and fuel, $b_{P,k}$, $b_{F,k}$; the environmental impact rate associated with the exergy destruction within the $k$-th component $\dot{B}_{D,k}$, the component-related environmental impact of a component $k$, $\dot{Y}_k$, and the sum of this two rates, $\dot{B}_{D,k} + \dot{Y}_k$ is very small.

The contribution of the component-related environmental impact $\dot{Y}_k$ to the total environmental impact associated with the $k$-th component $\dot{B}_{D,k} + \dot{Y}_k$ is very small. With this information, we may conclude that we do not necessarily need to calculate the value of $\dot{Y}_k$ for the environmental analysis of the plant. The high values of $\dot{B}_{D,k}$ for the RO1 and HPP of lane E, for the Pelton turbine and the RO1 of lane C and for the RO2 of lane A indicate that these components should be considered at first place in order to reduce the overall environmental impact.

Fig. 5 shows the relative difference of specific environmental impacts $r_{b,k}$, which represents the environmental quality of a component. This exergo-environmental variable is an indicator of the potential for reducing the environmental impact associated with a component. The High pressure pump in lane C and the Booster pump in lane E offer a relatively large potential for improvement of their environmental performance.

The factor $f_{b,k}$, which indicates how much the impact is coming from the device exergy destruction, is very low for all the components of the three frames, not only for the recovering devices. This means that the impact is caused mainly by operation of the plant, and that exergy destruction has a greater weight for the impact with respect to other environmental indicators. As a matter of fact, the construction, maintenance and disposal of the components do not have a large relative impact when considering the whole life cycle of the plant. Consequently, the values of $\dot{Y}_k$ obtained by the LCA with SimaPro, do not give a large contribution in determining the environmental impact. This result is directly linked to the

**Table 4**
Exergo-environmental variables of the main components of lanes A, C and E.

| Component | $b_{F,k}$ (mPt/kJ) | $b_{P,k}$ (mPt/kJ) | $\dot{Y}_k$ (mPt/s) | $\dot{B}_{D,k}$ (mPt/s) | $\dot{Y}_k + \dot{B}_{D,k}$ (mPt/s) |
|---|---|---|---|---|---|
| *Lane A* | | | | | |
| $HPP_A$ | 11.8 | 15.0 | 0.10 | 1612 | 1612 |
| $RO1_A$ | 18.6 | 34.7 | 0.14 | 1155 | 1155 |
| $RO2_A$ | 19.9 | 29.5 | 0.13 | 3693 | 3693 |
| $BP1_A$ | 4.3 | 6.3 | 0.10 | 325 | 325 |
| $BP2_A$ | 0.7 | 1.2 | 0.10 | 10 | 10 |
| $DWEER_A$ | 21.6 | 21.9 | 0.10 | 209 | 209 |
| *Lane C* | | | | | |
| $HPP_C$ | 12.9 | 36.0 | 0.10 | 2948 | 2948 |
| $RO1_C$ | 38.0 | 68.3 | 0.10 | 2247 | 2247 |
| $RO2_C$ | 34.1 | 49.4 | 0.09 | 9031 | 9031 |
| $BP_C$ | 3.7 | 5.5 | 0.12 | 7645 | 7645 |
| $PELTON_C$ | 36.7 | 60.5 | 0.10 | 245 | 245 |
| *Lane E* | | | | | |
| $HPP_E$ | 20.1 | 27.5 | 0.10 | 5902 | 5902 |
| $RO1_E$ | 33.2 | 59.5 | 0.12 | 9617 | 9617 |
| $RO2_E$ | 33.0 | 40.4 | 0.13 | 1402 | 1402 |
| $BP_E$ | 3.2 | 7.2 | 0.10 | 313 | 313 |
| $ERI_E$ | 34.9 | 36.7 | 0.09 | 1022 | 1022 |

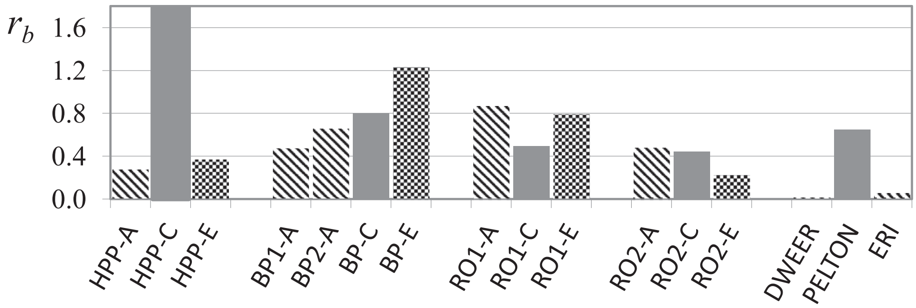


**Fig. 5.** Relative difference between the average specific environmental impacts, $r_{b,k}$ of the main components of lanes A, C and E.

exergy destroyed during operation, fundamentally, by the electricity consumption (this is the reason why a well-performing expander is a great help in the case of a RO plant).

## 5. Conclusions

In this paper, the exergy and exergo-environmental analysis is applied to a desalination plant located in Gran Canaria using real operating data. A comparison between different lanes has been carried out, taking into account the different energy recovery method used in them (Pelton turbine or pressure exchanger systems DWEER or ERI).

Regarding the lane with a Pelton turbine, a third part of the exergy destruction takes place in the turbine; another third part in the pumps (high pressure pump and booster pump) and the rest in the reverse osmosis stages. In the lane with ERI, more than 50% of the exergy destruction occurs in the pumps, due to the inefficiencies in the HPP; 45% is destroyed in the reverse osmosis membranes and just a 4% in the energy recovery system. The exergy destruction taking place in the DWEER device is insignificant, just 2% of the total exergy destruction in this lane. Other devices in this lane destroy less exergy than similar components in other lanes.

Total exergetic efficiency of the lanes is within the range of 26–32%. This value is considerably higher than that reported in literature for similar systems (4%). The reason is that in literature, common model represents seawater as an ideal mixture of liquid water and solid sodium chloride. However, in an ideal mixture model, the chemical exergy part is neglected. This assumption leads to doubtful negative flow exergy values. In this paper, a real mixture model, together with the most up-to-date thermodynamic properties of seawater have been used in order to conduct the exergy analysis; as a result, correct trends for the flow exergy are obtained.

The exergo-environmental analysis show that the largest potential for reducing the overall environmental impact is associated with RO1 and HPP of lane E, the Pelton turbine, the RO1 of lane C and the RO2. The contribution of the component-related environmental impact $\dot{Y}_k$ to the total environmental impact associated with the k-th component $\dot{B}_{D,k} + \dot{Y}_k$ is in this case negligible.

To better understand the interconnections among components and to develop additional suggestions for reducing the overall environmental impact of the plant, an advanced exergetic analysis could be applied [35]. Also an exergoeconomic analysis could provide important information on cost reduction, in parallel with the reduction of environmental impact.

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