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Exergy cost of water supply and water treatment technologies.

Amaya Martínez[a], Javier Uche[a]*, Carlos Rubio[b], Beatriz Carrasquer

[a]*CIRCE Foundation, University of Zaragoza, Zaragoza, Spain*
Tel. +34976762584; Fax +34976732078; e-mail: javiuche@unizar.es
[b]*Mechanical Engineering Faculty, UMSNH, Morelia, (Michoacán, México), c/ Maria de Luna 3, 50018, Zaragoza, Spain*

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ABSTRACT

Exergy analysis (EA) has demonstrated to be useful in the assessment of the energy performance of technologies, including those regarding water management. In this paper, an EA-based index like the unit exergy cost (UEC) of different water-related technologies were obtained, from transport (pumping) to depuration and even brackish and seawater desalination. Those coefficients are important to quantify the additional energy consumption of present technologies with respect to the ideal ones, which correspond to the behaviour of a reversible process. Minimum UEC values were obtained in pumping techniques (1.5). Wastewater treatment plants (WWTP) ranged from 4 to 5, and commercial desalination varied from 5 (reverse osmosis) to 21 (multi-stage flash distillation). This affirms the fact that chemical-based water treatments are less efficient from the point of view of thermodynamics, however further improvements might be reached in those processes. Besides their embedded energy-efficiency information, the UEC values could be applied to assess water costs. For instance, the European Water Framework Directive (WFD) considers that environmental costs (those to restore water bodies up to an objective state) have also to be charged to water users. Consequently, the UEC values of water technologies together with energy prices could easily be used to estimate those environmental costs associated to physico-chemical degradation of water bodies.

Keywords: Exergy; Exergy costs; Energy efficiency; Desalination; Pumping; Wastewater treatment plant; Water cost

1. Introduction

Fresh water withdrawal increases yearly at a higher rate than the world population does: while the world's population tripled in the twentieth century, the use of renewable water resources has grown six-fold according to the United Nations [1]. The trend towards more urbanized societies and growing population (increase of 40–50% in the next 50 y) living in large cities will have very large implications for freshwater use and wastewater management. Apart from fresh water abstracted from the natural hydrological cycle, seawater desalination and reclaimed wastewater are nowadays alternative options for water supply and further uses. Thus, when diverse fresh water supply alternatives are feasible, comprehensive methodologies are required in order to take decisions about the most suitable one for each situation.

Energy efficiency can be analyzed by means of the thermodynamic property exergy (''*useful energy*''). The exergy of any water body represents the maximum mechanical work that can be obtained from it until

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*Corresponding author

reaching the complete equilibrium with the reference environment (that is, it is totally diluted into the ocean). Alternatively, it could be also understood as the minimum energy to replace the useful energy of that water body from the ocean (zero exergy).

Exergy differs from the *specific energy demand* concept, since the latter is exclusively concerned on the First Law. Nevertheless, within the exergy term, both quantitative and qualitative features are jointly analyzed and, therefore, the completeness of the Second Law of Thermodynamics is accounted for. Exergy analysis (EA) has been successfully applied to study the energy performance of complex energy systems [2–4]. Moreover, exergy could be easily linked to economic values (through the use of energy prices) and/or to environmental penalties (through the use of emission factors). Its application to water issues is a very promising alternative in order to deal with water issues from the point of view of natural resources degradation, that is, through the calculation of the exergy losses associated to the consumption and contamination of natural water bodies.

This field of study is framed within the physical hydronomics (PH) discipline, defined as the specific application of Thermodynamics to physically characterize the degradation and restoration of water bodies [5–6]. PH compares the exergy profile of a river along its course (which is characterized by its flow and quality) with the exergy profile of that river in its objective condition, according to the environmental normative. As some restoration technologies will be eventually required to restore both the quantity (desalination and pumping) and the quality (depuration) of water bodies, to know the unit exergy costs (UEC) of water treatment techniques is essential to fairly apply the PH methodology. High UEC values mean that technology is far from the best energy-efficient one for that purpose. Then, guidelines could be immediately derived to improve that performance.

2. Unit exergy cost definition. Application to water resources evaluation

Exergy is a thermodynamic property that measures the capacity of a system to produce useful work during the process that leads to its thermodynamic equilibrium with the environment (or reference, which contains zero exergy by definition). The specific exergy of a water body (b) is mainly characterized by its composition and concentration with respect to the environment –chemical component – its temperature with respect the surrounding environment – thermal component – and its altitude with respect to sea level – potential component. As this work deals with the hydrological cycle, reference adopted to calculate exergy value is seawater. Total exergy (B) of a water resource (WR) is then obtained by multiplying the specific exergy by its corresponding flow.

The UEC concept has been widely used in EA. It is defined as the inverse of the exergy efficiency of a process. It is dimensionless. If the input–output analysis of complex energy systems is used, the UEC is calculated as the ratio between the exergy needed to produce a resource (fuel, F) and the exergy of the product where the interest is focused on (product, P), as reproduced in Eq. (1). If the process were reversible, its value would be 1. Therefore, it gives information about the irreversibility of the process.

$$\mathrm{UEC} = \frac{F}{P} \quad (> 1). \tag{1}$$

When a technology is analyzed from the exergy approach, the first step lies on the flows identification. All the inputs and output flows within the plant must be identified and classified as *fuels* or *products*. Then, from the obtained products, the non-useful ones (*residues*) have to be labelled as well. Therefore, it is possible to define different UEC values attending to the targeted products. In this work, the UEC is focused on treated water (''product'') of analyzed technologies as the desired final product through the UEC ratio ($\mathrm{UEC_{prod}}$) indicated in Eq. (2). It means that the rest of output flows are defined as residues and they are not considered. Alternatively, when the entire process is observed, the exergy value of any output flow of the system is included in that ratio and then the UEC of the whole ''process'' ($\mathrm{UEC_{proc}}$) is calculated (see Eq. (3)). As expected, lower values will be usually obtained with $\mathrm{UEC_{proc}}$ with respect to $\mathrm{UEC_{prod}}$, values.

$$\mathrm{UEC_{prod}} = \frac{F}{P} (>> 1), \tag{2}$$

$$\mathrm{UEC_{proc}} = \frac{F}{\sum_i P_i} (> 1). \tag{3}$$

Once the UECs of the different water-related technologies were obtained, their economic costs could be easily assessed. The real energy consumption to restore one cubic meter of water is given by the specific exergy cost (SEC in kJ/m^3), which is defined as the product of the exergy gap ($\triangle b$) between the initial and final states of that water resource (WR) and the UEC (Eq. (4)):

$$\mathrm{SEC} = \mathrm{UEC} \cdot \Delta b. \tag{4}$$

The total exergy replacement cost (ERC in kJ/y) of a water resource (WR in m^3/y) previously degraded by human activities (by means of a reduction of flow, height or quality) could finally be calculated as the product of the SEC and the WR (see Eq. (5)):

$$\mathrm{ERC} = \mathrm{SEC} \cdot \mathrm{WR}. \tag{5}$$

Main advantage of ERC with respect to conventional economic coefficients is that it also embeds the thermodynamic efficiency of the water treatment process applied and, since exergy is an extensive property, if diverse processes occur, they could be added separately and it would not lead to inconsistencies. As different technologies are required (pumping for potential component and desalination or wastewater treatment for the chemical one), a separated analysis for each of them is formally required.

In general, a WR could be any water body suffering from any kind of degradation. In a previous work [4], WR were associated to global water resources, that is, total water stocks and water abstracted every year from the natural hydrologic cycle. At that point, the emphasis was made on the amount of energy needed to restore available water and water consumed by mankind along the year. The analysis could however be reduced up to a small river basin or to any water body. In that case, a deep knowledge of the UEC of the considered water-related technologies is required, since they will be translated into economic costs. Disproportionate costs could appear if quality degradation or water abstraction is severe in a River Basin, therefore the fulfilment of the WFD objectives could be locally delayed.

3. Unit exergy cost of desalination technologies

A black box system shown in Fig. 1 was used to analyze the UEC of a generic desalination technology.

Raw seawater (SW) and required energy (electricity W and/or heat Q) are the inputs in the EA. Main output flows are distillate/permeate (D) and brine blowdown (BD). Thermal technologies also include cooling water (CW) to reject flow. Recovery ratio (R_c, freshwater produced per raw seawater fed) is also included as a parameter, since its value is representative of the $\mathrm{UEC_{prod}}$ and $\mathrm{UEC_{proc}}$ differences in desalination.

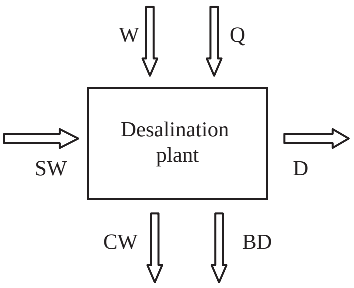

Fig. 1. Schematic i/o EA of a desalination unit.

The cornerstone of the analysis relies on the detailed calculation of the exergy flows entering and leaving the generic scheme presented in Fig. 1. It is maybe worth at this point to remember that power in energy terms is equal to its exergy, since electricity has the highest energy quality ($W = b_W$). The exergy of the heat flow (b_Q) is however defined by the Carnot factor, according to Eq. (6):

$$b_Q = Q \cdot \left(1 - \frac{T_{\mathrm{ref}}}{T_{\mathrm{sw}}}\right), \tag{6}$$

where T_{ref} is the reference temperature of water. Table 1 shows the main averaged features input properties (salts concentration, C, temperature, T) and requirements (power, W, and heat, Q) of main commercial desalination technologies and their associated exergy flow values.

In particular, $b_{\mathrm{ch,sw}}$ and $b_{\mathrm{t,sw}}$ are, respectively, the chemical and thermal component of specific exergy of seawater, and b_W and b_Q the exergy of the electricity and heat consumed in the plant. Then, from typical performance parameters of desalination processes (MSF, MED, RO and ED units), the flow, composition and temperature (see Table 2) and the exergy flows of distillate and brine were then calculated (see Table 3).

After assessing the exergy flows, the corresponding $\mathrm{UEC_{prod}}$ (exergy of distillate or permeate is the unique product) and of the whole process ($\mathrm{UEC_{proc}}$, brine and cooling water outfall exergies also compose the plant output) are obtained by applying Eqs. (2) and (3), respectively. Results shown in Table 4 indicate that low R_c values imply strong differences between $\mathrm{UEC_{prod}}$ and $\mathrm{UEC_{proc}}$ values, since plant residues have valuable energy (exergy).

4. Unit exergy cost of wastewater treatment units

A wastewater treatment plant (WWTP) process usually includes three stages: primary, secondary, and tertiary (optional) treatments. Primary treatment involves little more than removing suspended solid materials from wastewater and the returning liquids to a stream. Secondary treatment removes suspended solids and a larger percentage of organic matter. If nitrogen and phosphorus removal is compulsory for WWTPs discharging in sensitive areas affected by diffuse pollution, a third stage is then required.

A general input–output schema of a WWTP is presented in Fig. 2. Input flows were the untreated input

Table 1
Input flows and their exergy values for generic desalination technologies

	C_{sw} (ppm)	T_{sw} (°C)	W (kWh/m$^{3^*}$)	Q (MJ/m$^{3^*}$)	$b_{ch,sw}$ (kJ/kg)	$b_{t,sw}$ (kJ/kg*)	b_W (kJ/kg*)	b_Q (kJ/kg*)	b_{in} (kJ/kg*)
MSF	45,000	25	3.5	250	0	0.4312	1.51	7.3	9.2
MED	45,000	25	1.5	200	0	0.4312	1.08	6.2	7.7
RO	35,000	20	4.0	0	0	0.0619	6.48	0.0	6.5
ED	2,000	20	1.0	0	2.1325	0.0642	0.45	0.0	2.6

Table 2
Typical output parameters of diverse desalting units.

	R_c	C_D (ppm)	T_D (K)	C_{CW} (ppm)	T_{CW} (K)	C_{BD} (ppm)	T_{BD} (K)
MSF	0.12	0	293.7	45,000	310.2	63,000	305.2
MED	0.20	0	303.2	45,000	305.2	69,000	303.2
RO	0.45	300	293.7	_	_	63,391	293.7
ED	0.13	250	293.2	_	_	2,250	293.2

Table 3
Specific exergy of flows leaving a typical desalination unit

	$b_{ch,D}$ (kJ/kg*)	$b_{t,D}$ (kJ/kg*)	$b_{ch,CW}$ (kJ/kg*)	$b_{t,CW}$ (kJ/kg*)	$b_{ch,BD}$ (kJ/kg*)	$b_{t,D}$ (kJ/kg*)	$b_{ch,out}$ (kJ/kg)	$b_{t,out}$ (kJ/kg)	b_{out} (kJ/kg)
MSF	3.50	0.0841	0	2.590	0.0968	1.4640	0.45	1.95	2.40
MED	3.50	1.1060	0	1.464	0.2203	1.0970	0.84	1.15	2.00
RO	2.56	0.0840	_	_	0.4700	0.0816	1.41	1.20	2.61
ED	2.58	0.0664	_	_	2.0821	0.0642	2.14	0.06	2.21

water flow (IW), mainly described by its salts concentration (C), its chemical oxygen demand (COD) and the dissolved silica; chemical compounds (CC) consumed in the coagulation and flocculation processes; and the electricity consumption (W). Main output flows generated in a WWTP are the recovered treated water (TW), fat (Ft), silica (Sn) and sludge (S). Heat flow has not been included because it is usually consumed within the plant: hot gaseous products from the sludge treatment are used as energy source for further gasification. Solids handling was not included in the analysis, since it is considered to be outside of the control volume of the WWTP.

Because of the process heterogeneity in the existing WWTP, it would not be accurate enough to deal with average performance data at this stage. In order to assess the UEC of the WWTP, 12 real plants were analyzed from the exergy point of view. They are located at the Inland Basins of Catalonia, northeast Spain. Operating parameters were taken from historic operating data [7–9]. Most relevant physical input–output measurements were salinity (C) and COD.

A detailed and comprehensive study of the participating streams is necessary to know its flow exergies, since they are not usually calculated. It is synthesized in the following.

4.1. Chemical compounds flow

Aluminium sulphate, $Al_2(SO_4)_3$, is the dominant coagulant in many WWTP processes. It has been

Table 4
Unit exergy costs for typical desalination units

	UEC_{proc}	UEC_{prod}
MSF	3.8	21.4
MED	3.8	8.3
RO	2.5	5.5
ED	1.2	8.0

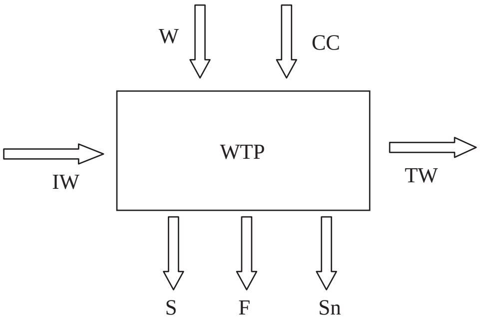

Fig. 2. Main inputs and outputs of a WTP.

also considered as representative to calculate the specific exergy of the whole set of chemical compounds intervening in the depuration process. Note that coagulant fraction is much more important than polyelectrolyte (flocculant) fraction. Anyway, it seems almost impossible to find specific exergy tables or empirical correlations to calculate the exergy of polymeric liquid substances without sulphur [10]. Total averaged chemical dosing was estimated in 0.04083 kg/m^3, with a molecular mass of 342 g/mol [10,11]. Finally, specific exergy value of chemical compounds ($b_{ch,cc}$) is then calculated from its specific molar exergy value.

4.2. Silica flow.

Silica content can be found within the plant in four different streams: dissolved on water (input and output flows), recovered silica (output flow), and a fraction included in the recovered sludge. Dissolved silica concentration in input raw water has been taken as 0.1008 mg/l, a typical value for Catalonian rivers. The mass fraction of silica dissolved in water has been calculated as the following equation

$$x_{Sn,out} = x_{Sn,in} - \frac{m_{Sn,S}}{m_{TW}} - x_{Sn}, \tag{7}$$

where $x_{Sn,in}$ and $x_{Sn,out}$ are the input and output dissolved silica mass fractions in raw water respectively; $m_{trt,w}$ and $m_{Sn,S}$ represent the total mass of treated water and silica within the sludge; and x_{Sn} represents the mass of silica recovered per m^3 of treated water. The specific concentration exergy of dissolved silica b_{Sn} is calculated by Eq. (8) as a function of the dissolved silica and reference concentrations.

$$b_{Sn} = R \cdot T_{ref} \cdot \left(\frac{\overline{x}_{Sn}}{1000 \cdot M_{Sn}} \ln \frac{x_{Sn}}{x_{ref,Sn}} \right), \tag{8}$$

where R is the universal gas constant and T_{ref} is the reference temperature; M_{Sn} stands for the molecular weight of silica (represented by SiO_2). Finally, the amount of silica recovered in the sludge is obtained from its composition and an empirical equation which depends on the C, H, N and O composition of the sludge and the gross heating value. Recovered silica flow concentration was estimated about 8 mg/l of treated water [12].

4.3. Organic matter flow

Organic matter (OM) content is not representative in the sea, thus it does not take part of the reference environment (RE). Consequently, its exergy contribution has to be determined by their formation chemical exergy ($b_{ch,OM}$). Relationship obtained by Tai [13] (Eq. (9)) has been applied for exergy calculations of input and output flows as a function of the COD parameter

$$b_{ch,OM} = 13,6 \cdot \mathrm{COD}. \tag{9}$$

4.4. Sludge

Any water treatment involves sludge generation. That sludge residue possesses valuable energy which is basically composed by carbon, hydrogen oxygen and nitrogen. According to Kotas [14], the corresponding chemical exergy could be calculated as Eq. (10) indicates. This author related empirically the exergy of the dry combustion material and its calorific values (HV) through a coefficient (Eq. (11)). Castells et al. [15] estimated the heating value of sludge in 19,451 kJ/kg dry sludge. Term S represents the sludge generation per cubic meter of treated water

$$b_s = \mathrm{coef} \cdot \mathrm{HV}_s \cdot \frac{S}{1000}, \tag{10}$$

$$\mathrm{coef} = 1.0437 + (0.1882 x_H / x_C) + (0.0610 x_O / x_C) + (0.0404 x_N / x_C). \tag{11}$$

In Eq. (11), fractions x_C, x_H, x_O and x_N represents the average mass fractions of carbon, hydrogen, oxygen, and nitrogen, respectively. Other authors [16] consider a moisture percent in the organic material when sludge composition is assessed, but it is not here the case, since the collected data reported dry organic sludge.

Regarding sludge management, the first concerns must be aimed to its minimization. When reused, sludge treatments are mainly focussed on agriculture (directly applied on crops, or by means of a previous aerobic or anaerobic stabilization). Anaerobic digestion is almost the only way to obtain energy from sludge

Table 5
Inputs and derived exergy flows of four selected Catalonian WWTPs

	WWTP capacity (m^3/day)	C (ppm)	COD (mg/l)	W (kWh/m^{3*})	b_{IM} (kJ/kg^*)	b_{OM} (kJ/kg *)	b_W (kJ/kg^*)
Begur	2,190	1,184	600	0.567	2.3142	8.160	2.0412
Blanes	23,500	883	640	0.377	2.3903	8.704	1.3572
Cadaqués	4,000	1,612	1,041	0.557	2.2150	14.160	2.0052
Castell d'Aro	35,000	1,555	540	0.483	2.2278	7.344	1.7388

in the analyzed WWTP. From sludge, with an approximately 4% OM content, averaged biogas composition of about 75% CH_4 and 25% CO_2 could be produced, which would be consumed in an internal combustion engine to generate power. According to the Environment Department of *Aragón* [17], around 0.13–0.16 kWh/m^3 of treated water could be obtained. Consequently, it represents an important percentage of the total energy required in a WWTP, which raises up to 0.20–0.35 kWh/m^3 in conventional activated sludge anaerobic treatments.

Specific chemical exergy of the sludge after the anaerobic process was also calculated from the mentioned empirical correlations given by Kotas [14].

4.5. Fat

The standard molecule $C_{18}H_{32}O_2$ represents the fat content in a WWTP, one of the most common fat acid molecules in the environment. The mass weight of the fat molecule is 282 g_{Ft}/mol and the corresponding net calorific value (HV_{Ft}) is 38.874 kJ/kg, considering the nutritional fat acid standard calorific value. Exergy calculations followed here were the same as those used to sludge flow.

Table 5 shows the input values for only four of the 12 WWTP studied here, and their corresponding exergy values. Values of chemical compounds, dissolved silica, fat and recovered silica flow were not included since they were kept constant for all WWTPs.

Table 6 shows the exergy values of the output flows analyzed in the abovementioned WWTPs.

After applying the UEC definitions, UEC_{proc} and UEC_{prod} values for the 12 Catalonian WWTPs are presented in Table 7.

5. Unit exergy cost of pumping techniques

In addition to desalination and depuration, pumping is a representative water-related technology as well. A natural water course always losses its capacity to produce shaft work. Potential energy is then an additional quality of water. Pumping also restores the quality of a water body and, in consequence, its UEC has to be also accounted for. A simple procedure is followed, since it can be just defined as the inverse of the mechanical efficiency η_{mec} of a typical pump (Eq. (12)),

$$UEC_{pump} = 1/h_{mec}, \tag{12}$$

which is estimated in a 70%. Here, there is no distinction between the UEC_{proc} and UEC_{prod}, since only one product and one output are obtained (water at higher elevation). The result for the UEC of pumping is then a constant value of 1.43.

6. Results and discussion

Because of fresh water scarcity, some water treatments consuming energy to provide new water will be probably spread on a large scale. Thus, the measurement of its energy efficiency by means of thermodynamic parameters is an adequate way to evaluate its environmental consequences. The UEC was then

Table 6
Selected WWTPs exergy outputs

	C (ppm)	COD (mg/l)	Sn (kg/m^{3*})	S (kg/m^3)	b_{IM} (kJ/kg^*)	b_{OM} (kJ/kg^*)	b_{Sn} (kJ/kg^*)	b_S (kJ/kg^*)
Begur	1,139.2	48	0.0883177	0.368232	2.325	0.6530	0.601	3.643
Blanes	755.2	29	0.0957378	0.226216	2.425	0.3943	0.618	2.225
Cadaqués	1,075.2	70	0.0880009	0.199906	2.341	0.9520	0.621	1.980
Castell d'Aro	640.0	49	0	0.255166	2.457	0.6663	0.615	2.525

Table 7
UEC values in catalonian WWTP plants analyzed

	UEC_{proc}	UEC_{prod}
Begur	1.83	4.46
Blanes	2.32	4.69
Cadaqués	3.23	5.81
Castell d'Aro	1.92	3.87
Colera	3.08	5.60
El Port de la Selva	2.07	4.10
Empuriabrava	1.99	4.39
L'Escala	2.47	4.62
Llançà	2.19	3.57
Lloret de mar	2.53	4.69
Palamós	2.06	3.44
Pals	2.17	4.16
UEC (average)	*2.32*	*4.45*

presented in this paper and calculated for diverse water treatment technologies.

First, four commercial desalination processes were analyzed from the exergy approach. Results show that, attending only to the output fresh water, that is, to the UEC_{prod} index, they range from 5.5 (RO) to 8.0 (ED), 8.3 (MED) and 21.4 (MSF). This order was maintained when the attention is focused on the energy efficiency of all output flows, that is, on the UEC_{proc}: ED (1.2), RO (2.5), MED (3.8) and MSF (3.8).

Results reinforce the idea that RO is the best energy-efficient technology to desalt seawater. Energy efficiency of ED permeate is really low beside of desalting brackish waters, this is mainly due to its low R_c value. Regarding distillation processes, main sources of irreversibility (exergy losses) are focused on cooling water to outfall and the temperature drop of the last stage with respect to seawater, and their relatively low R_c ratio. Furthermore, as MED consumes low-temperature thermal energy to feed the first stage of the unit, better UEC figures are obtained with respect to MSF units.

Secondly, the analysis was focused on WWTPs. The main difficulty to carry out the analysis was that organic compounds and some other chemical compounds are not well-known in the exergy context. In addition to that, strong differences could be found with respect to raw water characteristics and plant capacities. Thus, real data coming from 12 existing Catalonian WWTPs were taken. The average value obtained for the WWTPs operating in the region was 2.32 for the UEC_{proc} and 4.45 for the UEC_{prod}. The UEC_{prod} for the 12 case studies ranged between 3.44 and 5.81, however. They were close enough to assume that the average value could be extrapolated to other conventional WWTPs in Catalonia.

Water pumping has been also added to the analysis, since it is also a very common practice within the water cycle. Because of the simplicity of the process and the absence of co-products, no difference between the process and the product UEC values were found. The UEC value of pumping water is, on average, the lowest UEC one (1.43) of all technologies since only mechanical frictions have to be overcame in this mechanical process.

7. Conclusions

The UEC value is a guide to compare the energy efficiency of different available technologies for a given purpose. Those indexes allow analysing the processes and identifying their weaknesses and strengths from a thermodynamic perspective. However, when technologies really have different purposes, they should not be directly compared through their UEC values.

The most important challenge of introducing the UEC is that thermodynamic concerns regarding the efficiency of the process could be included in a multidisciplinary decision support system, which should be complemented with conventional economic analysis and any other environmental considerations (as the entire life cycle assessment of technologies).

Regarding the sensitivity of the results obtained in the paper, it is important to remember that exergy does not follow a linear behaviour with respect to input/output water quality variations and/or the energy required to any water treatment. The study presented here is also adequate to analyze the effect of some operating parameters (like R_c), apart from the analysis on a input variability, which really corresponds to diverse situations.

Finally, note that this way of assessing the cost of water-related technologies opens new research fields. In general, main differences between UEC_{prod} and UEC_{proc} were found in the energy quality (or exergy content) of the resulting co-products in each technology. The unit exergy cost of the product (UEC_{prod}) is obviously higher than the exergy cost of the process (UEC_{proc}) since the fact is that some output residues have available energy (exergy) which is not reused in other activities. So, thermodynamic inefficiency of that process is clearly shown. Attending to desalination technologies, cooling water preheating or power generation from brine [18] could take advantage of that energy potential that is presently misused. If better energy efficiency is pursued, higher R_c values will reduce the energy available (exergy) in brine. Brine concentration or even salt production should be carefully studied. Regarding energy efficiency in depuration, efforts should be focussed on new combinations which take advantage of the energy potential of sludges (by means of new valorised co-products in the sewage process).

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Symbols

b	specific exergy (kJ/kg or kJ/kg*)
B	total exergy (kJ)
BD	Brine blowDown (m^3/year)
C	salt concentration (ppm)
CC	chemical compounds (kg/kg*)
COD	chemical oxygen demand (mg/l)
CW	cooling water (m^3/y)
D	distilled water (m^3/y)
DSS	decision support system
EA	exergy analysis
ED	electrodialysis
ERC	exergy replament cost (kJ/year)
F	exergy or resources (Fuel)
Ft	fat (m^3/d)
HV	heating value
IM	inorganic matter
IW	input water (m^3/day)
M	molecular mass (kg/kmol)
MED	multiple effect distillation
MSF	multi-stage flash distillation
OM	organic matter
P	exergy of products (Product)
PH	physical hydronomics
Q	heat flow (kJ/m$^{3^*}$)
R	gas constant (kJ/kmol K)
RE	reference environment
R_c	recovery ratio (dimensionless)
RO	reverse osmosis
S	sludge flow (m^3/d)
SEC	specific exergy cost (kJ/m^3)
Sn	silica (m^3/d)
SW	seawater
T	temperature (K)
TOC	total organic carbon (mg/l)
TW	output treated water (m^3/d)
UEC	unit exergy cost (dimensionless)
W	electricity flow (kWh/kg*)
WFD	water framework directive
WR	water resource (m^3/year)
WWTP	wastewater treatment plant
x	mass fraction

Greek letters

$\triangle b$	exergy difference between two states of the water body (kJ/m^3).
η	efficiency

Subscripts

ch	chemical
in	input
mec	mechanical
ref	Reference Environment
out	output
proc	process
prod	product
pump	pumping
t	thermal

Superscripts

*	per unit of treated water.

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