Desalination and Water Treatment
www.deswater.com

10 (2009) 165–174

Assessment of the world fresh water resources through energy requirements in desalination technologies

Amaya Martínez[a]*, Javier Uche[a], Angel A. Bayod[b], Carlos Rubio[c]

[a]*CIRCE Foundation, Department of Mechanical Engineering, University of Zaragoza, Maria de Luna, 5 50018 Zaragoza, Spain Tel. +34 (976) 76 18 63; Fax +34 (976) 73 20 78; email: amayamg@unizar.es*
[b]*CIRCE Foundation-Department of Electrical Engineering, University of Zaragoza, Spain*
[c]*Faculty of Mechanical Engineering. University of Michoacan. Morelia, Mexico*

Received 2 October 2008; Accepted in revised form 4 September 2009

ABSTRACT

The world water withdrawal is presently about 4,000 km^3/y, which is around the 30% of the total annual technically renewable world water resources. The tendency of water consumption is to keep rising, even quicker than the energy consumption. Thus, the use of objective methodologies for assessing a value to fresh water resources is a mandatory task at this moment, in order to provide policy makers with objective and global decision tools. When water availability is measured in terms of its energy requirements, sustainability of new water-providing techniques could be analyzed. The close relationship between energy demand and climate change also support the interest of the proposed approach. From a thermodynamic perspective, two main features give exergy (available energy) value to water: its quality (chemical exergy) and its location (potential exergy). Water composition makes it useful for different economic uses such as drinking, industry, irrigation, whilst potential energy can be used to produce shaft work and electricity. The approach proposed in this paper defines the value of fresh water through its exergy replacement cost, that is, the energy consumed by hypothetical technologies that restore consumed or degraded water by mankind. In this paper, the amount of exergy required to restore water used worldwide in a year was evaluated by continents. The exergy requirements to obtain fresh water, both in quality (by means of seawater desalination) and in altitude (by means of pumping) were calculated. Present mix of desalination techniques (with their corresponding performance efficiencies) were introduced to evaluate the exergy costs of restoring the natural water cycle. Then, those exergy costs were compared to worldwide power demand and land requirements (if power were obtained from solar energy): in particular, with photovoltaics and parabolic through collectors. From this point of view based on Thermodynamics, global results obtained here question the use of desalination as the definite solution to world water scarcity. The figures show that the energy required for restoring world fresh water renewable resources would exceed by twenty times the present electricity demand. When the analysis is restricted to only the world water withdrawal, that energy is almost twice that demand.

Keywords: Water resources assessment; Exergy; Exergy replacement cost; Thermodynamic efficiency

* Corresponding author.

Presented at EuroMed 2008, Desalination for Clean Water and Energy Cooperation among Mediterranean Countries of Europe and the MENA Region, 9–13 November 2008, King Hussein Bin Talal Convention Center, Dead Sea, Jordan.

1. Introduction: water present and future needs

While the world's population tripled in the twentieth Century, the use of fresh water resources has grown six fold. According to the United Nations, the world's urban population increased more than ten fold and rural population only was doubled. The trend towards more urbanized societies and demographic predictions (increase of 40–50% in the next 50 years) will have dramatic implications for freshwater use and wastewater management.

The availability of water resources and their distribution in space and time has begun to be determined by human activity. In general, the water situation regarding its availability is not so alarming, but due to uneven distribution, some countries face water scarcity. Main problems are focused at Asia (36% of global water resources and 60% of the world population) and Europe (with 8% of resources and 13% of the population) [1].

In 2007, the Pacific Institute [2] estimated a water withdrawal of 3,714 km^3/y, which supposes the 30% of the total annual technically renewable water resources (in the range of 10,000–12,000 km^3/y). In the future, total water demand will grow by about 10–12% per decade. This fact, coupled with spatial and temporal variations in water availability, means that drinking water, as well as water to agriculture, industry and all the other uses is becoming scarce and competitive. This scarcity may intensify local conflicts related to water. A first step prior to take decisions is to know which is the physical value of fresh water (natural or produced by technologies), as any other natural resource. It could be done by means of thermodynamic parameters like exergy.

In thermodynamics, exergy is the energy that is available to be used, i.e., the exergy of a system is the maximum work that this system produces when it evolutes to the equilibrium with the surrounding environment. Electrical energy is the most valuable kind of energy and, in consequence, its exergy value coincides with its energy: both concepts can be used indistinctly in this case.

2. A methodology to assess water resources: Physical hydronomics (PH)

Since Meadows expressed his worries by the increased throughout caused by the *growth philosophy* of industrial countries [3], different authors have developed diverse methodologies aimed to assess and to obtain objective indicators able to help in the natural resources management. Mass and only sometimes energy have traditionally been the used tools for evaluating water resources [4].

In order to introduce the work presented here, it is important to retrieve the idea that all real processes taking place in an energy system are non-reversible. All natural resources have an economic, but also an exergy cost: the more irreversible a process is, the more natural resources and energy are consumed. That was the basic idea in thermo-economics (TE) [5], which combines economic and thermodynamic analysis by applying the concept of cost (originally an economic property) to exergy (a thermodynamic property). The purpose is, as stated by Bejan, Tsatsaronis and Moran [6], to provide information which is not available through conventional energy and economic analysis, but crucial to the design and operation of a cost-effective system.

Exergy analysis was initially developed in the fields of engineering. It can be considered as the most useful function to solve cost-optimization problems and to analyze energy conversion systems by evaluating the efficiency of energy systems and detecting the causes of the thermodynamic imperfection of thermal or chemical processes. In addition to that, it attracts escalating interests in environmental resource accounting, environmental impact assessment, ecological cost evaluation, and ecological modelling studies. It has also been successfully applied to natural resources assessment (e.g., [7–15]).

To sum up, a rather new discipline called exergoecology (EE) is starting to be considered as an adequate tool for natural resources accounting. In other words, EE is the application of the exergy analysis (second law analysis) to natural resources evaluation. The consumption of natural resources implies destruction of organized systems and dispersion, which causes entropy generation (or exergy destruction). This is why the exergy analysis can perfectly describe the depletion of natural capital and specifically, the degradation of fresh water resources: this branch of EE is denominated physical hydronomics (PH).

3. Physical hydronomics development

The analogy between the availability of a natural resource and its exergy helps us to relate each resource parameter with its exergy component (i.e., the temperature will determine the thermal exergy, the altitude the potential exergy, and so on). General expression of the exergy function [Eq. (1)] is presented here:

$$B = m\left[\left(u + Pv - u_0 - P_o v_o\right) - T_o\left(s - s_o\right) + \frac{c^2}{2} + gz\right] + \sum_{i=1}^{N} n_i\left(\mu_i - \mu_{io}\right) \quad (1)$$

where B is the total exergy and the specific exergy of the studied flow; u, v and s are respectively the specific internal energy, volume and entropy; P is the pressure and T the temperature; c stands for the velocity, g for the gravity acceleration and z is the altitude above the sea. Finally, n is the mol number of the i component of the mixture, and μ the chemical potential. Subscript 0 denotes the reference environment (RE) values.

Under the PH's approach, world's renewable water resources are evaluated using the minimum energy (that is, the exergy) required to restore physical and chemical conditions in which the resources were delivered by the ecosystem. This concept can be used for any renewable resource. In this case, it was used to calculate the physical cost of replacing the fresh water which is freely supported by the hydrological cycle.

The thermodynamic value of water is given by its exergy and it has, in general, five components: thermal, mechanical, chemical, kinetic and potential. They all can be directly derived from Eq. (1), assuming the incompressible liquid model [16]. However, there are two main basic components: its composition (chemical exergy), which makes it useful for different economic activities, and its altitude (potential exergy), that allows producing shaft work. The first one represents the minimum energy needed to return water quality, which could be obtained by desalination techniques. The second one is the minimum energy needed to return the resource to its original altitude as delivered by the hydrological cycle; and it is represented by the energy required to lift that resource.

Exergy calculations are always related to an RE, which has zero exergy (both potential and chemical terms) by convention. Here, an average ocean [17] was selected as the most adequate RE. Then, when a river water flow reaches the ocean after being partially used and it is completely mixed into seawater, its chemical exergy becomes zero, as well as its potential exergy.

Fresh water stocks have been previously studied from the exergy perspective [18], [19]. However, attending to the impact of human pressures, it could be more interesting and accurate to evaluate the annual renewable water flows and the mankind demands, taking into account that they become free throughout the natural water cycle.

3.1. Chemical exergy component

As world water withdrawal is mainly obtained from river courses, the average composition of rivers on earth was taken to chemically characterize water used by humankind. Although there is a great variation in dissolved substances concentration of river waters, an extensive amount of available data allowed Livingstone [20] to estimate the mean composition of world river water. That average composition was used here to calculate the chemical specific exergy (b_{ch}, measured in kJ/kg) of that water taken from the hydrological cycle, by applying the well-know expression of the chemical exergy component [Eq. (2)].

$$b_{ch} = R\,T_0 \sum x_i \ln \frac{a_{i,r}}{a_{i,o}} \tag{2}$$

where x_i is the molar concentration of a substance i, $a_{i.r}$ and $a_{i,o}$ are the activity coefficients on the river and the RE respectively. Activities are used rather than molar concentrations since aqueous solutions were dealt with. R is the ideal gas constant (kJ/kgK) and T_0 is the RE temperature (K).

The $a_{i,r}$ term is the most complex to calculate since three different contributions must be considered: pure water, inorganic and organic dissolved substances. Concentration in dissolved substances could be easily measured from rivers. Pure water activity is calculated by means of its colligative properties [21].

3.2. Potential exergy component

The potential specific exergy term b_{pot} is calculated taking into account the height z (m) in which the water flow measurement was taken [Eq. (3)] and the RE height (z_0). Parameter g represents the gravitational force of the earth.

$$b_{pot} = g\left(z - z_0\right) \tag{3}$$

This is a relevant term in the analysis of a watershed, since potential exergy will be converted successively into kinetic, mechanical and electrical energy within hydropower utilities.

3.3. Total exergy of a water flow

Once the specific exergy b, is calculated for chemical and potential contributions, the total exergy of a water flow B, in power units (kW) at certain point, can be obtained as shown in Eq. (4):

$$B = \dot{q} \cdot \rho_w \cdot b = \dot{m} \cdot b \tag{4}$$

where q (l/s) is the water flow of a river/channel/pipe (or the amount of water delivered during a time period, WR) and ρ_w is the density of the aqueous solution (kg/l); those two terms constitute the mass flow ($\dot{m}$, kg/s). This figure has to be understood as the minimum energy needed (exergy, that is, by assuming reversibility in the processes involved) to produce, starting from the oceans, the water resource at a certain point up to its original height and composition.

3.4. Exergy cost

The present water treatment techniques are usually far from reversibility and energy really consumed to operate is higher than ideal thermodynamic processes. With the objective of reflecting this fact, the exergy cost is defined as the amount of exergy resources needed to obtain a unit of exergy of a functional product. It cannot be measured as a physical magnitude of a flow stream as temperature or pressure [22]. Therefore, it needs precise calculation rules for estimating it from physical data.

Three different exergy cost-related concepts have been applied in this study: the unit exergy cost, the specific exergy cost and the replacement exergy cost. They all give information about the exergy (minimum energy) needed to restore fresh water resource by applying diverse water treatment and supply processes.

3.4.1. Unit exergy cost

The unit exergy cost [UEC, Eq. (5)] is defined as the inverse of the exergy efficiency of the analyzed process. The UEC is calculated as the ratio between the exergy needed to produce (fuel, F) a resource, and the exergy of the resource which was considered the product of a system (product, Pr). If the process were reversible, its value would be 1. Therefore, it gives information about the irreversibility of the process. It is a dimensionless value.

$$\mathrm{UEC} = \frac{F}{\mathrm{Pr}}(>1) \tag{5}$$

3.4.2. Specific exergy cost

Thus, the real exergy consumption to restore one cubic meter of water by diverse water treatment techniques (each of them with a different UEC), could be calculated through the specific exergy cost (SEC), which is defined as Eq. (6) indicates:

$$\mathrm{SEC(kJ/m^3)} = \rho_w \cdot \mathrm{UEC} \cdot \Delta b \tag{6}$$

where Δb is the specific exergy difference (kJ/kg) between two bodies with diverse qualities and ρ_w is the water density.

3.4.3. Exergy replacement cost

Finally, the exergy replacement cost (ERC), that is the energy needed to restore the natural water resource (WR), which was previously degraded by human economic activities (height and quality losses), could be calculated with Eq. (7):

$$\mathrm{ERC(kJ/y)} = \mathrm{SEC(kJ/m^3)} \cdot \mathrm{WR(m^3/y)} \tag{7}$$

The main advantage of ERC is that it embeds the thermodynamic efficiency of applied water treatment processes and, as exergy is an extensive property, if diverse techniques are required, their ERC could be added without any inconsistency. As different technologies are required (pumping for potential component and desalination for the quality one), a separated analysis is presented.

4. Exergy replacement cost to restore potential component

The exergy needed to locate a water resource from the ocean to its original location is its potential exergy replacement cost (ERC_{pot}). In order to calculate it [see Eq. (7)], the SEC_{pot} value is required, which is, in turn, a function of the potential exergy drop Δb_{pot} and the unit exergy cost of pumping processes (UEC_{pot}), which is approximately the inverse of the exergy efficiency (η) of a pump, a well-known parameter in thermodynamics. Eq. (8) shows the argument followed here:

$$\mathrm{ERC}_{pot} = \mathrm{SEC}_{pot} \cdot \mathrm{WR} = \mathrm{UEC}_{pot} \cdot \Delta b_{pot} \cdot \mathrm{WR} \approx \frac{1}{\eta_{\mathrm{pump}}} \cdot g \cdot z \cdot \mathrm{WR} \tag{8}$$

where Δb_{pot} can be also expressed as a function of Δz and finally z, since the starting point (RE) is sea level ($z_0 = 0$).

When the $\mathrm{ERC}_{\mathrm{pot}}$ of water resources on a global scale (renewable water resources or water withdrawal) is searched, a detailed description of water courses (and their mean flows) would be required in order to calculate the mean attitude z of the water course. A first attempt could be the use of the mean attitude of the territories, extracted from available geophysical data (see Table 3 for details).

A different alternative to obtain the $\mathrm{ERC}_{\mathrm{pot}}$ is suggested from the point of view of the second law of thermodynamics: the minimum energy to elevate water (potential exergy) coincides with the power produced by a reversible turbine. Therefore, available figures from the inventory of the world's hydropower capacity could be used to calculate the minimum energy required for pumping (or restoring potential exergy component). Hydropower generation is measured on a large scale in TWh/y and diverse definitions are commonly used: the gross theoretical capability (GTC) expresses the total amount of electricity which could potentially be generated, if all available water resources were turned to this use. Those figures are estimated on the basis of atmospheric precipitation and water run-off. The technically exploitable capability (TEC) means the hydropower capability which is attractive and readily available with the existing technology. The economically exploitable capability is that amount of hydropower generating capacity which could be built, after carrying out a feasibility study on each site at current prices, and producing a positive outcome [23]. As far as hydropower resources are concerned, the International Hydropower Association [24] estimated that only one-third of the economically exploitable capability (EEC) has been currently developed. Obviously, the GTC parameter is the only one that accounts for the figures involved in assessing the global hydrologic cycle.

Mean altitude of the continents was taken as the parameter to calculate the potential component, since it permits following the abovementioned methodology. The UEC_{pot} is assumed constant and equal to the inverse of the exergy efficiency of a generic pump around 0.7.

5. Exergy replacement cost for chemical component

The minimum separation energy for obtaining fresh water from the ocean is its ERC_{ch}, corresponding to its quality component as described in Eq. (9). Again, apart from the considered WR, the ERC_{ch} depends on the chemical SEC_{ch}, which is a function of the exergy gap (Δb_{ch}) provoked by the different composition of RE and mean river waters, and consequently on the UEC_{ch} of the selected technology to desalt seawater.

$$ERC_{ch} = SEC_{ch} \cdot WR = UEC_{ch} \cdot \Delta b_{ch} \cdot WR = UEC_{ch} \cdot \left(R \cdot T_0 \cdot \sum_i x_i \ln \frac{a_{i,r}}{a_{i,o}} \right) \cdot WR \quad (9)$$

At this point, it is necessary to study the different commercially available technologies and, afterwards, obtaining their corresponding UEC values. Seawater desalination is the technology predominantly used for alleviating the problem of water scarcity in coastal regions. At present, it accounts for a worldwide production capacity of 39 million m^3/d [25], the 62% of all desalinated waters.

Energy currently consumed by seawater desalination should be a guideline for the UEC_{ch} calculation, since they convert seawater into fresh water in a non-reversible manner. Different sources [25–27] have been consulted, even a quite low specific energy consumption of 2–2.3 kWh/m^3 has been reported for a seawater desalination plant that uses an energy recovery system [28]. This affirms that RO is nowadays the best option from the point of view of energy consumption, although not for final permeate salinity [27], as it will be seen later on. Anyway, a conservative value of 4 kWh/m^3 was taken in this paper for further analysis.

In order to get the UEC_{ch} for desalination techniques, their input and output flow exergies are required (b_{in}, b_{out}). Most representative inputs are seawater (whose exergy is equal to cero as taken by the RE), specific power (or exergy, see section 1) W and heat Q (whose exergy content is determined through its energy multiplied by the Carnot's factor defined by the second law, $1 - T_0/T$). Main outputs are fresh water and brine. Desalting plant recovery ratio (RR), is also presented because it is very indicative to understand the UEC_{ch} figures: a higher RR means a lower UEC_{ch} and vice versa. This information is summarized in Table 1.

Present share of desalting technologies were included in the analysis. For instance, the Middle East presents a mixture between MSF (85.5%), RO (8.5%) and MED (6%) [29]. On the other hand, RO is the predominant technology in Europe and America. If no data were available, mean world average partition (MSF: 27.6%, MED: 9.6%, RO: 59.2% and ED: 3.5%) according to the Global Water Intelligence report [30] was taken. Table 2 shows the mean continental and global UEC_{ch} attending to their desalination plant inventory.

5.1. Exergy content of brine

An important issue not very often treated is the useful energy that brine contains, a waste product in desalination plants. An important amount of energy has been invested in the separation process to obtain fresh water, but also to concentrate the salts initially dissolved in seawater: both streams contain exergy. One of the advantages of exergy analysis is that it permits to discover energy losses consumed in producing by-products or wastes in a process. Main inefficiency of RO lies in the

Table 1
UECch calculation for the different desalination technologies

	W (kWh/m^3)	Q (MJ/m^3)	RR	b_{in} (kJ/kg)	b_{out} (kJ/kg)	UEC_{ch}
MSF	3.5	250	0.12	9.22	2.40	21.4
MED	1.5	200	0.20	7.69	2.00	8.3
RO	4	0	0.45	6.54	2.61	5.5
ED	1	0	0.13	2.65	2.21	8.0

Table 2
Technologies in the continents and average UEC_{ch}.

	MSF	MED	RO	ED	UEC_{ch} (av)
Global	27.6%	9.6%	59.2%	3.5%	8.25
Africa	27.6%	9.6%	59.2%	3.5%	8.25
Asia	85.5%	6.0%	8.5%	0.0%	19.03
Australia and Oceania	27.6%	9.6%	59.2%	3.5%	8.25
Central America	1.5%	3.5%	95.0%	0.0%	2.99
Europe	1.5%	3.5%	95.0%	0.0%	2.99
North America	1.5%	3.5%	95.0%	0.0%	2.99
South America	27.6%	9.6%	59.2%	3.5%	8.25

available energy (exergy) contained in the brine which is not converted into any useful energy nowadays, but promising advances are being found [31]. The other main source of thermodynamic inefficiency (or irreversibility) is the additional pressure drop (with respect to osmotic pressure, the theoretical minimum) that it is needed to apply in present RO modules in order to obtain a competitive permeate flux.

Fig. 1 shows the chemical specific exergy profile with salinity in a reverse osmosis desalination process with a seawater salinity (RE) of 35,000 ppm. For instance, if a RR of 45% was considered, brine would lead to 63,000 ppm, and has a chemical exergy value which obviously is different from zero. Brine discharge and further dilution is then a very important exergy loss (or thermodynamic inefficiency) in desalination processes, in some way contradicting the present use of techniques to improve as much as possible brine dilution in order to minimize its environmental impact.

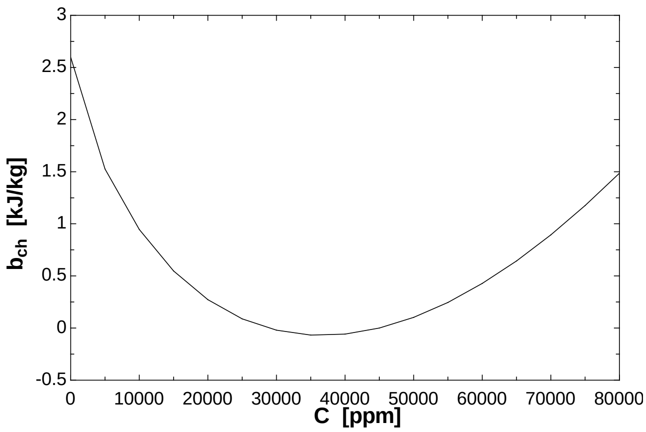

Fig. 1. Variation of chemical specific exergy with conductivity in aqueous solutions.

6. Exergy replacement cost of worldwide water resources

The exergy replacement cost (ERC) of water resources on the earth was calculated at two different perspectives: first, renewable fresh water provided by the hydrologic cycle is considered, and second, only world water withdrawal is included (in km^3/y). First number gives an idea of the huge amount of energy that would be theoretically consumed if natural hydrologic cycle were moved by humans' technology, and the second one estimated the energy required if all used waters were restored from ocean. This last figure was also compared with present energy consumption in order to present desalination (and pumping) as the end solution to water scarcity in the near future.

In Table 3, renewable water and water withdrawal are the two water resources (WR) which were alternatively evaluated. The average altitude in each continent (z_{av}) was used to obtain SEC_{pot}. Electricity generation and total surfaces will be later used to perform comparisons and to translate those energy demands into land requirements (if power were obtained from solar energy, SE).

6.1. Exergy replacement cost of the annual renewable fresh water resources

If fresh water resources supplied by the hydrologic cycle (see Table 3) were completely depleted, the minimum energy (exergy) that would be required to restore them was calculated. Chemical and potential unit exergy costs (UEC_{ch} and UEC_{pot}) were calculated in sections 4 and 5 respectively, by applying Eq. (7) and Eq. (8). The potential component of the ERC (ERC_{pot}) is calculated from mean attitude per continent given in Table 3; an alternative could be the above mentioned parameter denominated gross theoretical capability (see section 4). Chemical specific exergy was calculated from the average river composition as indicated in section 3.1 and, subsequently, the chemical component of the ERC (ERC_{ch}). Main figures obtained, as well as the total ERC, are presented in Table 4.

Table 3
General figures for renewable water resources and water withdrawal, by continents. Average altitude, surface and electricity generation

	Renewable water (km^3/y)	Water withdrawal (km^3/y)	h_{av} (m)	Electricity generation (TWh/y)	Surface (×10^3 km^2)
Global	42,862	3,714	855	19,020	134,220
Africa	4,151	213	750	515	30,300
Asia	13,509	2,295	960	6,540	44,900
Australia and Oceania	2,402	26	340	432	8,500
Central America	1090	101	720	88	2,720
Europe	2,900	392	340	3,436	9,900
North America	6,780	522	720	4,797	20,000
South America	12,030	165	590	792	17,900

Table 4
ERC of world renewable water resources

	Potential component (pot)					Chemical component (ch)					Total
	b_{pot} (MJ/m^3)	B_{pot} (MJ/y)	UEC_{pot}	SEC_{pot} (MJ/m^3)	ERC_{pot} (MJ/y)	b_{ch} (MJ/m^3)	B_{ch} (MJ/y)	UEC_{ch}	SEC_{ch} (MJ/m^3)	ERC_{ch} (MJ/y)	ERC (TWh/y)
Global	7.8	3.6E+14	1.43	11.22	5.1E+14	2.41	1.0E+14	8.25	19.90	8.5E+14	379,842
Africa	6.9	3.1E+13	1.43	9.85	4.4E+13	2.41	1.0E+13	8.25	19.90	8.3E+13	12,152
Asia	8.8	1.3E+14	1.43	12.60	1.8E+14	2.41	3.3E+13	19.03	45.91	6.2E+14	50,697
Australia and Oceania	3.1	8.0E+12	1.43	4.46	1.1E+13	2.41	5.8E+12	8.25	19.90	4.8E+13	3,195
Central America	6.6	7.7E+12	1.43	9.45	1.1E+13	2.41	2.6E+12	2.99	7.22	7.9E+12	3,060
Europe	3.1	9.7E+12	1.43	4.46	1.4E+13	2.41	7.0E+12	2.99	7.22	2.1E+13	3,847
North America	6.6	4.8E+13	1.43	9.45	6.8E+13	2.41	1.6E+13	2.99	7.22	4.9E+13	19,032
South America	5.4	7.0E+13	1.43	7.75	9.9E+13	2.41	2.9E+13	8.25	19.90	2.4E+14	27,718

The ERC value would rise until about 380,000 TWh/y (twenty times the world electricity demand), where about 63% of its contribution comes from the chemical component. By continents, the highest ERC is obtained, by far, for Asia, followed by America. Apart from their richness in renewable water resources (13,509 km^3/y) predominant desalination technology in Asia is MSF, the less exergy-efficient one. In consequence, high SEC_{ch} but also huge ERC_{ch} values are obtained. In America, the high ERC is mainly due to their vast water resources.

As a conclusion, in the ERC assessment of the worldwide renewable water resources, water availability has demonstrated to be more important than UEC values, that is, thermodynamic efficiency of the water treatment techniques to restore that water form the ocean.

6.2. *Exergy replacement cost of world water withdrawal*

When only water abstracted every year from natural sources is analyzed, the results and conclusions obtained for the exergy assessment of water resources could be more useful, since this ERC value could be understood as the minimum energy consumed in pumping and desalination utilities, in order to replace fresh water freely taken from the hydrologic cycle.

The yearly water withdrawal per continent was presented in Table 3. As it was done in the previous section, ERC_{ch} is calculated through the share of desalination technologies per continent and their mean rivers composition [Eq. (7)], and the ERC_{pot} by means of the inverse of the exergy efficiency of a typical pump, and the mean attitude per continent [Eq. (8)]. These two costs, as well as their addition, the total ERC, are shown in Table 5.

Total ERC of the global water withdrawal is about 33,000 TWh/y (almost twice the world electricity demand). By continents, the comparison with respect to their power demand is dramatic for South America, Africa and Central America and Asia (163%, 350%, 551%

Table 5
ERC of annual world water withdrawal

	Potential component					Chemical component					Total
	b_{pot} (MJ/m^3)	B_{pot} (MJ/y)	UEC_{pot}	SEC_{pot} (MJ/m^3)	ERC_{pot} (MJ/y)	b_{ch} (MJ/m^3)	B_{ch} (MJ/y)	UEC_{des}	SEC_{ch} (MJ/m^3)	ERC_{ch} (MJ/y)	ERC (TWh/y)
Global	7.8	3.1E+13	1.43	11.2	4.4E+13	2.41	8.9E+12	8.25	19.88	7.4E+13	32,895
Africa	6.9	1.6E+12	1.43	9.8	2.2E+12	2.41	5.1E+11	8.25	19.88	4.2E+12	1,802
Asia	8.8	2.2E+13	1.43	12.6	3.1E+13	2.41	5.5E+12	19.03	45.87	1.1E+14	37,846
Australia and Oceania	3.1	8.8E+10	1.43	4.5	1.3E+11	2.41	6.3E+10	8.25	19.88	5.2E+11	180
Central America	6.6	7.1E+11	1.43	9.5	1.0E+12	2.41	2.4E+11	2.99	7.22	7.3E+11	485
Europe	3.1	1.3E+12	1.43	4.5	1.9E+12	2.41	9.5E+11	2.99	7.22	2.8E+12	1,306
North America	6.6	3.7E+12	1.43	9.5	5.3E+12	2.41	1.3E+12	2.99	7.22	3.8E+12	2,510
South America	5.4	9.5E+11	1.43	7.7	1.4E+12	2.41	4.0E+11	8.25	19.88	3.3E+12	1,288

and 579% respectively). Better figures are found for developed countries, only raising the 42% of the electricity production in Australia, the 38% in Europe and the 52% in North America.

6.2.1. Use of solar energy to restore annual water withdrawal

Global energy use has risen by 70% since 1971, and continues to increase at a rate of about 2% per year for both developed and developing countries. As previously indicated, fresh water demand is growing faster and, in consequence, desalination facilities. Water scarcity is exacerbated by groundwater pollution (China and India), and population growth in areas of scarce water availability such as the Arabian Gulf states, southern Europe, North Africa and the American southwest. By the year 2025, some estimations indicates that 3.5 billion people will live in areas facing severe water shortages [32]. Fortunately, those areas are also characterized by its dry and sunny climate, and their solar potential could even be the only source to desalt and/or pump fresh water, especially in isolated areas.

Thus, the ERCs to restore fresh water withdrawal were translated into land requirements if solar irradiation were the only energy source. Firstly, photovoltaic (PV) technology was deeply studied (by analyzing diverse PV modules and tracking systems). Secondly, on the basis of concentrated solar thermal energy, the use of parabolic through collectors (PTC) was also considered.

6.2.1.1. PV systems to restore fresh water

Continental solar potential is given in Table 6, with the corresponding differences among the PV technologies. Different figures are given for the PV installation: amorphous silicon with about 10% efficiency and conventional mono-crystalline silicon (about 15% efficiency, with and without two-axis tracking system) were analyzed here [33].

Looking at the previously calculated energy requirements (Table 5) and dividing by the solar potential in each case, the solar power installed capacity was obtained. Irradiation was given in equivalent solar hours ($kWh \cdot m^{-2} \cdot d^{-1}$) and overall energy efficiency of the solar power plant was already included. Furthermore, Table 6 summarizes the land requirements for the diverse PV alternatives, assuming that all the energy required to produce and elevate fresh water were obtained from those disseminated installations.

The maximum percentage of surface occupied by PV panels (for the three analyzed technologies) is also shown in Table 6. Less than the 1% of the continent surface would be necessary except in Asia, where the growing demands of Gulf countries increases that surface up to the 2.5% of its territory.

6.2.1.2. PTC systems to restore fresh water

When the PTC technology is considered, similar land requirements are obtained. Solar potential includes 1-axis tracking system and, eventually can be operated with a energy storage unit in order to maintain a continuous daily operation (not considered here). An average footprint of four hectares per installed MW was taken for this mature technology. Table 7 shows the results, which were again classified by continents.

As it happened with the previous PV analysis, the hypothetical land requirements are quite low and Asia repeats with the highest percentage: 1.7% of its territory devoted to PTC driven solar power plants.

7. Conclusions

Global figures to assess the energy freely given by the Earth through its hydrologic cycle have been obtained

Table 6
Continents surface, power and land requirements to restore the yearly water withdrawal with different PV configurations and technologies

	Solar potential ($kWh/(m^2 \cdot d)$)			PV power (TW) to be installed			Land requirements (km^2)			
	Without tracking (Amorph)	Without tracking	With tracking	Fix (Amorph)	Fix	Track.	Fix (Amorph)	Fix, 15% eff	Track. 15% eff	% land (max)
Africa	1,600	2,000	2,700	1.1	0.9	0.7	11,260	13,345	40,034	0.13
Asia	1,200	1,500	2,025	31.5	25.2	18.7	315,386	373,790	1,121,371	2.50
Australia and Oceania	1,520	1,900	2,565	0.1	0.1	0.1	1,187	1,407	4,221	0.05
Central America	1,360	1,700	2,295	0.4	0.3	0.2	3,564	4,224	12,673	0.47
Europe	1,200	1,500	2,025	1.1	0.9	0.6	10,886	12,902	38,707	0.39
North America	1,200	1,500	2,025	2.1	1.7	1.2	20,917	24,791	74,373	0.37
South America	1,200	1,500	2,025	1.1	0.9	0.6	10,735	12,723	38,168	0.21

Table 7
Power and land requirements to restore the yearly water withdrawal, with PTC technology

	Solar potential ($kWh/m^2 \cdot y$)	PTC power (TW) to be installed	Land requirements (km^2)	% of the continent land
Africa	2,700	0.67	26,689	0.1
Asia	2,025	18.69	747,581	1.7
Australia and Oceania	2,565	0.07	2,814	0.03
Central America	2,295	0.21	8,449	0.3
Europe	2,025	0.65	25,805	0.3
North America	2,025	1.24	49,582	0.2
South America	2,025	0.64	25,445	0.1

in this paper. They have been studied from a physical approach, based on the second law of thermodynamics: the exergy replacement cost (ERC) of those resources has been calculated in each continent, separating chemical and potential contribution.

Two levels of analysis have been performed. First, in order to highlight the huge importance of the hydrologic cycle, the total available renewable fresh water on Earth was studied. Secondly, only present world withdrawal was considered in order to compare the magnitude and to quantify it from an energetic (and technologic) perspective. This second study provides a more realistic panorama, since it allows the comparison of the energy involved in the water cycle and the world energy demand.

Results show that ERC value for all the renewable fresh water is twenty times higher than the yearly world electricity consumption. When the study is focused only in the water withdrawal, the required energy "only" doubles the above mentioned demand. Chemical component account for 63% of that energy on average and the potential component represent the remaining 37%. It is due to the thermodynamic efficiency of desalination technologies), which is lower than the pumping efficiency. These both technologies have been analyzed through their UEC in this study.

Furthermore, the possibility of obtaining the exergy demand represented by the ERC, by only taking solar energy (SE) as primary source, was studied. Fixed-PV technology gives the lower surface requirements: although PV tracking systems increase the power generation, they do not compensate their additional space required to avoid shadowing. Asia would need the highest occupation of the territory if SE was selected (about the 2% by using PTCs, and the 2.5% in case of PV tracked systems).

As a conclusion, despite of the very low energy efficiency of the hydrologic cycle, if that huge amount of energy naturally obtained would be totally restored by desalination plus pumping systems, the required energy would not be affordable in the present context of the scientifically demonstrated climate change. Moreover, as exergy analysis gives the picture of the energy efficiency of water treatment processes, it could suggest new guidelines to reduce energy consumption in present desalination technologies, which seem to be the end solution to support human life needs in coastal areas, once water demand strategies have been fully implemented.

Acknowledgements

The authors wish to acknowledge the financial support for this research received from the Spanish Ministry of Science and Education (R+D Energy Program) under the IDERE project (ENE2007-67191).

Symbols

- a — Activity coefficient
- b — Specific exergy, kJ/kg
- B — Total exergy, kW
- c — Velocity, m/s
- C — Seawater salinity, ppm
- g — Gravity constant, m/s^2
- $\dot{m}$ — Mass flow, kg/s
- n — Mol number
- P — Pressure, kPa
- $\dot{q}$ — Water flow, m^3/s or l/s
- Q — Heat flow demand in desalination processes, MJ/kg
- R — Ideal gases constant, kJ/kgK
- s — Specific entropy, kJ/kgK
- T — Temperature, K
- u — Specific internal energy, kJ/kg
- v — Specific volume, m3/kg
- W — Specific power demand, kWh/m^3
- x — Molar concentration
- z — Altitude above the sea level, m

Subscripts

- av — Average
- ch — Chemical component
- i — Any of the substances present in water

in — Input to the system
o — Reference state
out — Output from the system
pot — Potential
pump — Pumping
r — River
w — Aqueous solution

Greek

Δ — Difference
η — Exergy efficiency
μ — Chemical potential, kJ/kg
ρ — Density, kg/m^3

References

[1] UN-WWAP, Water, a shared responsibility. World Water Assessment Programme, United Nations, 2006.
[2] G. Wolff, H. Cooley, M. Palaniappan, A. Samulon, J. Lee Morrison, D. Katz and P. Gleick, The World's Water 2006–2007, The Biennial Report on Freshwater Resources, Island Press, 2006.
[3] D.H. Meadows and J. Randers, Limits to Growth, Universe Books, New York, 1972.
[4] P.F. Chapman and F. Roberts, Metal Resources and Energy, Butterworth & Co., England, 1983.
[5] M. Tribus and R.B. Evans, A Contribution to the Theory of Thermoeconomics, UCLA, Dept. of Engineering. Report No. 62–63, Los Angeles, USA, 1962.
[6] A. Bejan, G. Tsatsaronis and M. Moran, Thermal Design and Optimization, John Wiley and Sons Inc., New York, USA, 1996.
[7] S.E. Jorgensen, S.N. Nielsen and H. Mejer, Energy, environ, exergy and ecological modelling. Ecol. Modelling, 77 (1995) 99–109.
[8] M.A. Rosen and I. Diner, Exergy-cost-energy-mass analysis of thermal systems and processes, Energy Convers. Manage., 44 (2003) 1633–1651.
[9] I. Dincer, Thermodynamics, exergy and environmental impact, Energy Sources, 22 (2000) 723–732.
[10] I. Dincer, Technical environmental and exergetic aspects of hydrogen energy systems, Int. J. Hydrogen Energy, 27 (2002) 265–285.
[11] M. Gong and G. Wall, On exergy and sustainable development, Part-2: Indicators and methods, Exergy Int. J., 1(4) (2001) 217–233.
[12] G. Wall, Conditions and tools in the design of energy conversion and management systems of a sustainable society, Energy Convers. Manage., 43 (2002) 1235–1248.
[13] J.T. Szargut, Optimization of the design parameters aiming at the minimization of the depletion of non-renewable resources, Energy, 29 (2004) 2161–2169.
[14] G.Q. Chen, Scarcity of exergy and ecological evaluation based on embodied exergy. Communic. Nonlinear Sci. Numer. Simulation, 11 (2006) 531–552.
[15] G.Q. Chen and X. Ji, Chemical exergy based evaluation of water quality, Ecol. Modelling, 200 (2007) 259–268.
[16] A. Valero, J. Uche, A. Valero-Delgado A. and Martínez, Physical hydronomics: Application of the exergy analysis to the assessment of environmental costs of water bodies. The case of the inland basins of Catalonia, Energy, article in press, corrected proof. available on line at: http://www.elsevier.com/energy.
[17] F. Millero, Chemical Oceanography, 2nd ed., CRC Press, 1996.
[18] E. Botero, Valoracion exergética de recursos naturales, minerales, agua y combustibles fósiles. Ph.D. thesis, Department of Mechanical Engineering, University of Zaragoza, 2000.
[19] A. Valero, E. Botero and L. Serra,. The world's renewable water resources and ice sheets. Proc. Conf. on Sustainable Development of Energy, Water and Env. Systems, Dubrovnik, June 2–7, 2002.
[20] D.A. Livingstone, Data of Geochemistry, 6th. ed., US Geological Survey, Ch. Chemical composition or rivers and lakes, 1963.
[21] I.M. Klotz and R.M. Rosenberg, Termodinámica Química. Teoría y métodos básicos. AC Editors, in Spanish, 1977.
[22] C. Torres Cuadra and A. Valero Capilla, Thermoeconomics, University of Zaragoza.. Center of Research for Energy Resources and Consumption, 2007, pp. 1–98.
[23] 2007 Survey of Energy Resources, World Energy Council, 2007.
[24] International Hydropower Association (IHA), The contribution of hydropower. Factsheets, available at: http://www.hydropower.org, 2008.
[25] International Desalination Association (IDA), 21st GWI/IDA Worldwide Desalting Plant Inventory, available at: https://www.idadesal.org, 2008.
[26] E. Gabbrielli, Nuevas fuente de agua: reutilización y desalación. Water in the world. Water tribune (thematic week number 10, 1–3 September 2008). International Exposition Zaragoza Water and sustainability, 2008.
[27] J. Uche, A. Valero and L. Serra, Potential role of desalination, in Water Crisis: Myth or Reality, Taylor & Francis., 2006, pp. 297–322.
[28] K. Paulsen and J. Hensel, Design of an autarkic water and energy supply driven by renewable energy using commercially available components, Desalination, 203 (2007) 455–462.
[29] S. Lattemann and T. Höpner, Environmental impact and impact assessment of seawater desalination, Desalination, 220 (2008) 1–15.
[30] Water Desalination Report, Global Water Intelligence (GWI), 2008.
[31] M. Ahmad, P. Williams and H. Al-Jabli, Application of salinity gradient power for brines disposal and energy utilisation. Desal. Water. Treat., in press.
[32] J. Alcamo, T. Henrichs and T. Rösch, World Water in 2025: Global Modeling and Scenario Analysis for the World Commission on Water for the 21st century, Kassel World Water Series, Report No. 2, Center for Environmental Systems Research, University of Kassel, 2000.
[33] A.A. Bayod,Sistemas Fotovoltaicos, Ed. Prensas Universitarias, Universidad de Zaragoza, in Spanish, 2009.