The world's renewable water resources and ice sheets.

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Summary.

A thermodynamic approach is proposed to measure the physical value of the world's renewable water resources and Antarctica and Greenland ice sheets. This involves the *Exergy Replacement Cost*, defined as the energy required by the best available technologies to return a resource to the same conditions as it was delivered by the ecosystem(s). The replacement cost of the world's renewable water resources varies between a minimum of 3,592 Mtoe/year and a reasonable value of 53,304 Mtoe/year. Thus, each year we would need between 0.4 to 6.4 times more fossil energy than consumed in 1997, to replace only part of the functions of the hydrological cycle. In the case of ice sheets, its minimum physical replacement cost is 3.840E+08 Mtoe, being the actual exergy replacement cost near of 20 times higher, that is 7.210E+09 Mtoe.If all existing ice sheets melted, the required exergy for recover them in the same conditions that are now in nature would be around 9,000 times greater than the total amount of fossil fuels reserves in the Earth. Accordingly, Earth´s ice sheets correspond to our most important global exergy reserve.

1. Introduction.

The world's renewable and useable water resources (renewable superficial runoff and aquifer recharge) are an estimated 42,785 km^3/year (Shiklomanov, [1]). In 1995, 3,800 km^3 were extracted for human use, 2,000 km^3 were consumed and the rest were returned in much poorer quality. Meadows et al. [2] conclude that only 12,000 km^3 (28 %) of all renewable water resources can technically be managed and assessed as a useable resource. This figure may be closer to 7,000 km^3/year (16,3 %) since some large rivers are located in sparsely populated areas.

If the current tendencies in the developed and developing world continue, world water withdrawals will surpass the 1995 value to reach 4,300 km^3 or even 5,200 km^3 in the year 2025. That is, we may soon be using between 61 and 74 % of all the available water resources (World Water Council [3]).

The World Water Council has proposed a series of steps to avoid a wider scale crisis. Among them are limiting the growth of irrigation agriculture (which uses the most water, 2,500 km^3/year), increasing water productivity by improving efficient use, increasing storage, reforming the institutions that administer water resources, supporting innovation and increasing the general appreciation of ecosystem functions. They consider that much more research is needed to determine the real value of the services provided by renewable freshwater ecosystems. One way to approach this value is to know the cost of its replacement, or in other words, the effort we should need to produce it artificially. Partially, at least.

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We determine the physical value of the world renewable water resources using the *Exergy Replacement Cost (E_xRC)*, defined as the exergy required by the best technology to return a resource to the physical and chemical conditions in which it was delivered by the ecosystem(s). This concept can be used for any renewable resource. Here it is used to calculate the physical cost of replacing some ecosystem functions, in this case the hydrological cycle.

In the case of water, its thermodynamic value has two basic components; its composition makes it useful for different human and agricultural activities and its potential energy can be used to produce shaft work and electricity. These two conditions should be returned to water from its more thermodynamically degraded state (the ocean in this case).

2. Theoretical Background.

There are several ways to determine the thermodynamic value of water resources, such as one recently performed by Zaleta, Ranz and Valero [4] for the exergy evaluation of a river. The methodology propose to measure the availability of a renewable resource, understanding the latter as "very accessible".First, a Reference Environment is defined, in which sea water at its level, pressure, temperature and composition has zero exergy. Then, any water resource will be characterised by its exergy components. The proposed model considers temperature, pressure, height, velocity and composition and assumes an approximation to an incompressible liquid where the exergy[1] is:

$$b_{H_2O} = Cp_{H_2O}\left[T_a - T_0 - T_0 \ln\left(\frac{T_a}{T_0}\right)\right] + v_{H_2O}(P_a - P_0) + \sum x_i \left(\mu_{i_a} - \mu_{i_0}\right) + \frac{1}{2}\left(V_a^2 - V_0^2\right) + g(z_a - z_0) \quad (1)$$

Total exergy = thermal Ex. + mechanical Ex. + chemical Ex. + kinetic Ex. + potential Ex.

According to this equation (1):

(a) The thermal exergy depends on the specific heat of the aqueous solution and its absolute temperature.
(b) The mechanical exergy is calculated using the specific volume and the pressure difference with the reference environment.
(c) The potential exergy is calculated taking into account the height where the measurement will be taken.
(d) The kinetic exergy is calculated by taking the velocity at the sampling site.
(e) The chemical exergy of the element is the most complex to calculate and is composed of the chemical exergy of pure water and the chemical exergy of the dissolved organic and inorganic substances.

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[1] Note that this equation corresponds to flow exergy. When estimating the exergy of world's water resources and ice sheets it should be more rigorous and appropriate to perform the calculations using the non-flow exergy equation. For non compressible substances, as it is the case of liquid water and ice in the range of temperatures and pressures considered in this work, the difference between both exergy values is not significant.

Given the quantity of information required to apply the model, a thermodynamic evaluation of water resources may not be very practical. The model can be applied to rivers and currents that have measuring stations, as done by the authors in the Ebro river, but it is almost impossible to obtain all the information necessary to correctly apply the model on a global scale.

Naredo and Gasco [5] used another method to physically evaluate water resources in Spain. They incorporated quantity accounts and used quantity and monetary accounts in the same system. The First Law of Thermodynamics governs the quantity accounts and the quality ones are determined by the Second Law. The latter has two components, which include the hydraulic power and osmotic power. The hydraulic power is calculated as:

$$P_h = 9{,}8Qh \qquad (2)$$

and the osmotic power, which measures the dilution capacity of water with respect to pure water, is calculated as the difference between the osmotic power of rain water (pure water) and the sample water. It can be expressed in terms of a flow as:

$$P_o = 1.970Q - 36{,}477QC_E \qquad (3)$$

The second model is more simple and seems more adequate than that proposed by Valero et al. [4] for the thermodynamic evaluation of global resources. Nonetheless, it also requires composition measurements to evaluate water quality and it is almost impossible to get this information for all currents and rivers.

We propose to thermodynamically evaluate the world's renewable water resources using the concept of Exergy Replacement Cost. It has two components, the first one is the energy needed to return the quality characteristics to water and is represented by the desalination exergy. The second one is the minimum energy needed to return the resource to its condition of potential disequilibrium as delivered by the hydrological cycle. That is represented by the exergy needed to lift this resource to the determined height (pumping exergy).

2.1. Desalination exergy.

A desalination plant can be considered a black box with water and energy flows (Figure 1). Normally there is only one source of sea water and two outputs, drinking water and concentrated brine. There is also an energy flow which enters as high quality energy and exits as low quality.

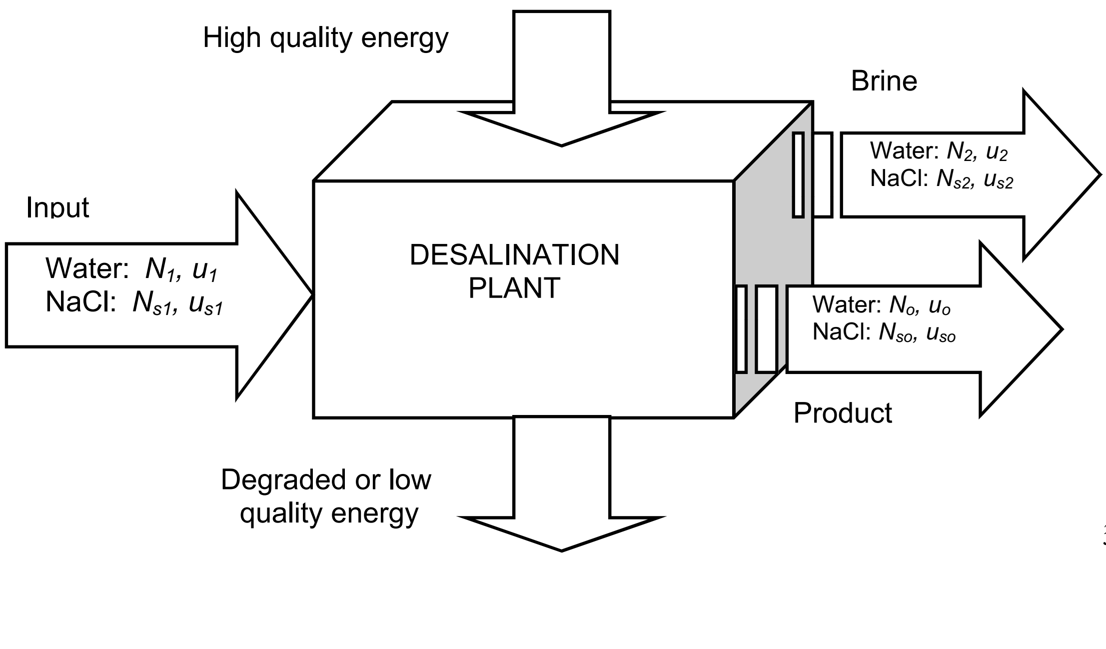

Figure 1. Characterisation of the flows in a desalination plant.

The minimum desalination energy is the difference between the free energy of the input flow (salt water) and the output water flows (desalted water and concentrated brine).

$$dG = VdP - SdT + \sum \mu_i dN_i \tag{4}$$

At a constant pressure and temperature, the change in free energy can be expressed as:

$$\Delta G = \sum \mu_i \Delta N_i = \sum \mu_s N_s - \sum \mu_e N_e \tag{5}$$

For N_1 moles of water entering the plant, N_0 moles of water in product, N_2 moles of water in the concentrated brine, N_{s1} moles of salt entering the plant, N_{s0} moles of salt in product and N_{s2} moles of salt in brine, equation (5) can be written as:

$$\sum \mu_i \Delta N_i = -\mu_1 N_1 + \mu_2 N_2 + \mu_o N_o - \mu_{s1} N_{s1} + \mu_{s2} N_{s2} + \mu_{so} N_{so} \tag{6}$$

The mass balance for the water and salt implies that $N_1 = N_2 + N_o$ and $N_{s1} = N_{s2} + N_{s0}$. The recuperation ratio can be defined as $R_c = N_0/N_1$, the molar fraction of the salt in the entry flow as $x_1 = N_{s1}/(N_1 + N_{s1})$ and if the water produced is very pure $N_{s0} \approx 0$, so the minimal energy per unit of water produced can be expressed using the equation (6):

$$\frac{\Delta G}{N_o} = \left[\frac{1}{R_c} - 1\right](\mu_2 - \mu_1) + (\mu_o - \mu_1) + \frac{1}{R_c}\frac{x_1}{1 - x_1}(\mu_{s2} - \mu_{s1}) \tag{7}$$

Expressing the chemical potentials in relation to the molar concentrations in the input and output, we obtain the expression to calculate the desalination exergy in function of the recuperation ratio and the molar salt fraction at the input flow of the plant:

$$b_{des} = \frac{\Delta G}{N_o} = \frac{vRT}{R_c}\frac{x_1}{1 - x_1}\ln\left[\frac{1}{1 - R_c}\right] \tag{8}$$

According to equation (8), the minimal desalination energy varies between 2.6 MJ/m^3 and 6.5 MJ/m^3 for a plant input of sea water with a salt concentration of 35,000 ppm and a recuperation ratio (R_c) that varies between 0.1 and 0.9 respectively.

The second component of the physical replacement cost of the water resources is the minimum energy needed to return the resource to its conditions of physical disequilibrium (or potential) with the chosen reference level (the ocean). This energy can be calculated using the following equation:

$$b_{phys} = 9{,}8Qh \tag{9}$$

To calculate this component on a global scale we need data on the height at which the hydrological cycle discharges the resources in the different countries and continents. These data are not known exactly. From the point of view of the second law, the minimum energy to elevate water coincides with the maximum energy obtained when it is turbined using a reversible machine. If we had enough information about the world's hydroelectric power, the second component would be the water based energy currently used, or that could be used under existing technological limitations or that would be useful if all the local water resources in each country were turbined to sea level.

3. The real energy requirements of desalination technologies.

Three basic technologies are now used to desalinate brackish water and seawater. MSF plants (multiple stage flash distillation) which makeup 47.6 % of the total capacity of installed desalination, RO plants (reverse osmosis) which represent 38.6 %, and MED plants (multiple effect distillation) which make up 4.3 % (Alawadhi, [6]).

The energy requirements of MSF plants depend on the configuration (one trough or with brine re-circulation), whether it is operating under a cogeneration scheme, on the recuperation ratio *Rc*, the number of evaporation stages in plant *N*, the input temperature of water and the relationship between the cooling water and the entry flow of water.

According to Afgan et al. [7], in an MSF plant with 12 mgd capacity (1 mgd = 3,785 m^3/day), operating under a cogeneration scheme due to steam consumption, 40.6 MW_e of the power is not generated in the turbine. This implies that 116 MW_t should be supplied by the fuel to evaporate the water (220.6 MJ/m^3 of desalted water) if we consider a 35 % generation efficiency of electrical energy. The steam consumption in the ejectors is 10 MW_t, which represents a primary energy consumption of 11.1 MW_t (21.1 MJ/m^3 of desalted water) under a 90 % generation efficiency of steam in the boiler. Finally, the electrical energy consumption of the MSF plant is 10 MW_e equivalent to 28.6 MW_t of primary energy (54.4 MJ/m^3 desalted water). In summary, the specific energy consumption in a large MSF plant is on the order of 296.1 MJ/m^3 of water produced. A representative value for this type of technology would be 300 MJ/m^3.

The main competition for MSF plants are RO plants, which are simpler and have lower energetic requirements. According to Criscuoli and Drioli [8], the energetic requirements of an RO plant are in the range of 4.2 and 7.9 kWh/m^3 (15.12 to 28.4 MJ/m^3), but Afgan et al. [7] quote a maximum energy consumption for this type of technology around 7.5 kWh/m^3 (27 MJ/m^3).

If the electrical energy consumed by an RO plant is generated using a traditional thermal power plant with an efficiency of 35 %, the minimum specific primary energy from the fuel for this type of plant is 43.2 MJ/m^3 desalted water.

Finally, MED plants consume energy using many more parameters than MSF or RO plants. According to the IAEA [9], the thermal energy required in an MED plant (defined by the R_c), is between 90 and 432 MJ/m^3. Uche [10] presents data on the energetic requirements for this type of plant operating under a cogeneration scheme between 200 y 250 MJ/m^3.

Table 1 summarises the energetic requirements of the three most important desalination technologies.

Table 1. Energy requirements of the main desalination technologies.

Technology	Exergy cost MJ/m^3 of desalted water	Unit exergetic cost$^{(1)}$	Fuel consumption kg oil/m^3 water
MSF	300	115	7.1
RO	43.2$^{(2)}$	16.6	1.0
MED	200 Ð 250$^{(3)}$	76.9 - 96.1	7.62 Ð 10.65

(1) Calculated as the relation between the exergy invested in the real process and the exergy to carry out the desalination in a reversible way, 2.6 MJ/m^3, corresponding to an ideal plant with a recuperation factor of 10 %.
(2) Including the energy recovery system.
(3) Desalination plant operating under a cogeneration scheme.

According to these data we choose reverse osmosis as the best available technology to evaluate the replacement cost of water resources. However, this is not totally true since at very high salt concentrations as they occur in the Persian Gulf reverse osmosis may have severe drawbacks. In this way, we can calculate the minimum value based on the desalination exergy and a real value that takes into account the irreversibility of the best industrial desalination process.

In next sections we present the world inventory of water resources according to several references and our results after applying the above methodology to this inventory.

4. World renewable water resources.

According to the latest estimates, our hydrosphere contains 1,386 million km^3 of water, 97.5 % salt water and 2.5 % freshwater. Most freshwater (68.9 %) is permanently frozen ice or snow that covers polar and mountainous regions, 29.9 % are subterranean and 0.3 % make up lakes, reservoirs and river systems. The latter can be used without considering technical or economic limitations (Shiklomanov, [1]).

Solar energy evaporates 577,000 km^3 of water every year, 502,800 km^3 (87 %) from the ocean surface and 74,200 km^3 from the continents. This same quantity of water is precipitated but 458,000 km^3 on the oceans and 119,000 km^3 on the continents. The difference between the evaporation and the precipitation on the continents (44,800 km^3/year) represents the total amount of water in rivers (42,600 km^3/year) and the subterranean flow to the oceans (2,200 km^3). This water fulfils the present human and economic requirements (Shiklomanov, [11]).

The average renewable water resource is approximately 42,785 km^3 per year, with variations in space and time. The distribution of renewable water resources, their availability on the continents, and yearly fluctuations are shown in Table 2.

Table 2. Renewable water resources and their availability on the continents (taken from Shiklomanov[1]).

Continent	Area $km^2 * 10^6$	Population Millions 1995	Water resources (km^3/year)			Availability (1000 m^3/year)	
			Average	Maximum	Minimum	Per km^2	Per capita
Europe(1)	10.46	684.7	2,900	3,410	2,254	277	4.23
N. America	24.3	453	7,890	8,917	6,895	324	17.4
Africa	30.1	708	4,050	5,082	3,073	134	5.72
Asia	43.5	3,445	13,510	15,008	11,800	311	3.92
S. America	17.9	315	12,030	14,350	10,320	622	38.2
Australia	8.95	28.7	2,404	2,880	1,891	269	83.7
TOTAL	**135.2**	**5634.4**	**42,785**	**49,647**	**36,433**	**317**	**7.60**

(1) including Western Europe, Eastern Europe and Russia.

Most renewable water resources are in Asia (13,500 km^3) and South America (12,000 km^3) and the least in Europe (2,900 km^3) and Australia (2,400 km^3).

The rapid growth of the world population has helped to decrease the availability of water from 12,900 m^3/hab/year in 1970 to 7,600 m^3/hab/year in 1994. The greatest decrease was in Africa (2.8 times), Asia (2 times) and South America (1.7 times). In Europe, the same potential decreased 16 % during the same period (World Water Council [3]).

5. The physical replacement cost of the world's water resources.

The first component of the replacement cost of renewable water resources was evaluated using the world inventory data [1] in Tab.2 and data on the minimal and real energy requirements of the best available desalination technology (reverse osmosis). The minimum and maximum replacement costs are summarised in Table 3.

Table 3. Summary of the real and minimum Exergy replacement costs in the composition component of the world's renewable water resources.

Continent	Minimum cost Mtoe/year	Maximum cost Mtoe/year
Europe.(1)	371.50	6,259.87
North America.	375.98	6,335.42
Central America.	66.40	1,118.81
South America.	679.09	11,442.99
Africa	246.00	4,145.19
Asia	767.23	12,928.14
Oceania	93.09	1,568.57
TOTAL	**2,599**	**43,798**

(1) including Western Europe, Eastern Europe and Russia.

As seen in Table 3, 2,600 Mtoe per year (or 31.4 % of the fossil fuel energy consumed in 1997, 8,272 Mtoe; Brown et al., [12]) are needed to replace the composition component of the renewable water resources from a completely degraded state. The maximum first value of the replacement cost (43.799 Mtoe/year) is the energy needed to replace the resource by reverse osmosis. Thus, the real replacement cost is five times higher than the primary energy consumption from fossil fuels in 1997.

The second component of the replacement cost is the minimum energy required to elevate water from sea level in order to use its potential energy for the production of shaft work and electrical energy. It is practically impossible to calculate the pumping energy everywhere in the world, since we would need data on precipitation, evaporation and runoff in every country at different heights. Thus, we obtained the second component from the inventory of potential hydroelectric resources, periodically published in the International Water Power & Dam Construction Handbook (IWP&DC) and by the Department of Energy (DOE) of the United States.

Table 4 summarises the potentials per continent according to data from the IWP&DC [13], which defines the potentials as follows:

- *Gross Hydroelectric Potential*: the hydroelectric potential of a country if all its water flows were turbined until sea level or to the country borders (if the flow continues into other countries), under 100% system efficiency.

- *Technically Useful Hydroelectric Potential*: the hydroelectric energy obtained from all the exploitable or exploited places under existing technological limits, without taking into account environmental, economic or other restrictions.

- *Economically Exploitable Hydroelectric Potential:* part of technically feasible potential that can be or that has been developed under the local economic conditions of each country and in a competitive way with other energy supply sources. Some of the places that can be exploited economically can have restrictions from the environmental point of view. Nonetheless, this limitation is not taken into account when determining this potential.

As seen in Table 4, the gross potential generation is 3.1 times greater than the technical potential, and the latter is 1.6 times greater than the economic potential.

Table 4. Summary of the world's hydroelectric potential (based on data from the International Water Power & Dam Construction Handbook,[13])

Continent	Potential Capacity		Potential Generation		
	Technical MW	Economic MW	Technical GWh/year	Economic GWh/year	Gross GWh/year
Africa	260,919	59,992	1,522,108	602,547	2,936,050
Central and South America	316,238	643,025	3,933,770	2,530,492	9,306,226
North America	310,058	NA(1)	631,713	376,000	1,505,283
Asia	875,444	476,075	4,189,693	2,620,601	15,164,153
Old Soviet Union	NA	NA	603,200	242,450	3,942,200
Europe	3,338	424	974,726	882,933	3,558,205
Oceania	17,978	9,315	78,323	168,858	592,345
TOTAL	**1,783,975**	**1,188,831**	**11,933,534**	**7,423,880**	**37,004,462**

(1) NA, information not available.

Table 4 is a summary of potential hydroelectric energy by continent but the technically useful capacity is incomplete for many countries. We propose the following criteria to help complete these data in most cases.

a) Data on technical potential capacity is understood as the technically useful potential capacity, since it is the maximum utility that could be obtained from the resource under current technological conditions.

b) If there are no data on potential capacity, but we know the technically useful generation potential, we can determine the technical potential capacity using the hours of operation per year (utilisation factor) from the information on the installed and generation capacities in each country. For this we used data on the world installed capacity and the world generation of electrical energy, published by the DOE in 1997.

c) If the above data are unavailable, we use the economically useful potential capacity If this is not available either, we use data on the economically useful generation potential, which can be used to calculate the capacity that can be installed using the number of hours of operation per year of the installed systems.

d) If none of the above data are available (technical or economic potential capacity and technical or economic generation) we use the information on the gross potential generation and the gross potential capacity calculated using the utilisation factor (hours/year) of the installed capacity in each country.

e) Finally, if IWP&DC [13] provides no information on the country in question, we use the data on actual installed capacity and current generation from the DOE [14].

Using these criteria, we completed the data on the useful hydroelectric potential on the planet by country (Table 5).

According to the IWP&DC [13] (see Table 4) the world's gross generation potential is 37,004,462 GWh/year (3,171.8 Mtoe/year), the technical generation potential is 11,933,534 GWh/year (1,002.8 Mtoe/year) and the economic generation potential is 7,423.886 GWh/year (636.3 Mtoe/year). The technical generation potential only differs by 3 % from the data in Table 5. The difference is much greater for the technically viable potential capacity (1,784 GW according to the IWP&DC [13]) which we calculated to be 3,009 GW (40.7 % greater) based on the previously cited criteria.

The installed hydroelectric capacity was 667.3 GWe (U.S. DOE [14]) and the generation was 2,536,300 GWh (217.4 Mtoe) in 1997. We only use 22 % of the potential and hydroelectric energy that could technically be installed and generated on the planet. This figure does not, however, take into account the economic or environmental restrictions of increasing the current levels of use.

The world potential hydroelectric capacity under actual technological limitations is 3.009 GW. The potential hydroelectric energy generation is 11,586,686 GWh/year or 993 Mtoe if the average operation is 3,851 hours per year, which is equivalent to a utilisation factor of 44 %.

Table 5 also includes data on the gross generation potential per country which are not published by IWP&DC [13]. We first consider the technical potential capacity. In its absence we use the economic potential or, finally, the current installed potential. The gross generation is determined using a 100% utilisation factor of used or useful potential (or 8760 h/year).

Table 5. Summary of the technical and gross generation potential of hydroelectric energy on a global scale.

Continent	Technical potential			Gross gen. potential	
	Capacity MW	Generation		GWh/year	Mtoe/year
		GWh/year	Mtoe/year		
Africa	293,661	1,565,406	134.2	3,166,217	271.4
Central and South American	785,786	3,080,414	264.0	9,348,887	801.3
North America	310,058	1,007,713	86.3	1,505,283	129.0
Asia	1,027,579	3,921,352	336.1	16,683,813	1,430.0
Old Soviet Union	208,312	603,200	51.7	3,942,200	337.9
Europe	323,876	1,201,558	103.0	3,582,543	307.0
Oceania	59,800	207,043	17.7	593,203	50.8
TOTAL	**3,009,072**	**11,586,686**	**993**	**38,822,146**	**3,327.4**

The gross generation potential is 38,822,146 GWh/year, 5 % higher than in IWP&DC [13]. In the generation case, the gross potential is 3.35 times higher (3,327.4 Mtoe/year) than the technical potential (993 Mtoe/year), since the latter considers both the current technological limitations and the load factors of the installed systems per country.

The second component of the replacement cost has a technical value and a gross value. The first is 993 Mtoe/year and can be interpreted as the physical exergy of the world renewable water resources under current technological and exploitation limits. The second is 3,327.4 Mtoe/year and represents the total resource exergy without taking into account the capacity to use it. If this exergy were generated by a conventional thermal power plant with an average efficiency of 35 %, the replacement cost of the physical component of the resource would vary between 2,837.1 Mtoe/year and 9,506.8 Mtoe/year.

According to the above, the total replacement cost of world renewable water resources would vary between a minimum value of 3,592 Mtoe/year (including the desalination exergy and the physical exergy that can be obtained from the resource under existing technological limitations) and a maximum of 53,304.8 Mtoe/year (including the real physical costs of desalination as the conventional thermal technologies to generate electrical energy). We would need this primary energy in addition to what is consumed today. The consumption of the primary energy from fossil fuels (coal, petroleum and gas) was 8,276 Mtoe in 1997 (Brown et al., [12]). Thus, each year we would need 0.4 and 6.4 times the fossil energy to supply only a part of the functions of the hydrological cycle.

If coal (whose reserves are estimated in 532,561 Mtoe, including anthracites, bituminous coal and lignites; DOE, [14]) was used to replace the chemical and physical conditions of the water resources, the relationship between reserves/production (now 210 years), would be reduced to a minimum value of 91 years or a maximum of 9.5 years (assuming 1997 consumption levels). Similarly, oil (whose reserves are calculated in 150,692 Mtoe), the relationship reserves/production would be 43.2 years to 21.2 years in the best case and in the real condition of availability of reserves would be 2.6 years. For natural gas (reserves of 131,558 Mtoe), the relationship reserves/production would be reduced to, in the case of the estimated minimum from 57 years to 21.4, and in the condition of real requirements the availability of the reserves would be only 2.3 years.

The previous numbers indicate the extreme cost, even at minimum replacement, that it would take to provide the renewable water resources in the case of not having the hydrological cycle. There are not enough fossil fuel reserves to maintain the availability of renewable water. In the ideal case it would be more than 69 years, and in the worst case they would only be able to replace the hydrological cycle function for 13 years (under 1997 consumption levels).

Table 6 demonstrates the above based on the local reserves of renewable water in the six countries with the most water resources: Brazil, Canada, Russia, the USA, China and India (48.7 %). We note the exergy replacement cost of their water resources and their petroleum reserves.

Table 6. Replacement costs of the renewable water resources and petroleum reserves of some countries.

Country	Water resources km^3/year	Exergy Replacement cost (Mtep/year)		Petroleum reserves. Mtep
		Minimum$^{(1)}$ *E_xRC*	*Maximum E_xRC*	
Brazil	6,220	472.3	7,077.9	942
Russia	4,053	259.3	4,839.3	7,499

Canada	3,287	252.8	3,738.7	834
U.S.A.	2,930	209.9	3,115.2	3,679
China	2,701	328.1	4,206.6	4,046
India	1,456	139.4	2,129.4	570
TOTAL	**20,647**	**1661.8**	**25,107.1**	**17,570**

(1) The minimum value of the replacement cost takes into account the desalination exergy and the physical energy that is possible to obtain from the resource under the existing technological limitations.

Even at minimum replacement cost, countries such as Brazil, Canada and India would only have enough petroleum to replenish their renewable water resources for 2, 3.3 and 6 years respectively. At maximum exergy replacement cost, only a few countries (Russia, USA and China) would have enough reserves to maintain their supply of renewable water resources for more than one year. The real replacement cost is so high that, for example, Brazil would only be able to pay it for barely two months.

6. Exergy replacement cost of world's ice sheets

According to the Encyclopaedia Britannica, a glacier may be defined as "*a large mass of perennial ice that originates on land by recrystallization of snow or other forms of solid precipitation and that shows evidence of past or present flow[...] and all persisting snow and ice masses larger than 0,1 square kilometre should be counted as glaciers[...]*".

Two great ice masses, the Antarctic and Greenland ice sheets contain about 99% of world's glacier ice, 91% percent in Antarctica alone (Enc.Brit.).

6.1 Antarctic ice sheet

The ice sheet, with its associated ice shelves, covers an area of 13,800,000 square kilometres. The mean thickness of the ice is between 1,720 and 2,200 metres (Enc.Brit.). Because of the thick ice cover, Antarctica has by far the highest mean altitude of the continents (2,200 metres).

At the South Pole the snow surface is 2,800 metres in altitude and the mean annual temperature is about Ð50 ºC, but at the Soviet Vostok Station, 3,500 metres above sea level, the mean annual temperature is Ð58ºC. Along the coast of East or West Antarctica, where the climate is milder, mean annual temperatures range from Ð20ºC to Ð9ºC (Enc.Brit.).

6.2 Greenland ice sheet

The Greenland ice sheet is huge compared with all the other glaciers in the world, except that of Antarctica. Greenland (2,190,000 km^2) is mostly covered by ice (1,730,000 km^2), but isolated glaciers and small ice caps totalling 76,000 km^2 occur around the periphery. The mean altitude of the ice surface is 2,135 metres (Enc.Brit.), and the bedrock surface is near sea level over most of the interior of Greenland, but the mountains occur around the periphery. Thus the ice sheet, in contrast to the Antarctic ice sheet is confined along most of its margin. The unconfined ice sheet does not reach the sea along a broad front anywhere, so that no large ice shelves occur (Enc.Brit.).

The climate of Greenland, though cold, is not as extreme as that of Antarctica. The lowest mean annual temperatures, about Ð31ºC, occur on the north central part of the north dome, and temperatures at the crest of the south dome are about Ð20ºC (Enc.Brit.).

6.3 Minimum exergy replacement cost of ice sheets

From these data, it is possible to estimate the minimum exergy replacement cost of ice sheets following a similar procedure than applied for water resources already explained in section 2. Note that our aim consists on obtaining an order of magnitude of this figure more than an accurate value.

Similarly to the estimations performed for the liquid water resources, we propose equation (1) for the calculation of exergy. In this case, it has been considered only the thermal , potential and chemical exergy components. Mechanical and kinetic exergy components have been neglected.

Table 7 shows the minimum exergy replacement cost values of ice sheets of Antarctica, Greenland and an average value for the whole ice of the Earth. These values correspond with the minimum exergy required for obtaining the ice from sea water, which is the situation that would reach the Earth's ice sheets if all existing ice melted. Specific potential and desalination exergies have the same values. In the case of potential exergy, according to the data presented in previous subsection the average altitude of ice in Antarctica and Greenland, which involves the 99% of ice sheets of the Earth, is around 2,000 metres. In the case of desalination exergy, it has been calculated applying equation (8), which corresponds to the minimal exergy required for desalting sea water considering an average salt concentration of 35,000 ppm and a recuperation ratio of 0.1. Finally, the thermal exergy has been calculated considering and average ice temperature of Ð30ºC, -15ºC and Ð28.9ºC for the ice of Antarctica, Greenland and average ice in the Earth respectively.

Table 7 Minimum exergy replacement cost of world's ice sheets

	Average Earth's Ice				**Antarctica's Ice**				**Greenland's Ice**			
	Total	Therm	Pot	Desalt	Total	Therm	Pot	Desalt	Total	Therm	Pot	Desalt
kJ/kg	38.42	26.02	9.80	2.60	38.80	26.40	9.80	2.60	34.60	22.20	9.80	2.60
Mtoe	**3.840E8**				**3.529E8**				**3.112E7**			

Even the minimum exergy replacement cost of ice sheets in the Earth is a huge quantity, which is very close to the exergy content of ice sheets. It is two orders of magnitude higher than the exergy content of the Earth's fossil fuel reserves, which are around 814,811 Mtoe (U.S. Department of Energy,[14])

Analyzing the exergy values of the different contributions, the less significant is that corresponding to the desalination exergy. Furthermore, this exergy content evaluated for different hypothetical salt contents of seawater (between 25,000 Ð 45,000 ppm) does not vary too much the total exergy value (less than 10%).

Potential exergy is significant because of the great thickness of ice sheets in Antarctica and Greenland.

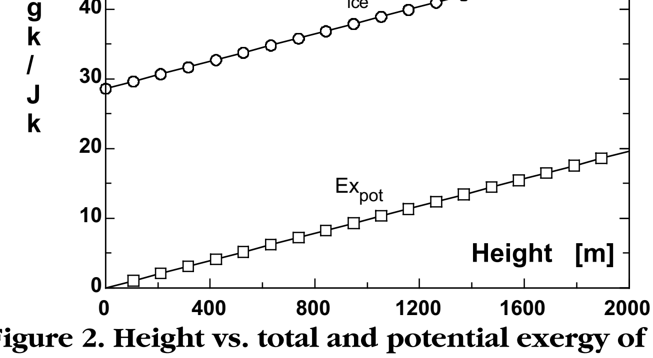

Figure 2. Height vs. total and potential exergy of ice

The most important component is the thermal exergy, which represents more than 65% of the minimum exergy replacement cost. Moreover, the lower is the temperature of the ice the higher is the exergy increase. In the case of desalination and potential exergies concentration and altitude variation involve a linear modification of the exergy value, which is not the case with a temperature variation.

In Figure 3 are compared the total exergy content of ice (Ex_{Ice}) and the exergy values of different thermal exergy components of ice -total thermal exergy (Ex_{Therm}), the exergy required for the solidification process, which is called latent exergy (Ex_{Fus}), and the exergy required for cooling the ice from 0 ºC (Ex_{Cool})- with respet to the ice temperature. Latent exergy (dotted line in Figure 3) is a significant and constant value (18.12 kJ/kg), which is the most important factor of thermal exergy of ice, when the temperature of ice is higher than Ð55 ºC. The exergy required for cooling the liquid water from ambient temperature (15 ºC) until the freezing point (0 ºC) is a little value (1.69 kJ/kg) with a low significance in the exergy content of ice. Note that the exergy required for cooling the ice presents a non linear shape, being almost negligible (less than 1.5 kJ/kg) when the ice temperature is higher than Ð10 ºC and taking a non negligible value of 15.42 kJ/kg when the ice reaches the temperature of Ð50 ºC.

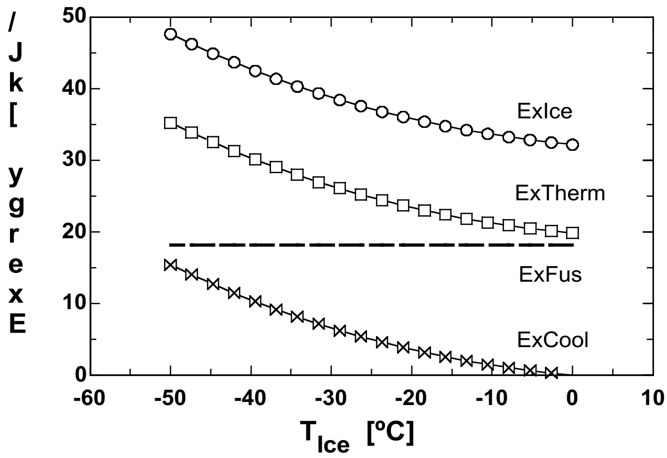

Figure 3. Effect of Temperature of ice on its total exergy (Ex_{Ice}), thermal exergy (Ex_{Therm}), latent exergy (Ex_{Fus}) and exergy of cooling the ice (Ex_{Cool}).

6.3 Real exergy replacement cost of ice sheets

The exergy replacement cost of ice sheets is estimated using a similar procedure than applied to the calculation of the exergy replacement cost of liquid water resources.
First it is calculated the primary energy required for desalting the sea water with the best technology available today. As explained in section 3, it has been considered reverse osmosis consuming 4,2 kWh/m^3 driven by electrical energy that has been produced in a thermal power plant with an efficiency of 35%.
Once the water has been desalted it is necessary to pump it until 2,000 m, which is the average altitude of the ice sheets. In this case it has been considered an isoentropic efficiency of 80% for the pumping process. The pumps are electrically driven (35% efficiency of electricity production). The third step consists on freezing the water since the environment temperature (15ºC, which is the average temperature of the Earth) until the ice temperature. The selected technology in this case is an electricity driven vapor compressor refrigerator with a coefficient of performance equal to 2. This parameter

means that the refrigerator produces 2 units of cold (thermal energy) per each unit of electrical energy consumed.

Table 8 Real exergy replacement cost of world's ice sheets

	Average Earth's Ice				Antarctica's Ice				Greenland's Ice			
	Total	Therm	Pot	Desalt	Total	Therm	Pot	Desalt	Total	Therm	Pot	Desalt
kJ/kg	721.35	643.15	35.00	43.20	724.31	646.11	35.00	43.20	684.29	606.09	35.00	43.20
Mtoe	**7.210E9**	6.429E9	3.498E8	4.318E8	**6.588E9**	5.877E9	3.184E8	3.929E8	**6.156E8**	5.452E8	3.149E7	3.886E7

Table 8 shows the impressive obtained values. The exergy replacement cost is near of 20 times higher than the exergy content of ice.

If all existing ice sheets melted, the required exergy for recover them in the same conditions that are now in nature would be around 9,000 times higher than the total amount of reserves of fossil fuels in the Earth.

Of course, this calculation is only intended to provide an order of magnitude of the huge amount of exergy content of the ice sheets and its real replacement cost, i.e. about the treasures existing in nature. If all ice sheets melted the effects on the global Earth climate and even on its orbital movement due to perturbations on the Milankovich fluctuations [15] would be so strong that it is not possible to evaluate neither estimate or imagine what could happen and, hence it makes no possible to perform an accurate calculation.

7. Conclusions.

We propose the concept of Exergy Replacement cost to physically evaluate, from a thermodynamic viewpoint, the renewable water resources and ice sheets on the planet. The replacement cost takes into account the physical and chemical characteristics that makes this resources useful to man, such as its purity , heigth, temperature and so on.These properties give exergy because of its disequilibrium from the Reference Environment.

For the case of hydrological cycle, the composition component of the replacement cost has a minimum value of 2,600 Mtoe/year considering only the desalination exergy value and a value of 43,799 Mtoe/year that corresponds to the replacement value considering the best available technology for desalination (currently reverse osmosis). The potential exergy replacement cost of the resources has a minimum value of 993 Mtoe/year, taking into account the potential exergy than can be extracted from the resources under existing technological limits, and a maximum of 9,506,8 Mtoe/year taking into account the gross useable potential of the resources and the real physical cost that it would take to obtain their exergy using a thermal power plant with an efficiency of35 %.

The specific physical cost to replenish renewable water resources on the planet varies between a minimum of 3.53 MJ/m^3 and a maximum of 52.4 MJ/m^3. Practically no country is able to assume, from an energy point of view, the cost that it would take to replenish their local water resources.

For the case of ice sheets and particularly the Antartica, its replacement cost is around 9000 times higher than all the fossil fuel reserves of the Earth. Accordingly, Earth´s ice sheets correspond to our most important global exergy reserve. Even though this calculation would be of minor use it gives us a picture of the value of Antartica and Greenland as well as all ice sheets and world glaciers that are slowly but surely melting because of human intervention on climatic change. Both the loss of glaciers and the rise of sea level because of climatic change can now be measured in terms of exergy destruction and then compared with other global environmental effects.

The concepts of exergy and the exergy replacement cost are applicable to the thermodynamic evaluation of other renewable resources and not only for water. The Second Law allows the determination of the minimal costs that are incurred by nature to supply the resources under the physical and chemical conditions that make them useful to man. Note that a First Law analysis is not sensisitive to distinguish between pure and salted water and, on the contrary to exergy, the lower the temperature the less the energy content.Therefore, an energy analysis of fresh water and ice sheets would result in zero energy resources.On the other hand, a systematic analysis of the technologies, allows one to determine the real costs that it would take if we had to replace many of the ecosystem functions that the planet provides for free. This concept allows us to open the door to a new view of evaluating all natural resources, which we will call from now on *Exergoecology*.

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9.Nomenclature.

Cp_{H2O} =Specific heat at constant pressure.

T_a, T_0 =Temperature in reference environment and absolute temperature of water, respectively.

v_{H2O} =Specific volume of water.

P_a , P_0 =Pressure of water and pressure in the reference state.

x_i =Fraction of the component i in water.

μ_{ia} , μ_{i0} =Chemical potential of component i in water and chemical potential of component i in the reference state.

V_a, V_0 =Water velocity and velocity of the reference state.

z_a, z_0 =Water height and height of reference environment.

Q =Volumetric caudal of water.

h =Height.

P_o =Osmotic pressure.

CE =Electrical conductivity of water.

G =Gibb's free energy.

v =Volume.

s =Entropy.

N_i =Number of moles of component i.