EMERGY ANALYSIS OF DESALINATION SYSTEMS

By

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A thesis submitted to the Graduate School

in partial fulfillment of the requirements

for the degree

Master of Science

Major Subject: Environmental Engineering

New Mexico State University

Las Cruces, New Mexico

December, 2009

"Emergy analysis of desalination systems" a thesis prepared by Akash Mummaneni in partial fulfillment of the requirements for the degree, Master of Science in Environmental Engineering, has been approved and accepted by the following:

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This research work is dedicated to my parents Bhavani Mummaneni and Satyanarayana Mummaneni and my brother Avinash Mummaneni who always inspired me to continue my studies, giving me encouragement and strength.

ACKNOWLEDGEMENTS

First of all, I would like to express my sincere thanks to my academic advisor Prof. N. Nirmalakhandan for his continuous support and timely guidance throughout my studies at New Mexico State University. With gratitude, my special thanks to him for his support through research assistantship throughout my studies. Meanwhile, I would like to express my thankfulness to my other committee members, Dr. Adrian Hanson and Dr. Abbas Ghassemi, for their contribution in improving this report and invaluable suggestions.

My special thanks to Dr. Mark T. Brown for his invaluable and timely support and guidance. Also, I would like to thank Dr. Veera Gnaneswar Gude and Mr. Aravind K Mannarswamy for their support and suggestions to improve my research works.

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ABSTRACT

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Emergy analysis is a relatively new approach for evaluating and comparing alternate technologies and to assess their resource utilization efficiencies, environmental impacts, and sustainability. In this study five different indices based on the emergy approach were estimated which took into account factors such as renewable and non-renewable energy used by the process, benefit of the process to society, and the cost of the process. These indices were then used to compare a low temperature desalination process based on the barometric distillation principle against a direct distillation process and a traditional reverse osmosis process. Four different configurations of the low temperature barometric distillation process were evaluated in this study considering the following energy sources: electricity from the grid; electricity from photovoltaic panels powered by solar energy; thermal energy from a solar water heater; and direct solar energy. Based on the indices estimated in this study, the configuration utilizing thermal energy from a solar water heater was found to be the most promising sustainable technology. Based on efficiency and commercial feasibility, the low temperature barometric distillation process ranked below the traditional reverse osmosis process; but, sustainability of the reverse osmosis process is low. Results of this study indicate that future research and development work on the barometric distillation process should focus on further refining the configuration utilizing thermal energy from a solar water heater.

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Chapter 1

INTRODUCTION

1.1 Background

Owing to the exponential increase in population and industrial requirements, fresh water resources are becoming scarce. Even though water covers at least 70% of the total earth's surface, 98% of it is saline. Based on a fair prediction, use of desalinated water becomes important for which an effective and efficient technology needs to be developed. According to Gude (2007), desalination techniques can be grouped into two categories, one which uses the thermal energy termed "thermal desalination" and the other which involves restrictive flow through a membrane termed "membrane techniques." Desalination techniques that fall into the first category are multistage flash distillation (MSF), multiple effect distillation (MED) and vapor compression (VC). The membrane technology includes reverse osmosis (RO) and electro dialysis reversal (EDR) (Gude, 2007).

There are advantages and disadvantages between the two technologies. The disadvantages of thermal desalination techniques are the use of higher total thermal energy, while the effluent of reverse osmosis facilities contains chemicals added to the brine rejects such as hydrochloric acid or sulfuric acid which are not eco-friendly. A thermal desalination unit can use waste heat from a power station while it is also efficient in handling large volumes. A reverse osmosis unit is usually easy to install and implement due to the availability of robust reverse osmosis modules.

1.2 Drawbacks of Membrane Technologies and Thermal Desalination Techniques

According to Mehdizadeh (2006), RO process is generally not favoured for desalination due to high salinity, high temperatures, high silt density, high bacterial activity and pollution. Reverse osmosis systems also require pretreatment and have the problem of fouling. On the other hand, the energy demand for this process is high, accounting for 30% of the production cost (Semiat, 2000). Due to the constant increase in energy demand, the cost of energy also increases substantially.

Thermal desalination technologies are energy intensive processes and disposal of brine is also a major issue with these plants. Distillation process is a costly process and it requires high level of technical knowledge for its design, operation and maintainance. This technology also requires the use of chemical products which require special handling.

The use of conventional non-renewable energy sources contributes to increased carbon dioxide emission, which is one of the green house gases responsible for global warming and climate change. Many governments have already started to propose plans to reduce the per capita carbon dioxide emission.

1.3 Scope of This Research

Considering the factors discussed, researchers are constantly searching for alternate technologies which are more feasible in terms of energy demand and less detrimental on the environment than the available ones. Thus the method of evaluating the technologies becomes crucial. This aspect is the focus of this thesis report. The goal of this thesis was to evaluate a low temperature barometric distillation process (Gude, 2007) and its sustainability.

Chapter 2

LITERATURE REVIEW

2.1 Concept of Energy Evaluation

The method of energy evaluation is crucial as it aids in the comparison of various designs and techniques. According to Brown and Ulgiati (2002), the time limit to the availability of the non-renewable energy resources and the limits to the waste absorption by the biosphere are important. Considering these perspectives, a tool is needed to evaluate a product or service in terms of energy efficiency and sustainability. This thesis focused on the emergy method for the evaluation of alternate technologies and comparing them, and thereby to suggest the most feasible one for the constraints specified.

2.2 Methods of Energy Evaluation

Popular methods available for comparing alternative technologies include life cycle assessment method (LCA), the exergetic version known as ExLCA, the thermo-economic theory, the cumulative exergy cost accounting (CexC), the extended exergy accounting (EEA), the enviroeconomic theory, and emergy accounting (Tonon et al., 2006). Currently there is an emphasis on the LCA method which is more popular and widely used in the evaluation of a product or service in industries when compared to the other available techniques. In general, the technology selection process is based on economics, emergy evaluation and impact assessment.

The ‘life cycle assessment’ as the name indicates is an analysis based on the evaluation of the time period of survival of the product involved. The idea is to choose a product or technology which has the least impact for the available range of product or technology. It necessarily involves careful energy and material balances for a product or the technology under investigation, carried out in a stage-by-stage process. A typical case could be a product which consumes more energy to be manufactured but can be recycled with less energy later versus a product which would consume less energy for manufacturing but use more energy for its recycling or disposal. A comparison on this basis gives a reasonable measure of a product’s or technology’s impact on the environment on a relative scale (sainivas, 2009).

Although life cycle assessment is a powerful tool in quantifying the environmental impacts, many a times situations arise where assigning a numerical value to a qualitative parameter becomes difficult. Also such an assessment would require a range of professionals from engineers to cost accountants, which is another major shortcoming for this kind of evaluation method.

Another method of assessing sustainability of energy sources is based on the greenhouse gases. Sources with more gas release are considered less sustainable and vice versa. This method accounts for the emission of carbon dioxide and helps in monitoring the greenhouse gases under control. This method also suffers from the limitation of not considering the net energy sources but just carbon dioxide. Due to the later reason, this method is not widely accepted. To summarize, sustainability judgments must take into account the net energy, environmental loading, and recycling ability.

2.3 Concept of Emergy

Emergy is defined as the amount of useful energy obtained by an investment in energy to obtain that energy. It is technically the ratio of energy acquired to the energy spent on receiving that energy. The energy measured for this method is expressed in terms of some common form of energy such as sunlight. Emergy is usually expressed in terms of solar em joules (seJ). Also, emergy can be complimented by life cycle assessment but not replaced by it for the evaluation of desalination systems.

Brown and Ulgiati (2002) have evaluated different electricity production systems using emergy accounting techniques and ranked them based on thermodynamic and environmental efficiencies. In their evaluation they used different emergy indices to explain the effect on environment including the effect of carbon dioxide produced from these production systems. They also showed how renewable energy source plants are more sustainable compared to non-renewable energy source plants using the sustainability emergy index.

Paoli et al. (2008) reported the challenges concerning the renewable energy sources lie in making them efficient and competitive with the non-renewable sources by considering the environmental performance. In explaining the effect of renewable resources in a sustainability perspective, they considered the emergy accounting method as a valid approach. By using this approach the authors have calculated the emergy indices for thermal and photovoltaic power plants which shower the remarkable emergy savings for solar technologies. This evaluation suggested the use of solar power technologies for conserving the non-renewable energy resources.

Odum et al. (1987) presented several studies on emergy values of water. He calculated emergy based dollar values of water which were consumed by the irrigation sector in Texas, both for agricultural water and for municipal water. As cited in Buenfil (2000), Odum et al. (1987) calculated the emergy values of water and its economic contribution to various states in Mexico. In evaluating the alternatives for fresh water supply to Windhoek, the capital of Namibia, Buenfil (2000) evaluated the emergy based dollar values of water for the Kavango River which is discharged into the Okavango Delta. The approaches proposed by the above authors were used in this study to evaluate the sustainability of different configurations of barometric distillation process developed by Gude (2007) with a traditional reverse osmosis process.

Chapter 3

METHODOLOGY

3.1 Background

Emergy is a form of available energy which is consumed either directly or indirectly to make a product. It is also defined as the availability of energy of one kind that is used up in transformations either directly or indirectly involved in a product or a service.

Transformity is the ratio of emergy of a product or service to the energy that is contained by the same product or service. Transformity is also a measure of the impact of a product or service on the environment. Higher transformity of a product or service implies more work is needed by the environment to manufacture that product or service. A direct implication of this would also be that processes with lower transformity would have higher efficiency. For example, the transformity of sunlight is unity, meaning no environmental work is required to produce it.

The inclusion of time factor to the sustainability is important. It is mainly because sustainability of a system may not be the same with regard to time. The product or service that is sustainable for twenty years may not be sustainable after that time period. According to Brown and Ulgiati (1997), there could be phases like growth, transition and decline over a period of time. A process which is sustainable during one phase may or may not be sustainable for other periods. The three main factors suggested by Brown and Ulgiati (1997) to be included for making decisions on sustainability of processes based on human control are the net yield of the process, the environment load of the process, and corresponding use of the non-renewable resources. Therefore, various emergy indices discussed by Brown and Ulgiati (1997) relate the energy and emergy evaluated to sustainability.

Different types of emergy indices such as emergy investment ratio (EIR), emergy yield ratio (EYR), % of renewable emergy (% R), emergy benefits to the purchaser (EBR) and emergy dollar per volume (Em \$/ m^3) are used to evaluate the sustainability of a system.

3.2 Emergy Index Ratio (EIR)

The emergy index ratio is the ratio of purchased inputs (P) and services (S) to the non-renewable (N) and renewable resources (R). It reflects the impact of a system or service on the eco-system. With a lower EIR, the system is more sustainable and vice versa.

3.3 Emergy Yield Ratios (EYR)

The emergy yield ratio (EYR) is the ratio of emergy yield of a product or service to the sum of the purchased inputs (P) and services (S). It is a measure of the ability of the process to exploit local resources (Brown & Ulgiati, 1997). With a higher EYR the system is more beneficial to the society or economy. An emergy yield ratio close to unity implies that no net emergy is contributed to the society by the product or service.

3.4 Percentage of Renewable Emergy (%R)

Percentage of renewable emergy (%R) is the ratio of renewable emergy used to the emergy yield of the product or service. The sustainability of a system is directly proportional to percentage of renewable emergy ratio.

3.5 Emergy Benefit to the Purchaser (EBP)

The marginal emergy delivered in a product relative to the monetary worth of payment a purchaser makes is called emergy benefit to the purchaser. Hence, higher values of emergy benefit the purchaser more than lower values. The logic behind this parameter is that the environment is not compensated monetarily for its resources, and hence the marginal value of emergy becomes crucial for every purchaser.

3.6 Em-dollars per Unit Volume (Em$/m^3)

Em-dollars per unit volume is defined as the ratio of solar emergy yield of the product or service to the product of volume of water produced and Em dollar ratio. This index gives us the cost of producing the water. The process is more effective with a lower Em $ to volume ratio. Generally, the Em $ per cubic meter is more than the $ per cubic meter, because the monetary values do not includes the value of work done by the nature for a particular process.

3.7 Transformity

As described earlier, transformity is a measure of the efficiency of the process. With lower transformity, the efficiency of the process is higher.

3.8 Evaluation Procedure

The procedure for evaluating a technology or a process is as follows (Sciubba and Ulgiati, 2005):

a. Define the boundary of the system and developing the system diagrams for sources, components, processes and products arranged from left to right in the order of transformity.
b. Prepare the emergy evaluation tables with a line item for each item identified in the system diagrams. Determine the total emergy flow, storages and yields of each line item. Determine the emdollar (em $) equivalent of emergy values. An em$ is the proportion of the gross economic product determined from the portion of the nation emergy budget. Micro-computer models of the system may be run, which generate trends over time for different assumptions and alternatives. Emergy, em$ and transformity graphs may be generated by these simulations.
c. Compare results using emergy indices such as net yield ratios, investment ratios, exchange ratios, emergy/money ratios, etc. Recommend for policy choices those alternatives which contribute the most real wealth, measured by emergy, to the combined system of environment and economy.

d. For primary energy sources, use the net emergy yield ratios to select the ones that contribute most. For determining what uses are appropriate for an energy type, use the transformity value. For necessary process is that consume the primary sources, use the emergy investment ratio to predict which are likely to be economical.

The steps involved in emergy analysis are (Sciubba and Ulgiati, 2005):

a. Developing the necessary emergy diagrams which can display the ideology that is being followed and which can also give a clear picture of process flow.
b. Constructing the emergy analysis tables from diagrams.
c. Calculating the emergy indices and comparing the results for economic feasibility and environmental sustainability of the process.

Chapter 4

EMERGY EVALUATION

Emergy analysis is the only tool that can account for all the upstream energy inputs that are required to make a product or service. This analysis measures the environmental impact and sustainability of a system considering all the renewable and non-renewable inputs (Sikdar, 2005). Gude (2007) had used the barometric distillation technique in his design of the desalination systems which will be described in the later parts of this report. So emergy analysis was used to evaluate the sustainability of different configurations of barometric distillation as developed by Gude (2007).

4.1 Background for Barometric Distillation

Reali (1984) was the first to work on barometric distillation proposing a refrigerator-heat-pump desalination scheme (RHPDS). He concluded that a temperature difference of 10 K should be sufficient to drive the desalination process for 1 kg of saline water. Though his study showed the theoretical validity, no experimental data were presented to support the feasibility of the process. Improvement to this model, proposed by Bemporad (1995), was limited to conceptual design.

The basic technology used in this thesis was originally proposed by Midilli (2004) which was later modified by Al-Kharabsheh and Goswami (2004). He (Midilli) made use of low grade thermal energy from solar collecting panels which were then used as the energy source to produce heat to drive the desalination process. The important aspect of his design was that it did not require any mechanical pumping; rather the whole fluid flow was driven by atmospheric pressure. The heat transfer involved in this process was natural convection, which aided the evaporation of fresh water from saline water by dissipating the latent heat rejected in the condenser of the system.

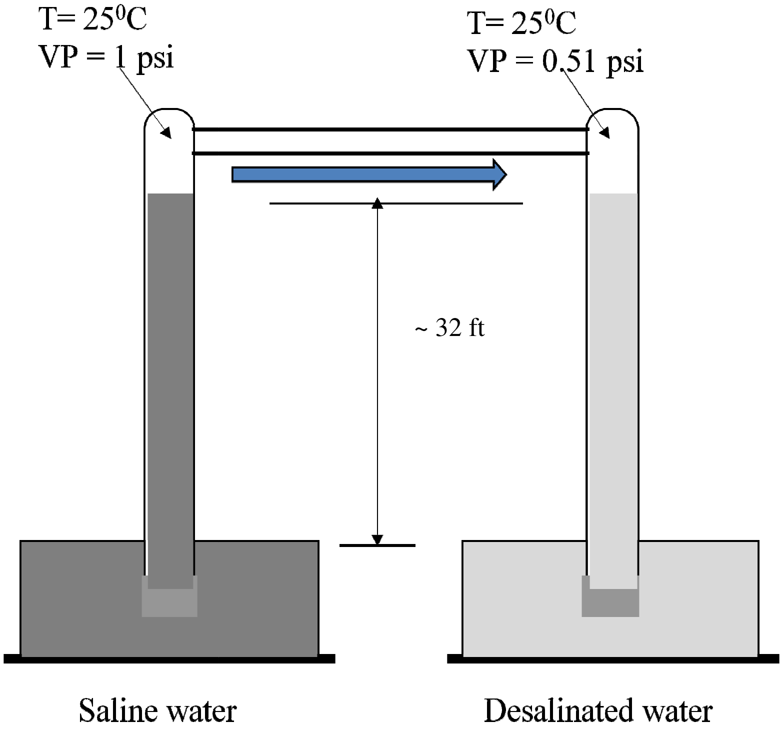

Figure 1: Schematic of the Natural Vacuum by Barometric Pressure Head (Gude, 2007)

The advantage of this system was mainly the replacement of a mechanical pump, which would have required energy for its operation by the barometric head at atmospheric pressure for the hydraulic flow. The second advantage was the utilization of the solar energy which is available in abundance. Al-Kharabsheh and Goswami (2004) also recovered the sensible heat from the brine using a heat exchanger for greater energy efficiency. The major systems considered is this work was at a height of 10 meters above the ground level; that is static pressure head of water at ambient conditions.

Many studies conducted on barometric distillation limited themselves to theoretical studies and batch operations. Scientific and technical information is required to develop a large scale continuous process. Gude (2007) proposed low temperature solar powered desalination system using low grade renewable energy sources such as PV panels, solar collectors, photovoltaic thermal collectors and geothermal sources (see in figure 2). He proposed a new design by utilizing the solar energy during the sunlight hours and PV energy during the non-sunlight hours to increase the efficiency of the process. The feasibility of the process was evaluated both theoretically and experimentally for continuous operation. Further, he succeeded in his studies to produce potable quality water from impaired water (Gude, 2007).

In this study a modified version of the barometric distillation system developed by Gude was considered. The energy analysis method was applied to evaluate five different configurations of the system developed by Gude (2007). A comparison of these five configurations with a traditional reverse osmosis plant was also made.

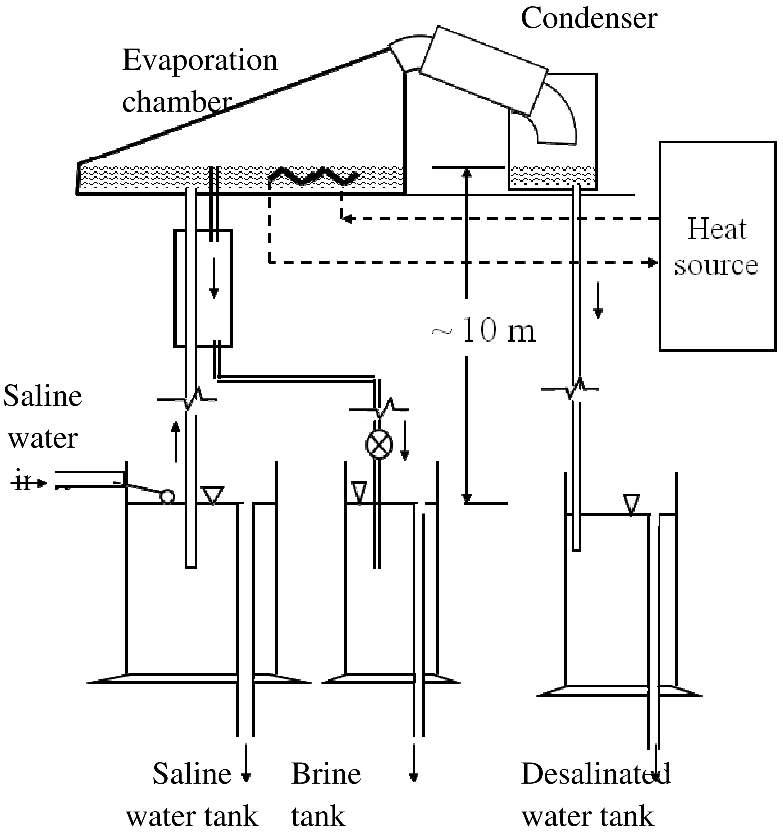

Figure 2: Schematic of the Proposed Desalination by Barometric Distillation using Various Low-grade Heat Sources (Gude, 2007)

4.2 Brief Overview of Systems Evaluated

Six systems were evaluated using the basic processes developed by Gude (2007). They are

System 1: Desalination unit which produces drinking water by distillation process with electricity as the source of heat.

System 2: Desalination unit which produces drinking water by barometric distillation process with electricity as the source of heat.

System 3: Desalination unit which produces drinking water by barometric distillation process with PV panels used to supply electricity for heating.

System 4: Desalination unit which produces drinking water by barometric distillation process and the saline water is heated using solar water heater.

System 5: Desalination unit which produces drinking water by barometric distillation process; the heat requirements for this process are obtained from direct solar energy.

System 6: Emergy evaluation for the plant that produces drinking water by Reverse Osmosis process located at Tampa Bay, Florida.

The brief description of these systems is given in the following sections of this report.

4.2.1 System 1

Distillation is the process by which a mixture of liquids is separated based on the difference in volatility of the boiling mixture. It is a physical process and no chemical reactions are involved. The system is assumed to be working as follows. The rate of fresh water production for the system is assumed to be 12 L/day and is considered as a basis in the evaluation of this design. The average yield is assumed to be 80%. In this system, drinking water is produced from saline water and this saline water is heated to its evaporation temperature and then is condensed in a condenser. The evaporation temperature of water is considered as 100^0C. It requires both specific as well as latent heat for the system and the requirements are shown below. The heat requirements for the distillation process are supplied using the electricity.

The setup of this system consists of an evaporation chamber assembled with an electric heater and a condenser. Saline water which is at a temperature of 25^0C was pumped to the evaporator and was heated in that evaporation chamber to its evaporation temperature; then the vapors were entered into condenser in which they condensed to obtain the potable water. Some amount of latent heat as well as specific heat was recovered from the condenser chamber by circulating the water around the condenser to increase the energy efficiency of the process. The system diagram of potable water produced from system 1 is shown in Figure 3. The emergy indices of potable water produced from system 1 is shown in Table 1 and 2.

The heat requirements for this distillation process are as follows:

Fresh water produced per day = $12\ \frac{L}{day}$.

= $12\ \frac{kg}{day}$.

Yield = 80%. (assumed).

Saline water used for treatment = $\frac{12}{80\%} = 15\ \frac{L}{day}$.

Temperature of the saline water = 25^0C.

Temperature to which saline water is heated = 100^0C.

Specific heat of water = $4.2\ \frac{kJ}{kg-K}$

Latent heat of vaporization of water = $2257\ \frac{kJ}{kg}$

Heat of vaporization required per day = $27084\ \frac{kJ}{day}$.

Heat required to raise the temperature of the water = $mC_p \nabla t$.

= $3.78\text{E}+03\ \frac{kJ}{day}$.

Total heat required (sensible heat + heat of vaporization) = $3.9\text{E}+04\ \frac{kJ}{day}$.

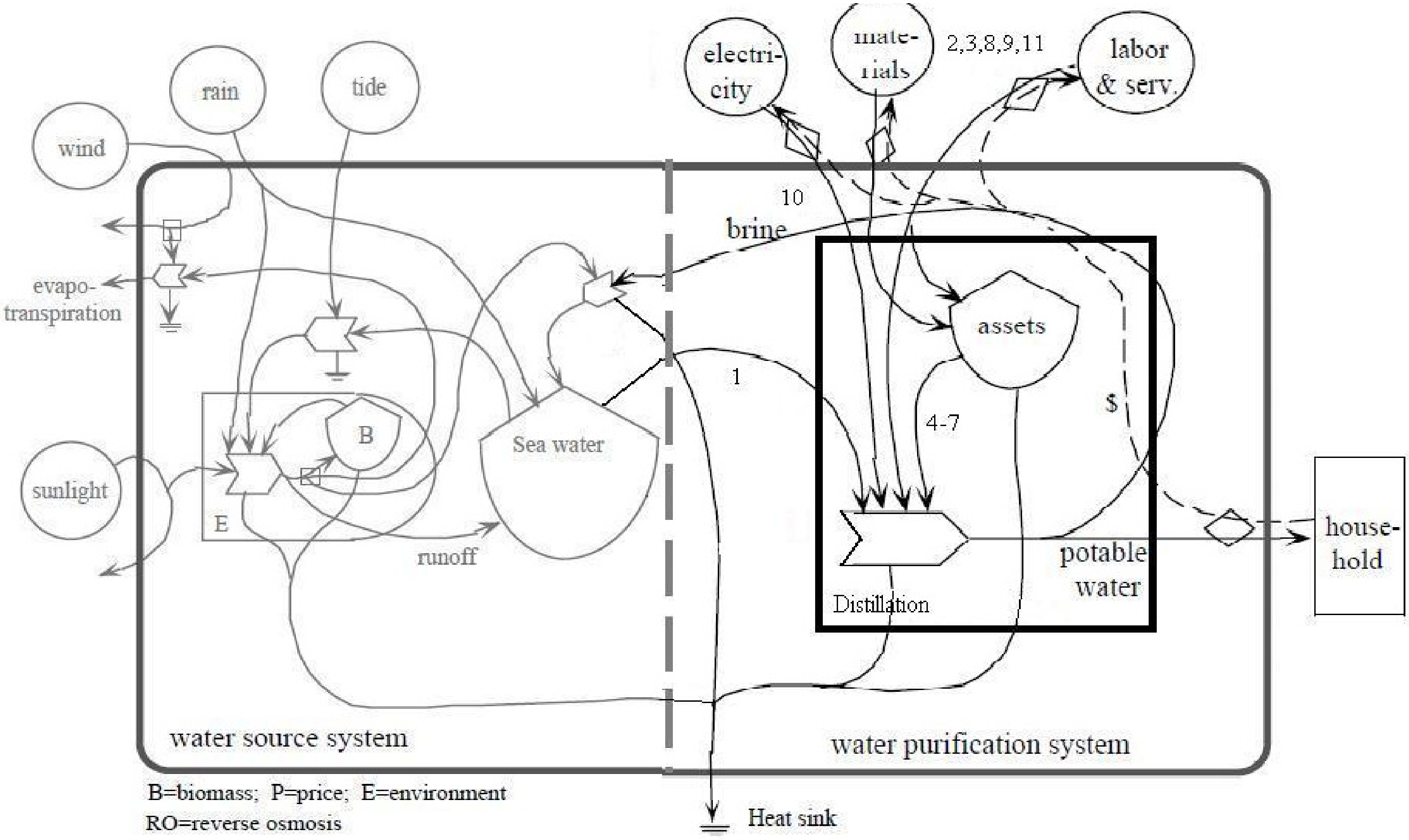

Figure 3: System Diagram for the Water Produced by Distillation (System 1)

Table 1: Emergy Evaluation of Drinking Water Produced from System1

		unit	Energy Data Unit/Year	Emergy/Unit sej/Unit	Solar Emergy sej/yr	Emergy/m^3
	Renewable Resources:					
1	Saline Water	J	3.98E+06	3.19E+04	1.27E+11	2.90E+10
	Purchased and operational inputs:					
2	Constructional & Operational Costs	$	74.46	5.40E+11	4.02E+13	9.18E+12
3	Work to carry Sea Water to Distiller	J	2.05E+07	6.76E+06	1.38E+14	3.16E+13
4	Stainless Steel	kg	1.33	1.80E+12	2.40E+12	5.48E+11
5	Aluminum	kg	1.33	1.25E+10	1.67E+10	3.81E+09
6	Glass	kg	1.47	8.40E+08	1.23E+09	2.81E+08
7	Concrete & Cement	kg	180.00	1.23E+12	2.21E+14	5.05E+13
8	Other Purchased Assets	$	13.33	5.40E+11	7.20E+12	1.64E+12
9	Money spent for Electricity	$	187.76	5.40E+11	1.01E+14	2.31E+13
10	Electricity	J	1.13E+10	1.60E+05	1.80E+15	4.12E+14
11	Land Lease	$	30	5.40E+11	1.62E+13	3.70E+12
	Emergy Per Unit of Distilled Water					
12	Potable Water	m^3	4.38	5.32E+14	2.33E+15	5.32E+14
13	Potable Water	J	2.16E+07	1.08E+08	2.33E+15	5.32E+14
14	Potable Water	g	4380000	5.32E+08	2.33E+15	5.32E+14
15	Potable Water W/o Services	J	2.16E+07	9.37E+07	2.03E+15	4.63E+14

Table 2: Emergy Indices and Ratios of Potable Water Produced from System 1

		Expressions	Quantity
17	Emergy Investment ratio	(P+S)/(N+R)	18348.15
18	Emergy yield ratio	Y/(P+S)	1.00
19	% Renewable Emergy	100(R/Y)	5.45E-03
20	Emergy Benefit to Purchaser	Em $/$	36.63
21	Em-Dollar Value of Potable Water/ m^3	Em $/ m^3	984.99
22	Transformity of Potable Water	sej/J	1.08E+08
23	Emergy per $m^3$of potable water	sej/ m^3	5.32E+14

Foot notes for the Tables 1 and 2 are available in the appendix, Table A-1

4.2.2 System 2

In this system the barometric distillation method proposed by Midilli (2004) was used for producing potable water. A natural vacuum created by barometric pressure head was used in this system to pump the water to the evaporation chamber. The static pressure head of water was about 10 meters. When the natural vacuum existed above this height, liquid water was evaporated. The rate of fresh water production for the system was assumed to be 12 L/day and was considered as a basis in the evaluation of this design (Gude, 2007). The average yield was assumed to be 70% (Gude, 2007). The energy requirements for this configuration was 3370 kJ per kg of fresh water produced (Gude, 2007). So in order to meet the heat requirement, various approaches were studied. In this system an electric heater powered with electricity was used for supplying heat requirements for the desalination process. The system consists of a naturally evacuated evaporation chamber attached with a condenser; the schematic of the system is shown in Figure 4. Therefore it was assumed that the naturally evacuated evaporation chamber was placed at the top of a 10 meters tall tower. The hydraulic flow of saline water to the evaporation chamber was maintained by the atmospheric pressure. This system uses no mechanical energy for its pumping requirements. The water in the evaporation chamber was evaporated due to heat supplied by using electricity. These water vapors from the evaporator were cooled in the condenser to collect the fresh water. Some amount of heat was exchanged by circulating water around the condenser. The system diagram of potable water produced from system 2 is shown in Figure 5. The emergy indices of potable water produced from system 2 is shown in Tables 3 and 4.

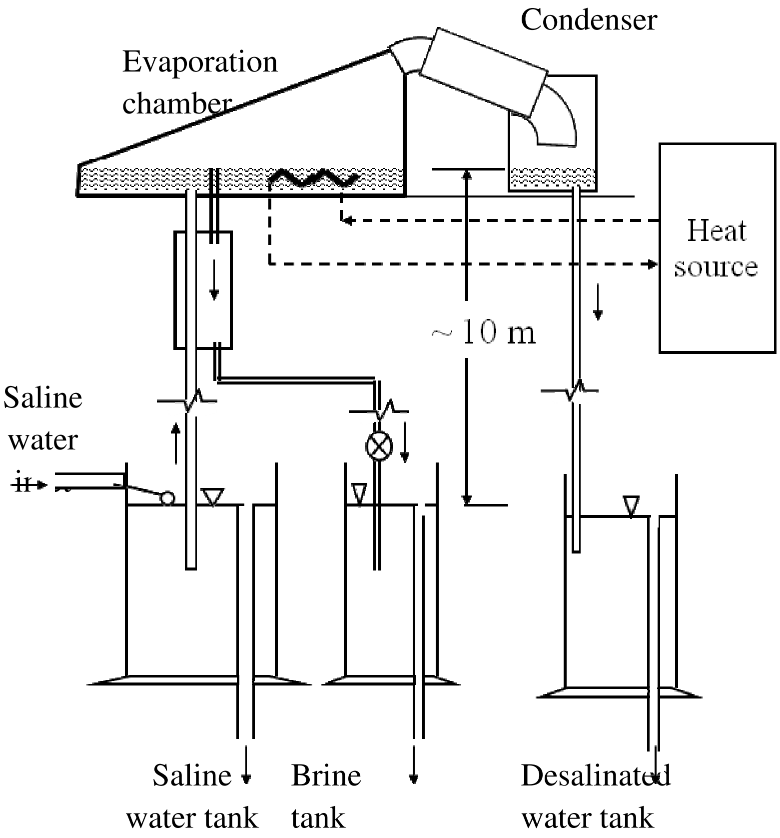

Figure 4: Schematic of the Desalination by Barometric Distillation using Electricity (Gude, 2007)

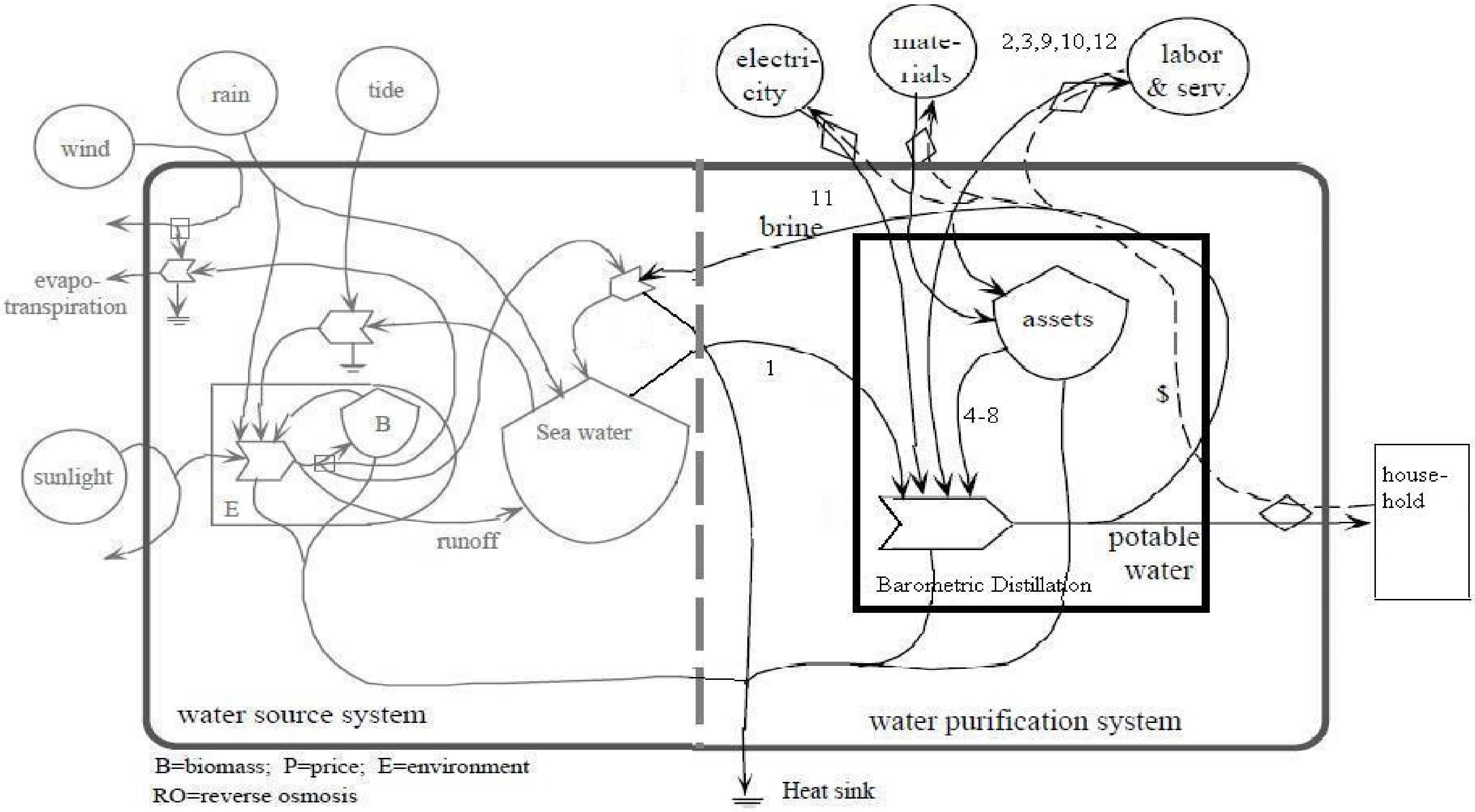

Figure 5: Systems Diagram for the Water Produced by Barometric Distillation (System 2)

Table 3: Emergy Evaluation of Drinking Water Produced from System2

		unit	Energy Data Unit/Year	Emergy/Unit sej/Unit	Solar Emergy sej/yr	Emergy/m^3
	Renewable resources:					
1	Saline Water	J	4.55E+06	3.19E+04	1.45E+11	3.31E+10
	Purchased and operational inputs:					
2	Constructional & Operational Costs	$	74.46	5.40E+11	4.02E+13	9.18E+12
3	Work to carry Sea Water to Distiller	J	2.05E+07	6.76E+06	1.38E+14	3.16E+13
4	Stainless steel	kg	100	1.80E+12	1.80E+14	4.11E+13
5	Aluminum	kg	6.67	1.25E+10	8.33E+10	1.90E+10
6	Glass	kg	1.47	8.40E+08	1.23E+09	2.81E+08
7	Concrete Cement	kg	180.00	1.23E+12	2.21E+14	5.05E+13
8	PVC	g	16964.60	5.85E+09	9.92E+13	2.27E+13
9	Other Purchased Assets	$	33.33	5.40E+11	1.80E+13	4.11E+12
10	Money spent for Electricity	$	246.01	5.40E+11	1.33E+14	3.03E+13
11	Electricity	J	1.48E+10	1.60E+05	2.36E+15	5.39E+14
12	Land Lease	$	50	5.40E+11	2.70E+13	6.16E+12
					3.22E+15	7.35E+14
	Emergy Per Unit of Distilled Water					
13	Potable Water	m^3	4.38	7.12E+14	3.12E+15	7.12E+14
14	Potable Water	J	2.16E+07	1.44E+08	3.12E+15	7.12E+14
15	Potable Water	g	4380000	7.12E+08	3.12E+15	7.12E+14
16	Potable Water W/o Services	J	2.16E+07	1.28E+08	2.76E+15	6.31E+14

Table 4: Emergy Indices and Ratios of Potable Water Produced from System 2

		Expressions	Quantity
17	Emergy Investment ratio	(P+S)/(N+R)	21499.47
18	Emergy Yield Ratio	Y/(P+S)	1.00
19	% Renewable Emergy	100(R/Y)	4.65E-03
20	Emergy Benefit to Purchaser	Em $/$	36.61
21	Em-Dollar Value of Potable Water/ m^3	Em $/ m^3	1319.03
22	Transformity of Potable Water	sej/J	1.44E+08
23	Emergy per cu.mt of potable water	sej/ m^3	7.12E+14

Foot note for the Tables 3 and 4 is available in the appendix, Table A-2

4.2.3 System 3

In this system, the operating principle was the same as the one used in system 2. This system was designed and constructed by Gude (2007). The system consisted of an evaporation chamber assembled with an electric heater and a condenser. Using the barometric distillation process, the assembly was placed on the top of a tower of 10 meters tall. Feed water to the evaporation chamber was supplied using the PVC pipes which were maintained by atmospheric pressure. Photovoltaic panels were used as the source of energy. They collect the solar energy and convert it into electrical energy which was stored in a battery. This system used solar energy during the day time and electrical energy stored in the batteries during the night time for the process to continue. The heat requirements for the system were supplied using the aforementioned sources. This (continuous) process increased the process efficiency as well as the energy efficiency of the system when compared to batch systems. The process schematic is shown in Figure 6. The system incorporated a heat exchanger to recover sensible heat from the brine that was draining out of the evaporator. From the experimental studies, the system produced around 12 L/day with an average process efficiency of about 81%. The specific energy requirement for this configuration was 2926 kJ for production of 1 kilogram of freshwater (Gude, 2007). The system diagram of potable water produced from system 3 is shown in Figure 7. The emergy indices of potable water produced from system 3 are shown in Table 5 and 6.

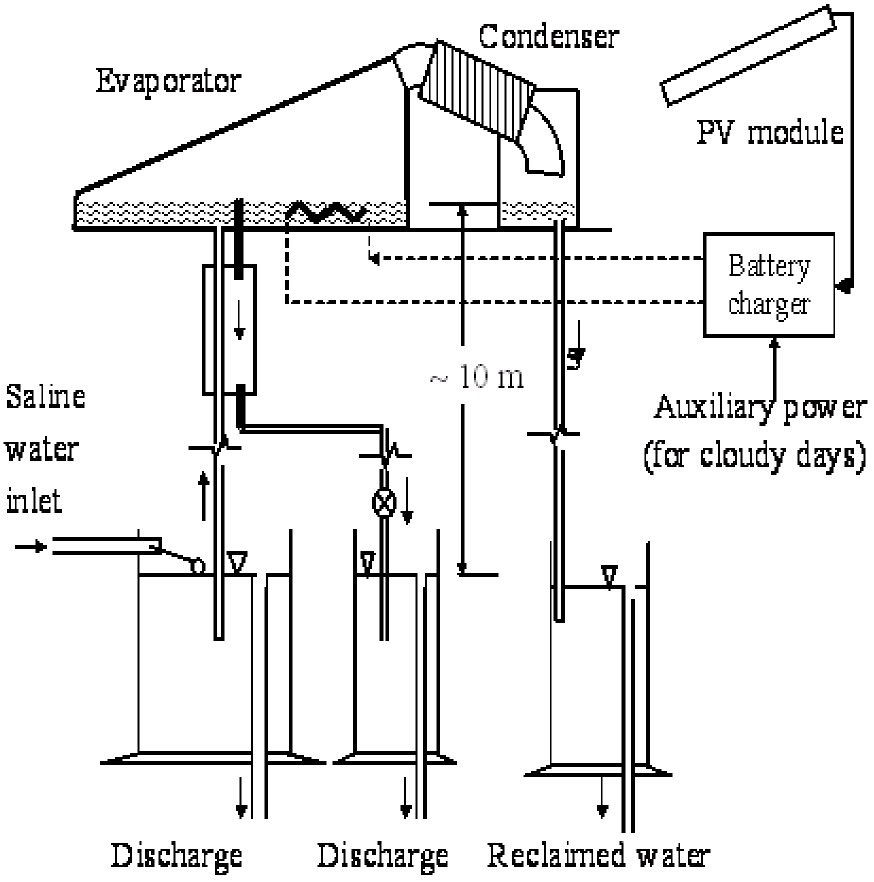

Figure 6: Desalination by Barometric Distillation using PV Panels (Gude, 2007)

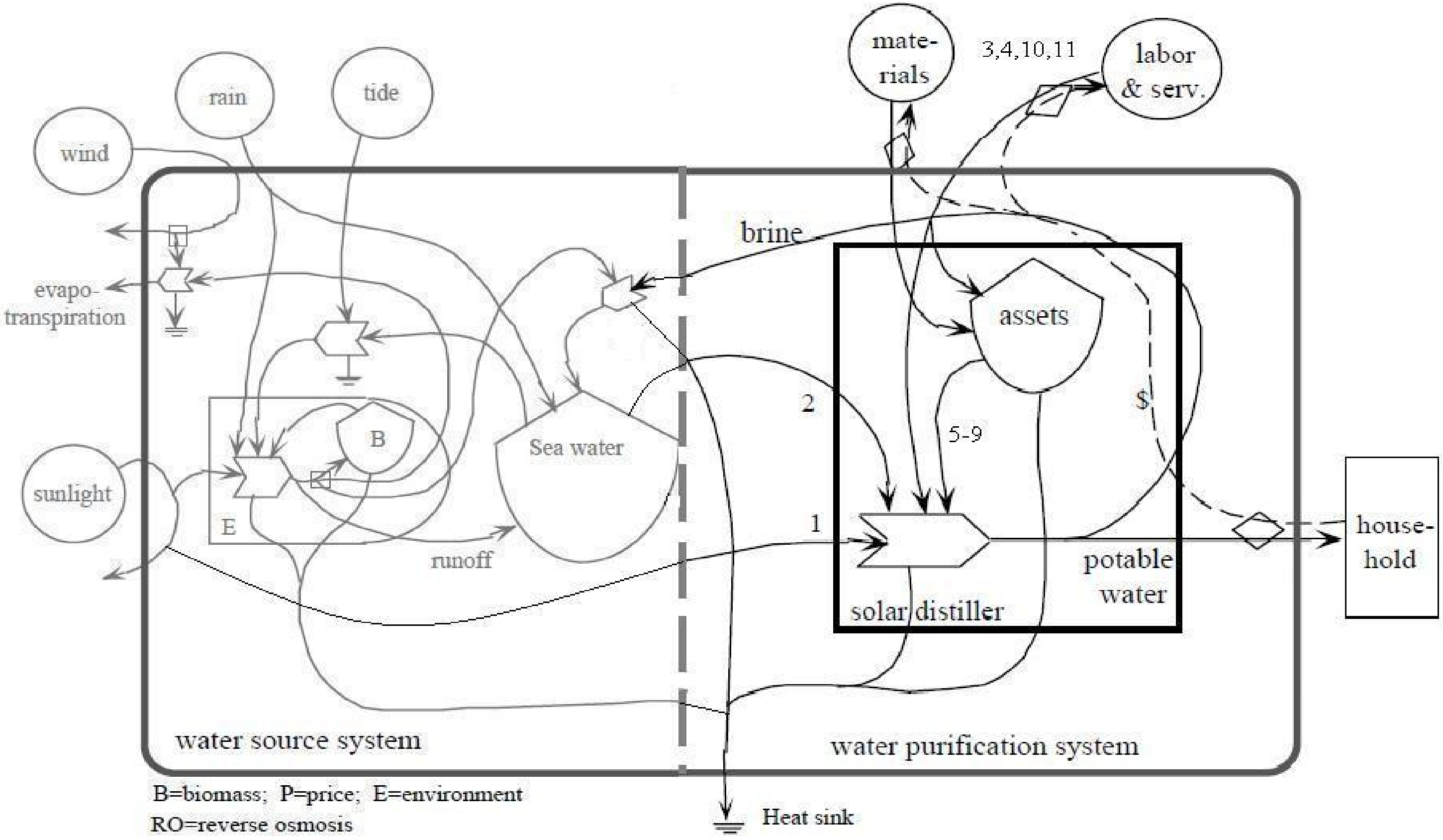

Figure 7: Systems Diagram for Water Produced from Barometric Distillation by using PV panels (System 3)

Table 5: Emergy Evaluation of Drinking Water Produced from System3

		unit	Energy Data Unit/Year	Emergy/Unit sej/Unit	Solar Emergy sej/yr	Emergy/m^3
	Renewable Resources:					
1	Sunlight	J	2.52E+13	1	2.52E+13	5.76E+12
2	Saline Water	J	3.93E+06	3.19E+04	1.25E+11	2.86E+10
	Purchased and operational inputs:					
3	Constructional & Operational Costs	$	74.46	5.40E+11	4.02E+13	9.18E+12
4	Work to carry Sea Water to Distiller	J	2.05E+07	6.76E+06	1.38E+14	3.16E+13
5	Stainless Steel	kg	100	1.80E+12	1.80E+14	4.11E+13
6	Aluminum	kg	6.67	1.25E+10	8.33E+10	1.90E+10
7	Glass	kg	1.47	8.40E+08	1.23E+09	2.81E+08
8	Concrete Cement	kg	180.00	1.23E+12	2.21E+14	5.05E+13
9	PVC	g	16964.60	5.85E+09	9.92E+13	2.27E+13
10	Other Purchased Assets	$	133.33	5.40E+11	7.20E+13	1.64E+13
11	Land Lease	$	50	5.40E+11	2.70E+13	6.16E+12
					8.04E+14	1.83E+14
	Emergy Per Unit of Distilled Water					
12	Potable Water	m^3	4.38	1.61E+14	7.04E+14	1.61E+14
13	Potable Water	J	2.16E+07	3.26E+07	7.04E+14	1.61E+14
14	Potable Water	g	4380000	1.61E+08	7.04E+14	1.61E+14
15	Potable Water W/o Services	J	2.16E+07	1.97E+07	4.27E+14	9.75E+13

Table 6: Emergy Indices and Ratios of Potable Water Produced from System 3

		Expressions	Quantity
16	Emergy Investment ratio	(P+S)/(N+R)	26.78
17	Emergy yield ratio	Y/(P+S)	1.04
18	% Renewable Emergy	100(R/Y)	3.60E+00
19	Emergy Benefit to Purchaser	Em $/$	5.06
20	Em-Dollar Value of Potable Water/m^3	Em $/m^3	297.84
21	Transformity of Potable Water	sej/J	3.26E+07
22	Emergy per m^{3}of potable water	sej/m^3	1.61E+14

Foot notes for the Tables 5 and 6 are available in appendix, Table A-3

4.3.4 System 4:

Currently available solar desalination techniques are based on two types of systems. The first one involves conversion of solar energy into electrical energy by employing photovoltaic cells. The other technology collects solar energy which is used to heat the feed water; the rest of the technology follows the standard distillation process. In this system, the operating principle was the same as that used in system 2. The rate of fresh water production for the system was assumed to be 12 L/day and was considered as a basis in the evaluation of this design (Gude, 2007). The average yield was assumed to be 80% (Gude, 2007). The energy requirements for this configuration were assumed to be 2926 kJ per kg of fresh water produced (Gude, 2007). The system consisted of the same configuration as in the earlier systems. But the feed water was heated using a solar water heater and was pumped to the evaporation chamber on the top of the tower. In this case the specific heat requirements for this process were supplied using the solar water heater; latent heat required for vaporization of saline water was supplied using the direct solar energy. The system diagram of potable water produced from system 4 is shown in Figure 8. The emergy indices of potable water produced from system 4 are shown in Tables 7 and 8.

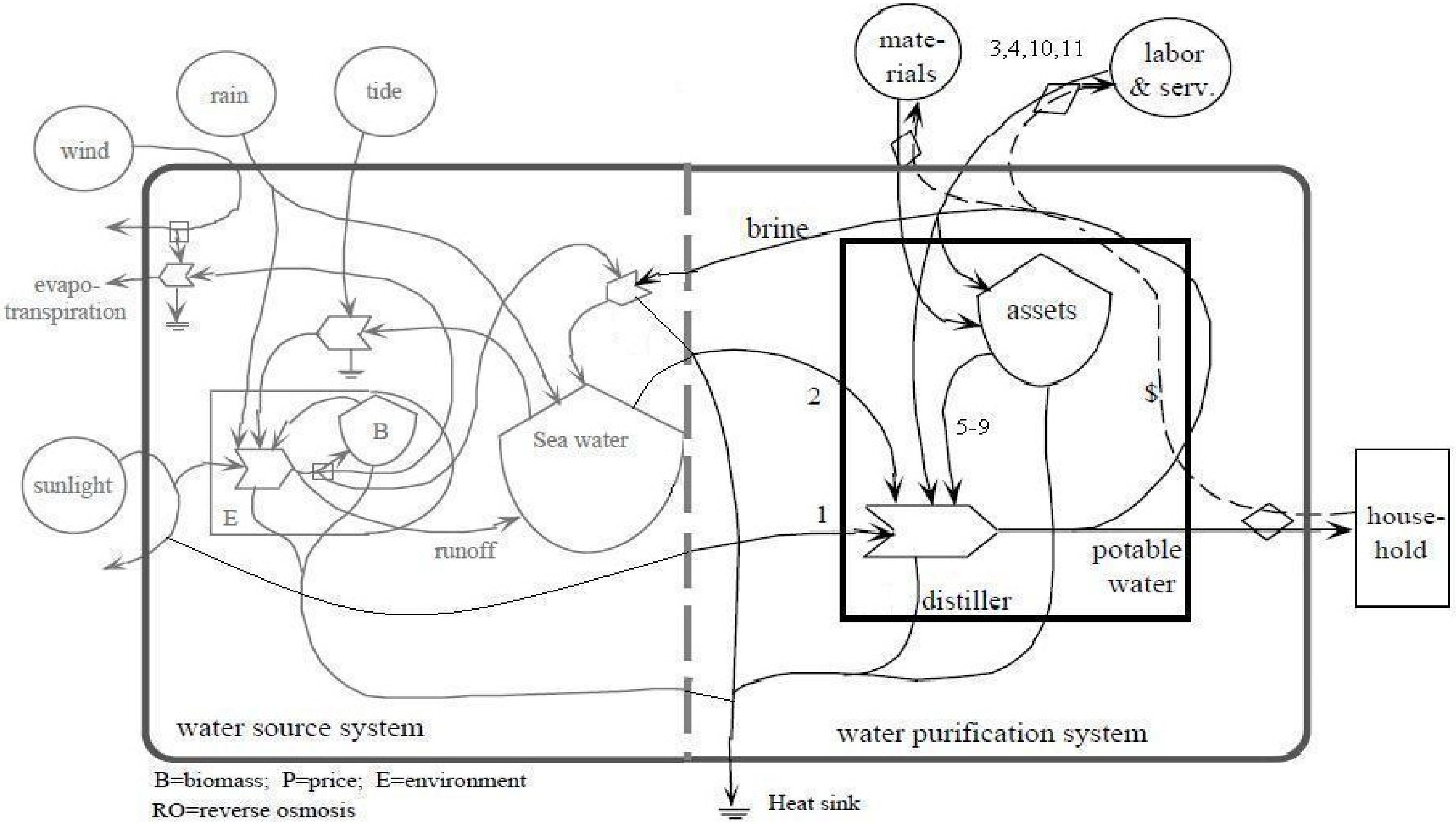

Figure 8: Systems Diagram for the Water Produced from Barometric Distillation by using Direct Solar Energy

Table 7: Emergy Evaluation of Drinking Water Produced from System4

		unit	Energy Data Unit/Year	Emergy/Unit sej/Unit	Solar Emergy sej/yr	Emergy/m^3
	Renewable Resources:					
1	Sunlight	J	2.52E+13	1	2.52E+13	5.76E+12
2	Saline Water	J	3.93E+06	3.19E+04	1.25E+11	2.86E+10
	Purchased and operational inputs:					
3	Constructional & operational costs	$	74.46	5.40E+11	4.02E+13	9.18E+12
4	Work to carry sea water to distiller	J	2.05E+07	6.76E+06	1.38E+14	3.16E+13
5	Stainless Steel	kg	100	1.80E+12	1.80E+14	4.11E+13
6	Aluminum	kg	6.67	1.25E+10	8.33E+10	1.90E+10
7	Glass	kg	1.47	8.40E+08	1.23E+09	2.81E+08
8	Concrete Cement	kg	180.00	1.23E+12	2.21E+14	5.05E+13
9	PVC	g	16964.60	5.85E+09	9.92E+13	2.27E+13
10	Solar Water Heater & Auxiliary Equipment	$	45.00	5.40E+11	2.43E+13	5.55E+12
11	Land Lease	$	50	5.40E+11	2.70E+13	6.16E+12
					7.56E+14	1.73E+14
	Emergy Per Unit of Distilled Water					
12	Potable Water	m^3	4.38	1.45E+14	6.34E+14	1.45E+14
13	Potable Water	J	2.16E+07	2.93E+07	6.34E+14	1.45E+14
14	Potable Water	g	4380000	1.45E+08	6.34E+14	1.45E+14
15	Potable Water W/o Services	J	2.16E+07	1.97E+07	4.27E+14	9.75E+13

Table 8: Emergy Indices and Ratios of Potable Water produced from System 4

		Expressions	Quantity
16	Emergy Investment ratio	(P+S)/(N+R)	24.01
17	Emergy yield ratio	Y/(P+S)	1.04
18	% Renewable Emergy	100 (R/Y)	4.0
19	Emergy Benefit to Purchaser	Em $/$	9.21
20	Em-Dollar Value of Potable Water/m^3	Em $/m^3	268.08
21	Transformity of Potable Water	sej/J	2.93E+07
22	Emergy per m^3 of potable water	sej/m^3	1.45E+14

Foot note for the Tables 7 and 8 are available in appendix, Table A-4.

4.3.5 System 5

In this system, the operating principle was the same as that used in system 2. This system was designed and constructed by Gude (2007). The system consisted of an evaporation chamber assembled with an electric heater and a condenser. Using barometric distillation process, the assembly was placed on the top of a tower of 10 meters tall. Feed water to the evaporation chamber was supplied using the PVC pipes which were maintained by atmospheric pressure. This was a batch process and the system used solar energy for its heat requirements. This process was similar to that proposed by Al-Kharabsheh (2004). The schematic of the process is shown in Figure 9. The system incorporated a heat exchanger to recover sensible heat from the brine that was draining out of the evaporator. From the experimental studies, the system produced around 4.9 L/day with an average process efficiency of about 61%; the specific energy requirements for this configuration was 4157 kJ for production of 1 kilogram of freshwater (Gude, 2007). The schematic of the process and system diagram of potable water produced from system 5 are shown in Figure 9 and 10. The emergy indices of potable water produced from system 5 is shown in Table 9 and 10.

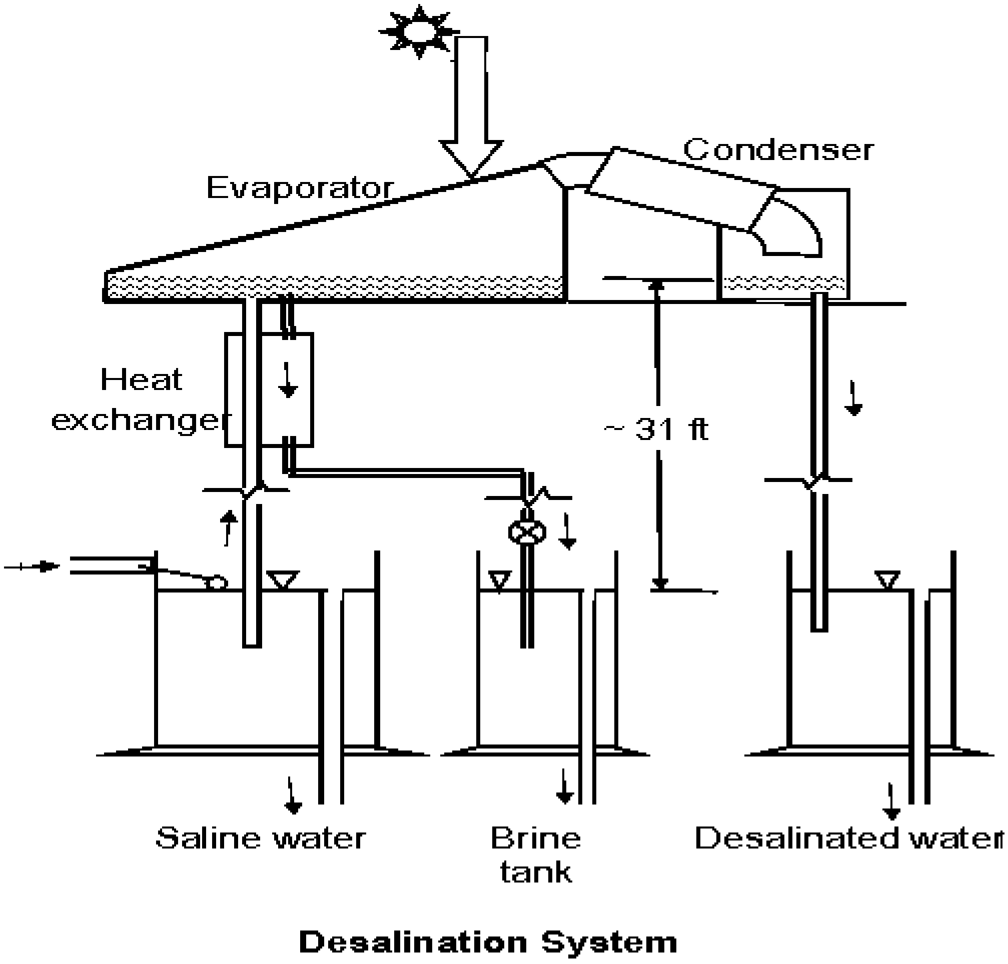

Figure 9: Schematic of Desalination System using Direct Solar Energy (Gude, 2007)

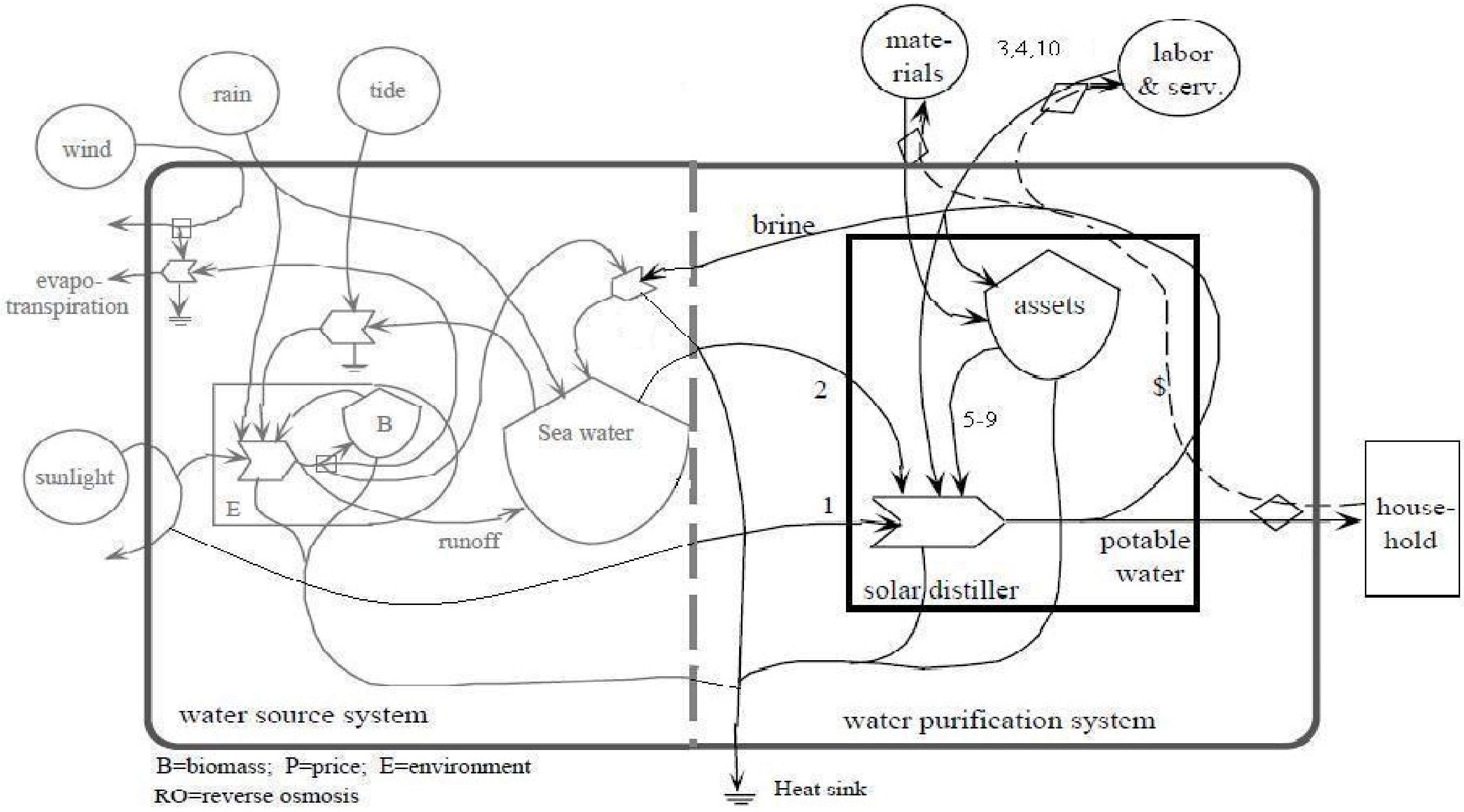

Figure 10: Systems Diagram for the Water Produced from Barometric Distillation by using Solar Water Heater

Table 9: Emergy Evaluation of Drinking Water Produced from System 5

		unit	Energy Data Unit/Year	Emergy/Unit sej/Unit	Solar Emergy sej/yr	Emergy/m^3
	Renewable Resources:					
1	Sunlight	J	2.52E+13	1	2.52E+13	1.41E+13
2	Saline Water	J	2.13E+06	3.19E+04	6.80E+10	3.80E+10
	Purchased and operational inputs:					
3	Constructional & operational costs	$	30.4045	5.40E+11	1.64E+13	9.18E+12
4	Work to carry sea water to distiller	J	2.05E+07	6.76E+06	1.38E+14	7.73E+13
5	Stainless Steel	kg	100	1.80E+12	1.80E+14	1.01E+14
6	Aluminum	kg	6.67	1.25E+10	8.33E+10	4.66E+10
7	Glass	kg	1.47	8.40E+08	1.23E+09	6.89E+08
8	Concrete Cement	kg	180.00	1.23E+12	2.21E+14	1.24E+14
9	PVC	g	16964.60	5.85E+09	9.92E+13	5.55E+13
10	Land Lease	$	50	5.40E+11	2.70E+13	1.51E+13
					7.08E+14	3.96E+14
	Emergy Per Unit of Distilled Water					
11	Potable Water	m^3	1.7885	3.45E+14	6.17E+14	3.45E+14
12	Potable Water	J	8.84E+06	6.98E+07	6.17E+14	3.45E+14
13	Potable Water	g	1.79E+06	3.45E+08	6.17E+14	3.45E+14
14	Potable Water W/o Services	J	8.84E+06	4.83E+07	4.27E+14	2.39E+14

Table 10: Emergy Indices and Ratios of Potable Water Produced from System 5

		Expressions	Quantity
15	Emergy Investment ratio	(P+S)/(N+R)	23.38
16	Emergy yield ratio	Y/(P+S)	1.04
17	% Renewable Emergy	100 (R/Y)	4.10E+00
18	Emergy Benefit to Purchaser	Em $/$	11.97
19	Em-Dollar Value of Potable Water/m^3	Em $/$m^3$	638.54
20	Transformity of Potable Water	sej/J	6.98E+07
21	Emergy per m^3 of potable water	sej/m^3	3.45E+14

Foot note for the tables 9 and 10 are available in appendix, Table A-5.

4.3.6 System 6

This system is based on the reverse osmosis process and is located in Tampa Bay, Florida. The plant is operating with a capacity 25 MGD. It also releases more concentrated brine into the ocean which retards the biological activity (Buenfil, 2001). It is represented in the emergy diagram. This system makes use of electricity for its operation. Much of the emergy input is used for the electricity, labor and services. The system diagram of potable water produced from system 6 is shown in Figure 11. The emergy indices of potable water produced from system 6 are shown in Tables 11 and 12.

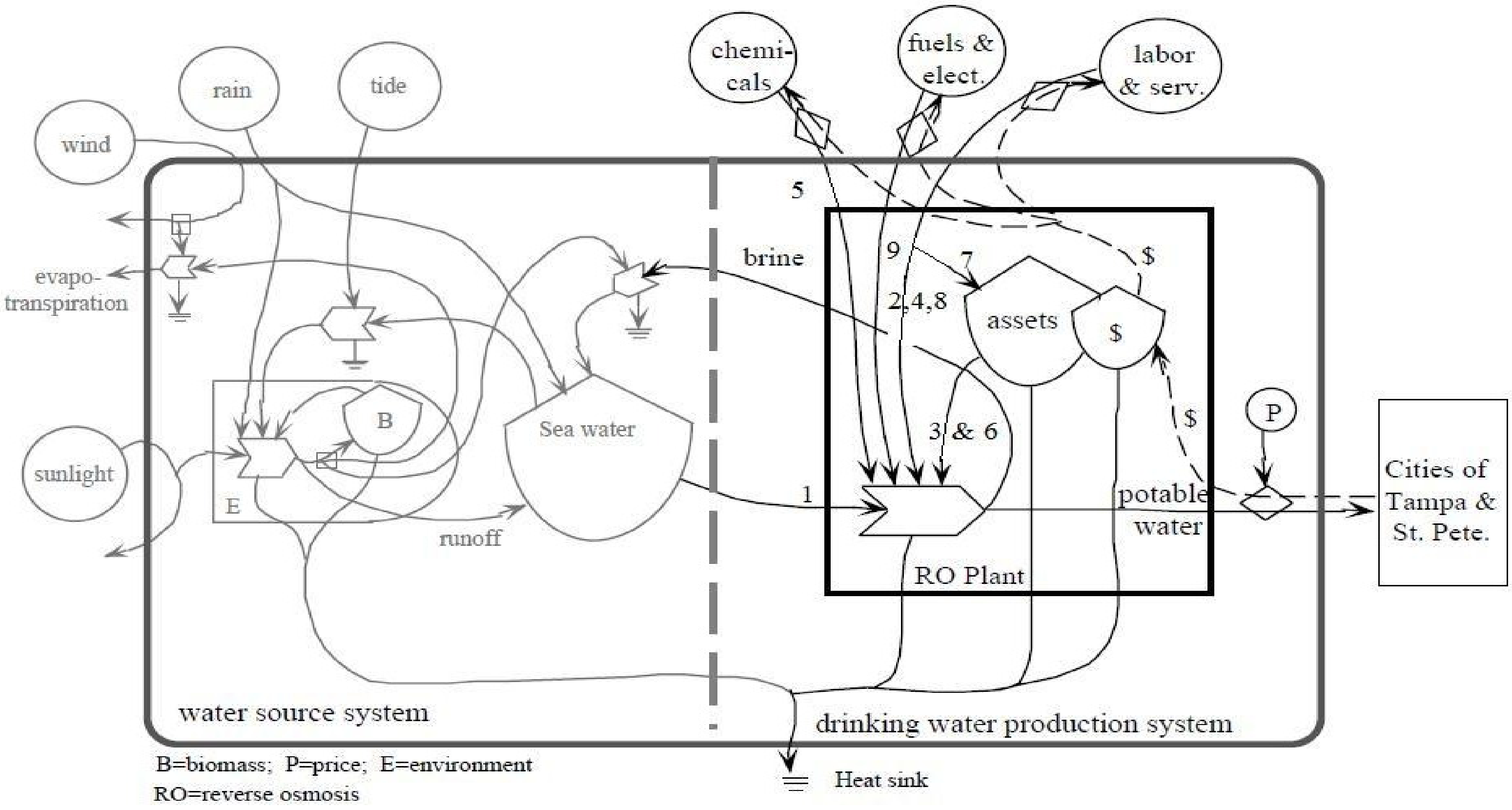

Figure 11: Systems Diagram for the Water Produced from Reverse Osmosis Plant Located in Tampa Bay, Florida

(Buenfil, 2001)

Table 11: Emergy Evaluation of Drinking Water Produced from System 6

		unit	Energy Data Unit/Year	Emergy/Unit sej/Unit	Solar Emergy sej/yr	Emergy/m^3
	Renewable Resources:					
1	Saline Water	J	7.32E+13	3.19E+04	2.33E+18	6.76E+10
	Purchased and operational inputs:					
2	Constructional & operational costs	$	2.31E+06	8.10E+11	1.87E+18	5.43E+10
3	Stainless Steel	kg	70000.00	1.80E+12	1.26E+17	3.65E+09
4	Chemicals	$	679173.00	8.10E+11	5.50E+17	1.59E+10
5	Chemicals	kg	724708	1.00E+12	7.25E+17	2.10E+10
6	Concrete	kg	9.23E+05	1.23E+12	1.14E+18	3.29E+10
7	Other Purchased Assets	$	8162150	8.10E+11	6.61E+18	1.91E+11
8	Money spent for Electricity	$	4.47E+06	8.10E+11	3.62E+18	1.05E+11
9	Electricity	J	3.81E+14	1.60E+05	6.10E+19	1.77E+12
	Emergy Per Unit of Distilled Water					
10	Potable Water	m^3	3.45E+07	2.26E+12	7.79E+19	2.26E+12
11	Potable Water	J	1.71E+14	4.57E+05	7.79E+19	2.26E+12
12	Potable Water	g	3.45E+13	2.26E+06	7.79E+19	2.26E+12
13	Potable Water W/o Services	J	1.71E+14	3.83E+05	6.53E+19	1.89E+12

Table 12: Emergy Indices and Ratios of Potable Water Produced from System 6

		Expressions	Quantity
14	Emergy Investment ratio	(P+S)/(N+R)	32.40
15	Emergy yield ratio	Y/(P+S)	1.03
16	% Renewable Emergy	100 (R/Y)	3.0
17	Emergy Benefit to Purchaser	Em $/$	4.91
18	Em-Dollar Value of Potable Water/m^3	Em $/$m^3$	2.79
19	Transformity of Potable Water	Sej/J	4.57E+05
20	Emergy per m^3 of potable water	sej/m^3	2.26E+12

Foot note for the tables 11 and 12 are available in appendix, Table A-6

Chapter 5

RESULTS AND DISCUSSION

The systems are evaluated based on emergy indices, and the first three indices reveal the consumption of both renewable and non-renewable environmental resources and the impact of the system or process on the environment. The other three indices give an idea of the efficiency of the system, commercial feasibility and production cost per unit. Comparison of Emergy Indices for the Systems evaluated is shown in Table 13.

Table 13: Comparison of Emergy Indices and Ratios for Potable Water Produced from Various Configurations of Desalination Systems

S.No	Emergy Indices of Potable Water	Expression	System 1	System 2	System 3	System 4	System 5	System 6
1.	Emergy Investment Ratio (EIR)	$\frac{P+S}{N+R}$	18348.15	21499.47	26.78	**24.01**	**23.38**	32.40
2.	Emergy Yield Ratio (EYR)	$\frac{Y}{P+S}$	1.00	1.00	1.04	**1.04**	**1.04**	1.03
3.	% of Renewable Emergy (% R)	$\frac{100*R}{Y}$	5.45E-03	4.65E-03	3.60	**4.00**	**4.10**	2.99
4.	Emergy Benefit to Purchaser (EBP)	$\frac{Em\,\$}{\$}$	36.63	36.61	5.06	**9.21**	11.97	**4.91**
5.	Em $ Value of Potable Water per Cubic Meter.	$\frac{Em\,\$}{Cu.mt}$	984.99	1319.03	297.84	268.08	638.54	**2.79**
6.	Transformity of Potable Water	$\frac{Sej}{J}$	1.08E+08	1.44E+08	3.26E+07	2.93E+07	6.98E+07	**4.57E+05**
7.	Emergy per m^3 of potable water	$\frac{Sej}{Cu.mt}$	5.32E+14	7.12E+14	1.61E+14	1.45E+14	3.45E+14	2.26E+12

P – Purchased inputs S – Services R – Renewable resources N – Non-renewable resources.

1. **Emergy Investment Ratio (EIR):** EIR gives an idea of the impact of the system on environment. With lower EIR the system has less impact on the environment. From the results it is very clear that systems1 and 2 are using electricity to produce drinking water which consumes a significant amount of non-renewable resources. System 5 is best sustainable one compared to the other systems by using direct sunlight and seawater, which are renewable resources in its process of producing potable water. System 4 is the next best sustainable system by consuming very little amount of non-renewable resources when compared to the other systems. The comparison of EIR for various systems evaluated is shown in Figure 12.

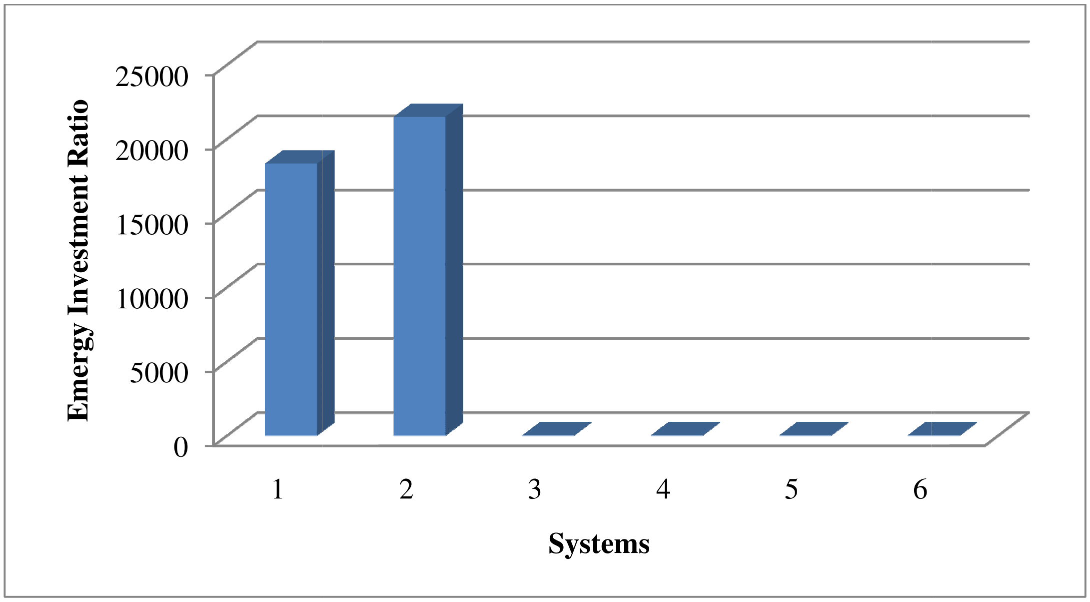

Figure 12: Comparison of Emergy Investment Ratio (EIR) for Various Desalination Systems

2. **Emergy Yield Ratio (EYR):** Higher Emergy Yield Ratio (EYR) indicates that more emergy is contributed to the society or economy. But EYR close to one indicates that no net emergy is contributed to the society or economy. All the systems evaluated indicate that net emergy was almost equal to one, so no net emergy was contributed to the society or economy. In a comparison of best one among these, Systems 4 and 5 are contributing more emergy than the other systems. . The comparison of EYR for various systems evaluated is shown in Figure 12.

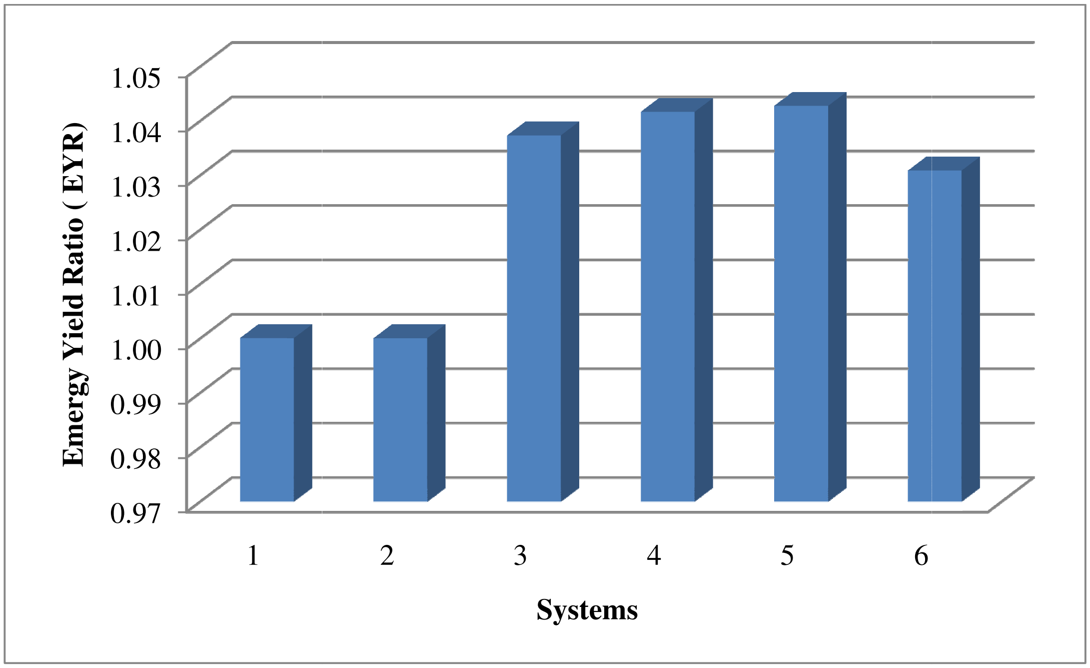

Figure 13: Comparison of Emergy Yield Ratio (EYR) for Various Desalination Systems.

3. **Percentage of Renewable Emergy (%R):** This index shows the consumption of the renewable emergy consumed by the system. Processes with high %R index imply the consumption of less fossil fuels. Of all the systems evaluated Systems 4 and 5 are consumed significant amount of renewable resources than the other systems. Systems 1 and 2 are consuming very little renewable resources which can create a significant of environmental impact. The comparison of %R for various systems evaluated is shown in Figure 14.

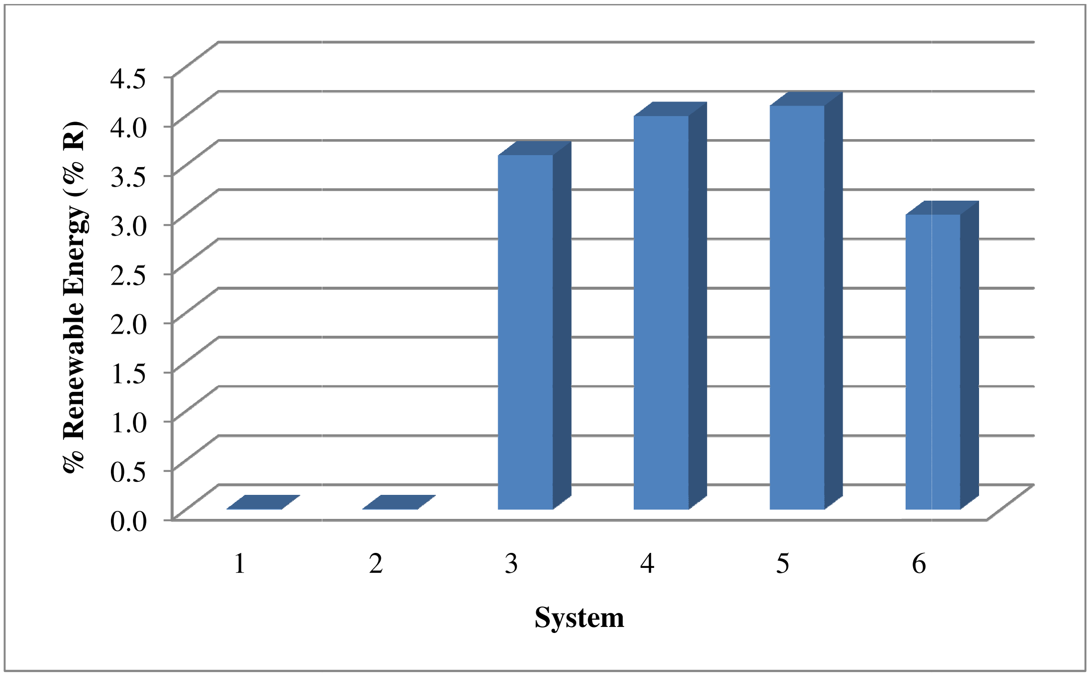

Figure 14: Comparison of % of Renewable Emergy for Various Desalination Systems.

4. **Emergy Benefit to the Purchaser (EBP):** Here emergy benefits to the purchaser give the value for the money paid by the consumer. The price of any product is based on money paid to people for their work, not to the environment for its work. Therefore, consumers receive more energy for the money they have paid because the product includes the work of the people as well as environment. If the EBP is higher, then the product is more beneficial to the consumer. Among all the six systems evaluated, system 5 gave highest EBP, followed by system 4 and system 6. At this point, system 4 was the best alternative to all the other systems. The comparison of EBP for various systems evaluated is shown in Figure 15.

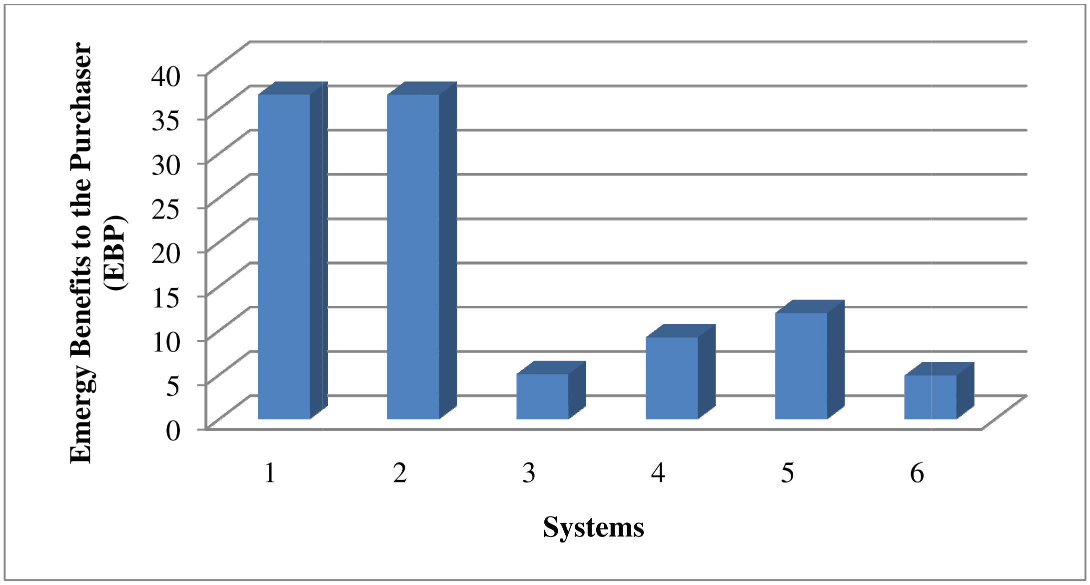

Figure 15: Comparison of Emergy Benefits to the Purchaser (EBP) for Various Desalination Systems.

5. **Em- Dollar per volume (Em \$/ m^3):** Em-\$ per cubic meter of water will give the cost of production of a product by a process. Here system 6, which produced water by the RO process will give the least Em \$/ m^3 of potable water. System 4 was the other available alternative among the evaluated technologies. The comparison of Em\$ value per cubic meter of potable water for various systems evaluated is shown in Figure 15.

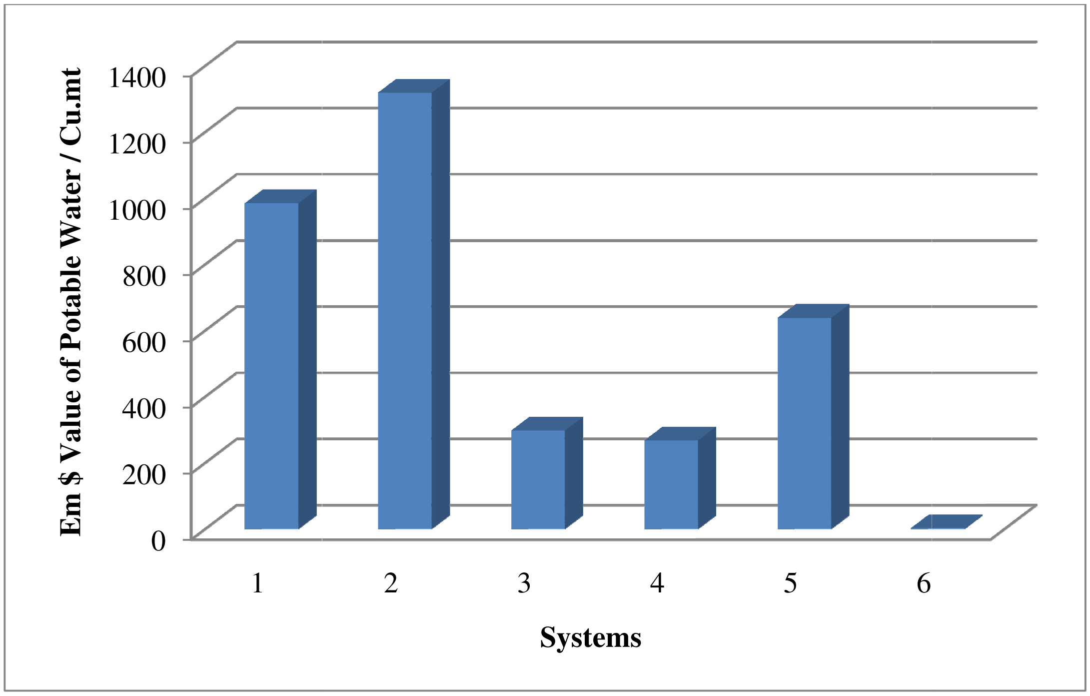

Figure 16: Comparison of Em \$ value of Potable Water / m^3 for Various Desalination Systems.

6. **Transformity:** Transformity is the rate of conversion of raw material to finished products, which is also called the efficiency of the process. With lower transformity, the efficiency of the system is higher. System 6 was the most efficient system among all the evaluated systems. System 4 was the next best efficient system among all the alternatives. The comparison of transformity of potable water for various systems evaluated is shown in Figure 15.

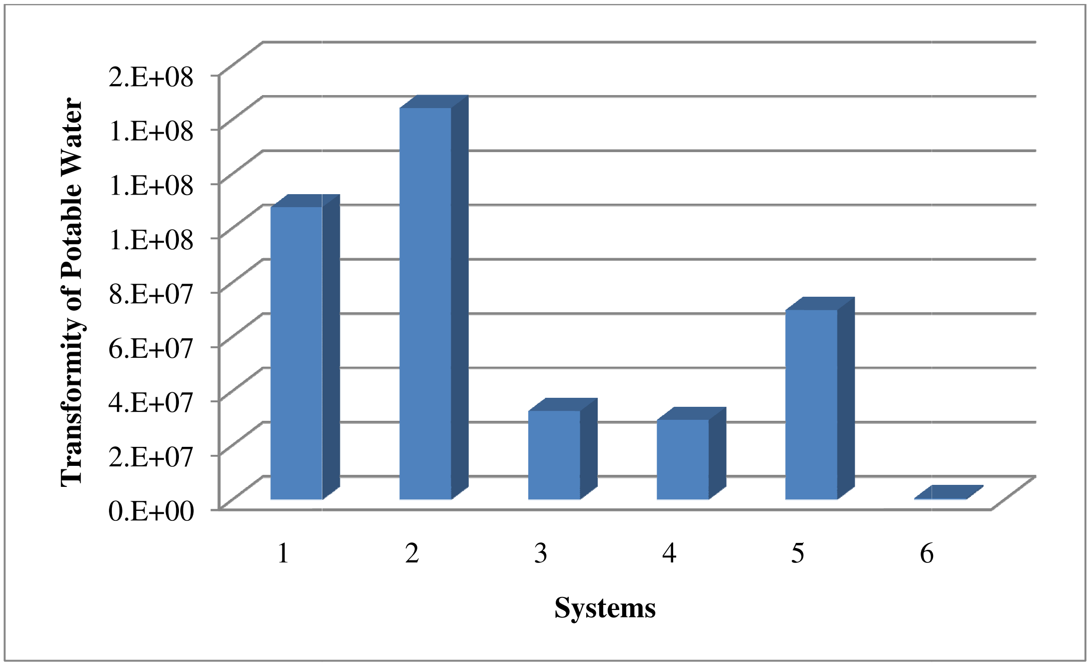

Figure 17: Comparison of Transformity of Potable Water for Various Desalination Systems.

Chapter 6

Conclusion

Based on the data provided in the results and discussion section, the indices such as emergy investment ratio (EIR), emergy yield ratio (EYR), emergy benefits to the purchaser (EBP) and percentage of renewable emergy (%R), it is evident that system 4 is the best green, eco-friendly and sustainable technology. On the other hand, if considered in terms of efficiency or commercial feasibility of the process, system 6 utilizing reverse osmosis processes proves to be less expensive and more efficient technology though it may not be eco-friendly.

Based on the percentage of renewable energy index, system 4 utilizes 4% of the renewable energy resources as against system 6 which has the same index, a value of 2.99. Also the transformity of potable water index which is inversely related to the efficiency of the system suggests that system 4 with a value of 2.93E+07 is less efficient as against system 6 whose value for the same index is 4.57E+05. Further, based on the emergy benefit to purchaser and the Em$ value per cubic meter of water, system 6 proves to be a better technology. But based on emergy investment and the emergy yield ratio which are the crucial measures of sustainability, it can be concluded that system 4 is a better alternative technology.

Further investigation needs to be done on technology in system 4 to improve its efficiency and decrease the cost of production. An important point worth noting is that the pressure and the area in reverse osmosis systems do affect the indices factor.

Also the systems 1 through 5 are lab scale but system 6 is industrial scale. A scaling factor could also be suspected to cause changes in the indices. Considering all the above discussed facts, desalination based on solar water heating needs to be investigated further in comparison with the other currently available technologies.

APPENDIX

Table A-1: Notes for the Emergy Evaluation of Drinking Water Produced from System 1 (Footnotes for Tables 1 and 2)

	Evaporating Surface Area per Distiller:	m^2	1	(assumed)
1	**Salty Water**			
	Average Fresh Water Produced per Day	L/m^2-day	12	(considered as the basis)
	Evaporating Area per Distillation System	m^2	1	(assumed)
	Fresh Water Produced per Unit per Year	L/Yr	4380	(L/day)*(365dasy/yr)
	% Efficiency of the System	%	80%	(assumed)
	Salt Water Used Per Year	L/Yr	5475	(L/day)(% recovery)x100
	Mass of Salt Water Used per Year	g/Yr	5.58E+06	(L/yr)(1.02E6 g/m^3)(10^6 m^3/L)
	Avg TDS of Salt Water Used	ppm	30000	measured
	Avg. Gibbs Free Energy of Water	J/g	7.13E-01	[(8.33J/mol/C)(290K)/(18 g/mol)] *ln(1E6-TDS in ppm/965,000ppm)
	Energy of Salt Water Used	J/Year	3.98E+06	(g/Yr)(J/g)
	Transformity	sej/J	3.19E+04	(Buenfil,2001)
2	**Constructional & Operational Costs:**			
	Total Cost of Water Production	$/L	0.017	(assumed)
	Fresh Water produced per unit /Year	L/Year	4380	(same as 1)
	Annual Cost of Water Production	$/Year	74.46	(Cost of water production)(Fresh water produced/ year)
	Emergy per Dollar Ratio in 2009	sej/$	5.40E+11	(Projected from 1993 sej/$ ratio in Odum(1996,p.314) using 5.7 % decrease/yr)
3	**Work To Carry Sea Water To Distiller**			
	Salt Water Required Per Week	L/Week	105.29	(same as 1)
	Weekly Time to Carry Sea Water	min/Week	45	(assumed)
	Calories required for Sea Water Transport	Kcal/Day	13.39	(3000 kcal/day)(min/week)/(10080 min/week)
	Work Required for Sea Water Transport	J/Year	2.05E+07	(kcal/day)(4186J/kcal)(365 days/year)
	Transformity	sej/J	6.76E+06	(Buenfil,2001)
4	**Stainless Steel**			
	Total Steel and Iron in Assets	Kg	20	(assumed)
	Useful Life of Assets	years	15	(assumed)
	Prorated Steel and Iron Assets	kg/Year	1.33	(Total assets in Kg)/(Yrs)
	Emergy per Mass of Steel	sej/Kg	1.80E+12	(Odum,1996;p.192)
5	**Aluminum**			
	Total Aluminum in Assets	Kg	20	(assumed)
	Useful Life of Assets	years	15	(assumed)
	Prorated Aluminum Assets	kg/Year	1.33	(Total assets in Kg)/(Yrs)
	Emergy per Mass of Aluminum	sej/Kg	1.25E+10	(Buranakarn,1998)

6 Glass

Average Area of the Glass Used	m^2	1	(Gude,2007)
Thickness of the Glass used	m	0.01	(Gude,2007)
Volume of the Glass Used	m^3	0.01	(area*thickness)
Density of the Glass	Kg/m^3	2200	
Average Life time of Glass	years	15	(assumed)
Weight of the Glass	Kg	1.47	(volume)(density)
Emergy per Unit	sej/Kg	8.40E+08	(Odum et al.,1987b)

7 Concrete & Cement

Weight of Concrete Used	Kg	2700	(Volume of concrete base * density of ready mix)
Useful Life of Assets	years	15	(assumed)
Weight Used per Year	Kg/Yr	180.00	(Total assets in Kg)/(Yrs)
Emergy per Unit	sej/Kg	1.23E+12	(Buranakarn,1998;p.175)

8 Heaters And Other Auxiliary Equipment

Purchase Price of the Auxiliary Equipment	$	200	measured
Replacement Time	Years	15	(assumed)
Annual Cost	$/Year	13.33	(total coast of equipment in $/ years)
Emergy per Dollar Ration	sej/$	5.40E+11	(Projected from 1993 sej/$ ratio in Odum(1996,p.314) using 5.7 % decrease/yr)

9 Money Spent for Electricity

Electrical Energy Used for Water	kWh/Year	3129.27	(J/yr)/(3.6E+06 J/kWh)
Cost of Electricity	$/kWh	0.06	Dept of energy web site
Money to be spent for Electricity	$/Year	187.76	(kWh/yr)($/kWh)
Emergy per dollar ratio in 2009	sej/$	5.40E+11	(Projected from 1993 sej/$ ratio in Odum(1996,p.314) using 5.7 % decrease/yr)

10 Electricity,J

Energy requirements for Water	kJ/Day	3.09E+04	(Theoretical requirements)
Total Mass of Drinking Water Produced	Kg/Year	4380	$(m^3/yr)(1E3\ Kg/m^3)$
Electrical Energy to be Used	J/Year	1.13E+10	(kJ/day)(365 days/Yr)*1000
Transformity	sej/J	1.60E+05	(Odum, 95;p.305)

11 Land Lease, $

Land Required	m^2	3	area required is taken 3 times the distiller area
Land Leasing rate	$\$/m^2/Year$	10	(from an average rates in NM)
Land Lease	$/Year	30	(area)(leasing rate)
Emergy per Dollar Ratio in 2000	sej/$	5.40E+11	(Projected from 1993 sej/$ ratio in Odum(1996,p.314) using 5.7 % decrease/yr)

12 Potable Water Produced, m^3:

Total Potable Water Produced	$m^3/year$	4.38	(L/yr)/1000
Total Emergy Yield	sej/Yr	2.33E+15	(sum of items 1-11)
Emergy per Volume of Drinking Water	sej/m^3	5.32E+14	$(sej/yr)(m^3/yr)$

13 Potable Water Produced,J:

Total Drinking Water Produced	$m^3/year$	4.38	(same as 12)
Total Energy Content of the Water	J/Year	2.16E+07	$(m^3/yr)(4.94\ J/g)(1E6\ g/m^3)$
Total Emergy Yield	sej/Yr	2.33E+15	(sum of items 1-11)
Transformity of Potable Water	sej/J	1.08E+08	(sej/yr)(g/yr)

14 Potable Water Produced,g:

Total Potable Water Produced	m^3/year	4.38	(same as 12)
Mass of Potable Water produced	g/Yr	4.38E+06	(m^3/yr)(1E6 g/ m^3)
Total Emergy Yield	sej/Yr	2.33E+15	(sum of items 1-11)
Emergy per Mass of Potable Water	sej/g	5.32E+08	(sej/yr)/(g/yr)

15 Potable Water Produced without services

Emergy Potable Water w/o Services	sej/Year	2.03E+15	(total emergy-services)=Y-S
Energy of Potable Water	J/Year	2.16E+07	(same as note 13)
Transformity without services	sej/J	9.37E+07	(sej/yr)/(J/yr)

16 Emergy Investment Ratio

P = items (5 -9+12)	sej/Year	2.03E+15	(P = Electricity, Fuels, goods & matrls)
S = items (3-4+10+11+13)	sej/Year	3.03E+14	(S = services-all money flows-)
N =	sej/Year	0	(N = local non-renewable resources)
R =	sej/Year	1.27E+11	(R = renewable resources)
EIR =		18348.15	(P+S)/(N+R)

17 Emergy Yield Ratio

Yield, Y =	sej/Year	2.33E+15	(Y = total emergy of potable water)
EYR =		1.00	(Y)/(P+S)

18 Percentage of Renewable Emergy

Yield,Y =	sej/Year	2.33E+15	
R =		1.27E+11	
% of Renewable Energy =		5.45E-03	100x(R/Y)

19 Ratio of Emergy benefit to the Purchaser

Em$ value of Water	Em$/Year	4314.26	(Y)/(sej/2009$ratio)
Annual Cost of desalinating	$/Year	117.7933333	(sum of all the operating costs in $ / yr)
Emergy Benefit to the Purchaser		36.63	Em $/$

20 Em $ Value of potable Water per m^3

Em $/Cu.m		984.99	(Y)/[(sej/2009$ratio)(potable m^3/yr)]

21 Transformity of potable Water,sej/J

Transformity of Potable Water	sej/J	1.08E+08	(see note 13)

22 Emergy per Cu.m of Potable Water

Emergy per Cu.m of Potable Water	sej/Cu.m	5.32E+14	(Y)/(m^3 produced /yr)

Table A-2: Notes for the Emergy Evaluation of Drinking Water Produced from System 2 (Footnotes for Tables 3 and 4)

	Evaporating Surface Area per Distiller:	m2	1	(assumed)
1	**Salty Water,J**			
	Average Fresh Water Produced per Day	L/m^2-day	12	(considered as the basis)
	Evaporating Area per Distillation System	m^2	1	(assumed)
	Fresh Water Produced per Unit per Year	L/Yr	4380	(L/day)*(365dasy/yr)
	% Efficiency of the System	%	70%	(assumed)
	Salt Water Used Per Year	L/Yr	6257.142857	(L/day)(% recovery)x100
	Mass of Salt Water Used per Year	g/Yr	6.38E+06	(L/yr)(1020 kg/m^3)(1e-3 m3/L)(1000g/Kg)
	Avg TDS of Salt Water Used	ppm	30000	measured
	Avg.Gibs Free Energy of Water	J/g	7.13E-01	[(8.33J/mol/C)(290K)/(18 g/mol)] *ln(1E6-TDS in ppm/965,000ppm)
	Energy of Salt Water Used	J/Year	4.55E+06	(g/Yr)(J/g)
	Transformity	sej/J	3.19E+04	(Buenfil,2001)
2	**Constructional & Operational Costs:**			
	Total Cost of Water Production	$/L	0.017	(assumed)
	Fresh Water produced per unit /Year	L/Year	4380	(same as 1)
	Annual Cost of Water Production	$/Year	74.46	(Cost of water produ)(Fresh water prod/ yr)
	Emergy per Dollar Ratio in 2009	sej/$	5.40E+11	(Projected from 1993 sej/$ ratio in Odum(1996,p.314) using 5.7 % decrease/yr)
3	**Work To Carry Sea Water To Distiller**			
	Salt Water Required Per Week	L/Week	120.33	(same as 1)
	Weekly Time to Carry Sea Water	min/Week	45	(assumed)
	Calories required for Sea Water Transport	Kcal/Day	13.39	(3000 kcal/day)(min/week)/(10080 min/wk)
	Work Required for Sea Water Transport	J/Year	2.05E+07	(kcal/day)(4186J/kcal)(365 days/year)
	Transformity	sej/J	6.76E+06	(Buenfil,2001)
4	**Stainless Steel**			
	Total Steel and Iron in Assets	Kg	1500	(assumed)
	Useful Life of Aquiduct Assests	years	15	(assumed)
	Prorated Steel and Iron Assests	kg/Year	100	(Total assets in Kg)/(Yrs)
	Emergy per Mass of Steel	sej/Kg	1.80E+12	(Odum,1996;p.192)

5 Alluminium

Total Alluminium in Assets	Kg	100	(assumed)
Useful Life of Assests	years	15	(assumed)
Prorated Alluminium Assests	kg/Year	6.67	(Total assets in Kg)/(Yrs)
Emergy per Mass of Alluminium	sej/Kg	1.25E+10	(Buranakarn,1998)

6 Glass

Average Area of the Glass Used	m^2	1	(Gude,2007)
Thickness of the Glass used	m	0.01	(Gude,2007)
Volume of the Glass Used	m^3	0.01	(area*thickness)
Density of the Glass	Kg/m^3	2200	
Useful Life of Assests	years	15	(assumed)
Weight of the Glass	Kg/yr	1.47	(volume)(density)/(useful life)
Emergy per Unit	sej/Kg	8.40E+08	(Odum et al.,1987b)

7 Concrete & Cement

Weight of Concrete Used	Kg	2700	(Vol of concrete * density of ready mix)
Useful Life of Assests	years	15	(assumed)
Weight Used per Year	Kg/Yr	180.00	(Total assets in Kg)/(Yrs)
Emergy per Unit	sej/Kg	1.23E+12	(Buranakarn,1998;p.175)

8 PVC

Volume of PVC Used	m^3	0.14	measured
Density of PVC Pipes Used	Kg/m^3	1800	
Useful Life of Assests	years	15	(assumed)
Weight Used per Year	g	16.96	(volume)(density)/(useful life)
Emergy Per Unit	sej/g	5.85E+09	(Buranakarn,1998)

9 Heaters And Other Auxillary Equipemnt

PurchasePrice of the Auxillary Equipemnt	$	500	purchased value
Replacement Time	Years	15	(assumed)
Annula Cost	$/Year	33.33	(Price of equipment)/(Replacement time)
Emergy per Dollar Ration	sej/$	5.40E+11	(Projected from 1993 sej/$ ratio in Odum(1996,p.314) using 5.7 % decrease/yr)

10 Money Spent for Electricity

Electrical Energy Used for Water	kWh/Year	4100.17	(energy required)(Mass of water produced)/(3.6E6J/kWh)
Cost of Electricity	$/KWh	0.06	Dept of energy web site
Money to be spent for Electricity	$/Year	246.01	(Energy used)(cost of energy)
Emergy per dollar ratio in 2009	sej/$	5.40E+11	(Projected from 1993 sej/$ ratio in Odum(1996,p.314)using 5.7 % decrease/yr)

11 Electricity,J

Specific Energy requirements for Water	Kj/Kg	3370	(Gude,2007)
Total Mass of Drinking Water Produced	Kg/Year	4380	(same as 1)
Electrical Energy to be Used	J/Year	1.48E+10	(Specific energy reqd)(Mass of water prod)
Transformity	sej/J	1.60E+05	(Odum, 95;p.305)

12 Land Lease, $

Land Required	m^2	5	area reqd is taken 5 times the distiller area
Land Leasing rate	$\$/m^2$/Year	10	(from an average rates in NM)
Land Lease	$/Year	50	(area)(leasing rate)
Emergy per Dollar Ratio in 2000	sej/$	5.40E+11	(Projected from 1993 sej/$ ratio in Odum(1996,p.314) using 5.7 % decrease/yr)

13 Potable Water Produced, m^3:

Total Potable Water Produced	m^3/year	4.38	(L/yr)/1000
Total Emergy Yield	sej/Yr	3.12E+15	(sum of items 1-12)
Emergy per Volume of Drinking Water	sej/m^3	7.12E+14	(sej/yr)(m^3/yr)

14 Potable Water Produced,J:

Total Drinking Water Produced	m^3/year	4.38	(same as 13)
Total Energy Content of the Water	J/Year	2.16E+07	(m^3/yr)(4.94 J/g)(1E6 g/ m^3)
Total Emergy Yield	sej/Yr	3.12E+15	(sum of items 1-12)
Transformity of Potable Water	sej/J	1.44E+08	(sej/yr)(g/yr)

15 Potable Water Produced,g:

Total Potable Water Produced	m^3/year	4.38	(same as 13)
Mass of Potable Water produced	g/Yr	4.38E+06	(m^3/yr)(1E6 g/ m^3)
Total Emergy Yield	sej/Yr	3.12E+15	(sum of items 1-12)
Emergy per Mass of Potable Water	sej/g	7.12E+08	(sej/yr)/(g/yr)

16 Potable Water Produced with out services

Emergyof Potable Water w/o Services	sej/Year	2.76E+15	(total emergy-services)=Y-S
Energy of Potable Water	J/Year	2.16E+07	(same as note 14)
Transformity with out services	sej/J	1.28E+08	(sej/yr)/(J/yr)

17 Emergy Investment Ratio

P = items (5 -9+12)	sej/Year	2.76E+15	(P = Electricity, Fuels, goods & materials)
S = items (3-4+10+11+13)	sej/Year	3.56E+14	(S = services-all money flows-)
N =	sej/Year	0	(N = local non-renewable resources)
R =	sej/Year	1.45E+11	(R = renewable resources)
EIR =		21499.47	(P+S)/(N+R)

18 Emergy Yield Ratio

Yield, Y =	sej/Year	3.12E+15	(Y = total emergy of potable water)
EYR =		1.00	(Y)/(P+S)

19 Percentage of Renewable Emergy

Yield,Y =	sej/Year	3.12E+15	
R =		1.45E+11	
% of Renewable Energy =		4.65E-03	100x(R/Y)

20 Raio of Emergy benefit to the Purchaser

Em$ value of Water	Em$/Year	5777.37	(Y)/(sej/2009$ratio)
Annual Cost of desalinating	$/Year	157.7933333	(sum of all the operating costs in $ / ye)
Emergy Benefit to the Purchaser	EM $/$	36.61	Em $/$

21 Em $ Value of potable Water per m^3

Em $/Cu.m		1319.03	(Y)/[(sej/2009$ratio)(potable m^3/yr)]

22 Transformity of potable Water,sej/J

Transformity of Potable Water	sej/J	1.44E+08	(see note 14)

23 Emergy per Cu.m of Potable Water

Emergy per Cu.m of Potable Water	sej/Cu.m	7.12E+14	(Y)/(m^3 produced /yr)

Table A-3: Notes for the Emergy Evaluation of Drinking Water Produced from System 3 (Footnotes for Tables 5 and 6).

1	**Solar Radiation„J**			
	Avg Surface Solar Radiation in Las Cruces:	Kcal/m^2/year	6.03E+09	(Gude,2007)
	Average Surface Solar Radiation in LC:	J/m^2/Year	2.52E+13	(Avg surface solar rad'n)(4186.8J/Kcal)
	Evaporating Surface Area per Distiller:	m2	1	(Gude,2007)
	Avg Solar Radiation per unit per year	J/Yr	2.52E+13	(avg surface solar radiation)(evap area)
	Transformity	sej/J	1	(Gude,2007)
2	**Salty Water,J**			
	Average Fresh Water Produced per Day	L/m^2-day	12	(Gude,2007)
	Evaporating Area per Distillation System	m^2	1	(Gude,2007)
	Fresh Water Produced per Unit per Year	L/Yr	4380	(L/day)*(365days/yr)
	% Efficiency of the System	%	81%	(Gude,2007)
	Salt Water Used Per Year	L/Yr	5407.41	(L/day)(% recovery)x100
	Mass of Salt Water Used per Year	g/Yr	5.52E+06	(L/yr)(1020 kg/m^3)(1e-3 m3/L)(1000g/Kg)
	Avg TDS of Salt Water Used	ppm	30000	measured
	Avg. Gibbs Free Energy of Water	J/g	7.13E-01	[(8.33J/mol/C)(290K)/(18 g/mol)] *ln(1E6-TDS in ppm/965,000ppm)
	Energy of Salt Water Used	J/Year	3.93E+06	(g/Yr)(J/g)
	Transformity	sej/J	3.19E+04	(Buenfil,2001)
3	**Constructional & Operational Costs:**			
	Total Cost of Water Production	$/L	0.017	(assumed)
	Fresh Water produced per unit /Year	L/Year	4380	(same as 1)
	Annual Cost of Water Production	$/Year	74.46	(Cost of water prod)(Fresh water prod/yr)
	Emergy per Dollar Ratio in 2000	sej/$	5.40E+11	(Projected from 1993 sej/$ ratio in Odum(1996,p.314) using 5.7 % decrease/yr)
4	**Work To Carry Sea Water To Distiller**			
	Salt Water Required Per Week	L/Week	103.99	(same as 1)
	Weekly Time to Carry Sea Water	min/Week	45	(assumed)
	Calories required for Sea Water Transport	Kcal/Day	13.39	(3000 kcal/day)(min/week)/(10080 min/wk)
	Work Required for Sea Water Transport	J/Year	2.05E+07	(kcal/day)(4186J/kcal)(365 days/year)
	Transformity	sej/J	6.76E+06	(Buenfil,2001)
5	**Stainless Steel**			
	Total Steel and Iron in Assets	Kg	1500	(assumed)
	Useful Life of Aqueduct Assets	years	15	(assumed)

	Prorated Steel and Iron Assets	kg/Year	100	(Total assets in Kg)/(Yrs)
	Emergy per Mass of Steel	sej/Kg	1.80E+12	(Odum,1996;p.192)
6	**Aluminum**			
	Total Aluminum in Assets	Kg	100	(assumed)
	Useful Life of Aqueduct Assets	years	15	(assumed)
	Prorated Aluminum Assets	kg/Year	6.67	(Total assets in Kg)/(Yrs)
	Emergy per Mass of Aluminum	sej/Kg	1.25E+10	(Buranakarn,1998)
7	**Glass**			
	Average Area of the Glass Used	m^2	1	(Gude,2007)
	Thickness of the Glass used	m	0.01	(Gude,2007)
	Volume of the Glass Used	m^3	0.01	(area*thickness)
	Density of the Glass	Kg/m^3	2200	
	Useful Life of Assets	years	15	(assumed)
	Weight of the Glass	Kg	1.47	(volume)(density)
	Emergy per Unit	sej/Kg	8.40E+08	(Odum et al.,1987b)
8	**Concrete & Cement**			
	Weight of Concrete Used	Kg	2700	(Vol of concrete * density of ready mix)
	Useful Life of Aqueduct Assets	years	15	(assumed)
	Weight Used per Year	Kg/Yr	180.00	(Total assets in Kg)/(Yrs)
	Emergy per Unit	sej/Kg	1.23E+12	(Buranakarn,1998;p.175)
9	**PVC**			
	Volume of PVC Used	m^3	0.14	measured
	Density of PVC Pipes Used	Kg/m^3	1800	
	Useful Life of Assets	years	15	(assumed)
	Weight Used per Year	g	16.96	(volume)(density)/(useful life)
	Emergy Per Unit	sej/g	5.85E+09	(Buranakarn,1998)
10	**Solar Panel & Batteries And Heaters And Other Auxiliary Equipment**			
	Purchase Price of the Auxiliary Equipment	\$	2000	purchased value
	Replacement Time	Years	15	(assumed)
	Annual Cost	\$/Year	133.33	(Price of equipment)/(Replacement time)
	Emergy per Dollar Ration	sej/\$	5.40E+11	(Projected from 1993 sej/\$ ratio in Odum(1996,p.314) using 5.7 % decrease/yr)
11	**Land Lease, \$**			
	Land Required	m^2	5	area reqd is taken 5 times the distiller area
	Land Leasing rate	$\$/m^2/Year$	10	(from an average rates in NM)
	Land Lease	\$/Year	50	(area)(leasing rate)
	Emergy per Dollar Ratio in 2000	sej/\$	5.40E+11	(Projected from 1993 sej/\$ ratio in Odum(1996,p.314) using 5.7 % decrease/yr)

12 Potable Water Produced, m^3:

Total Potable Water Produced	m^3/year	4.38	(L/yr)/1000
Total Emergy Yield	sej/Yr	7.04E+14	(sum of items 1-11)
Emergy per Volume of Drinking Water	sej/m^3	1.61E+14	(sej/yr)(m^3/yr)

13 Potable Water Produced,J:

Total Drinking Water Produced	m^3/year	4.38	(same as 12)
Total Energy Content of the Water	J/Year	2.16E+07	(m^3/yr)(4.94 J/g)(1E6 g/ m^3)
Total Emergy Yield	sej/Yr	7.04E+14	(sum of items 1-11)
Transformity of Potable Water	sej/J	3.26E+07	(sej/yr)(g/yr)

14 Potable Water Produced,g:

Total Potable Water Produced	m^3/year	4.38	(same as 12)
Mass of Potable Water produced	g/Yr	4.38E+06	(m^3/yr)(1E6 g/ m^3)
Total Emergy Yield	sej/Yr	7.04E+14	(sum of items 1-11)
Emergy per Mass of Potable Water	sej/g	1.61E+08	(sej/yr)/(g/yr)

15 Potable Water Produced without services

Emergy of Potable Water w/o Services	sej/Year	4.27E+14	(total emergy-services)=Y-S
Energy of Potable Water	J/Year	2.16E+07	(same as note 13)
Transformity without services	sej/J	1.97E+07	(sej/yr)/(J/yr)

16 Emergy Investment Ratio

P = items (5 -10)	sej/Year	4.02E+14	(P = Electricity, Fuels, goods & materials)
S = items (3-4)	sej/Year	2.78E+14	(S = services-all money flows-)
N =	sej/Year	0	(N = local non-renewable resources)
R =	sej/Year	2.54E+13	(R = renewable resources)
EIR =		26.78	(P+S)/(N+R)

17 Emergy Yield Ratio

Yield, Y =	sej/Year	7.04E+14	(Y = total emergy of potable water)
EYR =		1.04	(Y)/(P+S)

18 Percentage of Renewable Emergy

Yield,Y =	sej/Year	7.04E+14	
R =		2.54E+13	
% of Renewable Energy =		3.60E+00	100x(R/Y)

19 Ratio of Emergy benefit to the Purchaser

Em$ value of Water	Em$/Year	1304.53	(Y)/(sej/2009$ratio)
Annual Cost of desalinating	$/Year	257.7933333	(sum of all the operating costs in $ / ye)
Emergy Benefit to the Purchaser	EM $/$	5.06	Em $/$

20 Em $ Value of potable Water per m^3

Em $/Cu.m		297.84	(Y)/[(sej/2009$ratio)(potable m^3/yr)]

21 Transformity of potable Water,sej/J

Transformity of Potable Water	sej/J	3.26E+07	(see note 13)

22 Emergy per Cu.m of Potable Water

Emergy per Cu.m of Potable Water	sej/Cu.m	1.61E+14	(Y)/(m^3 produced /yr)

Table A-4: Notes for the Emergy Evaluation of Drinking Water Produced from System 4 (Footnotes for Tables 7 and 8).

1	**Solar Radiation,,J**			
	Avg Surface Solar Radiation in Las Cruces:	Kcal/m^2/year	6.03E+09	(Gude,2007)
	Average Surface Solar Radiation in LC:	J/m^2/Year	2.52E+13	(Avg surfacesolar radiation)(4186.8J/Kcal)
	Evaporating Surface Area per Distiller:	m2	1	(Gude,2007)
	Avg Solar Radiation per unit per year	J/Yr	2.52E+13	(avg surface solar rad’tion)(evapting area)
	Transformity	sej/J	1	(Gude,2007)
2	**Salty Water,,J**			
	Average Fresh Water Produced per Day	L/m^2-day	12	(Gude,2007)
	Evaporating Area per Distillation System	m^2	1	(Gude,2007)
	Fresh Water Produced per Unit per Year	L/Yr	4380	(L/day)*(365days/yr)
	% Efficiency of the System	%	81%	(Gude,2007)
	Salt Water Used Per Year	L/Yr	5407.41	(L/day)(% recovery)x100
	Mass of Salt Water Used per Year	g/Yr	5.52E+06	(L/yr)(1020 kg/m^3)(1e-3 m3/L)(1000g/Kg)
	Avg TDS of Salt Water Used	ppm	30000	measured
	Avg. Gibbs Free Energy of Water	J/g	7.13E-01	[(8.33J/mol/C)(290K)/(18 g/mol)] *ln(1E6-TDS in ppm/965,000ppm)
	Energy of Salt Water Used	J/Year	3.93E+06	(g/Yr)(J/g)
	Transformity	sej/J	3.19E+04	(Buenfil,2001)
3	**Constructional & Operational Costs:**			
	Total Cost of Water Production	$/L	0.017	(assumed)
	Fresh Water produced per unit /Year	L/Year	4380	(same as 1)
	Annual Cost of Water Production	$/Year	74.46	(Cost of water prod)(Fresh water prod/ yr)
	Emergy per Dollar Ratio in 2000	sej/$	5.40E+11	(Projected from 1993 sej/$ ratio in Odum(1996,p.314) using 5.7 % decrease/yr)
4	**Work To Carry Sea Water To Distiller**			
	Salt Water Required Per Week	L/Week	103.99	(same as 1)
	Weekly Time to Carry Sea Water	min/Week	45	(assumed)
	Calories required for Sea Water Transport	Kcal/Day	13.39	(3000 kcal/day)(min/wk)/(10080 min/wk)
	Work Required for Sea Water Transport	J/Year	2.05E+07	(kcal/day)(4186J/kcal)(365 days/year)
	Transformity	sej/J	6.76E+06	(Buenfil,2001)
5	**Stainless Steel**			
	Total Steel and Iron in Assets	Kg	1500	(assumed)
	Useful Life of Aqueduct Assets	years	15	(assumed)
	Prorated Steel and Iron Assets	kg/Year	100	(Total assets in Kg)/(Yrs)
	Emergy per Mass of Steel	sej/Kg	1.80E+12	(Odum,1996;p.192)

6 Aluminum

Total Aluminum in Assets	Kg	100	(assumed)
Useful Life of Aqueduct Assets	years	15	(assumed)
Prorated Aluminum Assets	kg/Year	6.67	(Total assets in Kg)/(Yrs)
Emergy per Mass of Aluminum	sej/Kg	1.25E+10	(Buranakarn,1998)

7 Glass

Average Area of the Glass Used	m^2	1	(Gude,2007)
Thickness of the Glass used	m	0.01	(Gude,2007)
Volume of the Glass Used	m^3	0.01	(area*thickness)
Density of the Glass	Kg/m^3	2200	
Useful Life of Assets	years	15	(assumed)
Weight of the Glass	Kg	1.47	(volume)(density)
Emergy per Unit	sej/Kg	8.40E+08	(Odum et al.,1987b)

8 Concrete & Cement

Weight of Concrete Used	Kg	2700	(Vol of concrete * density of ready mix)
Useful Life of Aqueduct Assets	years	15	(assumed)
Weight Used per Year	Kg/Yr	180.00	(Total assets in Kg)/(Yrs)
Emergy per Unit	sej/Kg	1.23E+12	(Buranakarn,1998;p.175)

9 PVC

Volume of PVC Used	m^3	0.14	measured
Density of PVC Pipes Used	Kg/m^3	1800	
Useful Life of Assets	years	15	(assumed)
Weight Used per Year	g	16.96	(volume)(density)/(useful life)
Emergy Per Unit	sej/g	5.85E+09	(Buranakarn,1998)

10 Solar Panel & Batteries And Heaters And Other Auxiliary Equipment

Purchase Price of the Auxiliary Equipment	$	45	purchased value
Replacement Time	Years	15	(assumed)
Annual Cost	$/Year	3	(Price of equipment)/(Replacement time)
Emergy per Dollar Ration	sej/$	5.40E+11	(Projected from 1993 sej/$ ratio in Odum(1996,p.314) using 5.7 % decrease/yr)

11 Land Lease, $

Land Required	m^2	5	area reqd is 5 times the distiller area
Land Leasing rate	$\$/m^2/Year$	10	(from an average rates in NM)
Land Lease	$/Year	50	(area)(leasing rate)
Emergy per Dollar Ratio in 2000	sej/$	5.40E+11	(Projected from 1993 sej/$ ratio in Odum(1996,p.314)using 5.7 % decrease/yr)

12 Potable Water Produced, m^3:

Total Potable Water Produced	m^3/year	4.38	(L/yr)/1000
Total Emergy Yield	sej/Yr	6.34E+14	(sum of items 1-11)
Emergy per Volume of Drinking Water	sej/m^3	1.45E+14	(sej/yr)(m^3/yr)

13 Potable Water Produced,J:

Total Drinking Water Produced	m^3/year	4.38	(same as 12)
Total Energy Content of the Water	J/Year	2.16E+07	(m^3/yr)(4.94 J/g)(1E6 g/ m^3)
Total Emergy Yield	sej/Yr	6.34E+14	(sum of items 1-11)
Transformity of Potable Water	sej/J	2.93E+07	(sej/yr)(g/yr)

14 Potable Water Produced,g:

Total Potable Water Produced	m^3/year	4.38	(same as 12)
Mass of Potable Water produced	g/Yr	4.38E+06	(m^3/yr)(1E6 g/ m^3)
Total Emergy Yield	sej/Yr	6.34E+14	(sum of items 1-11)
Emergy per Mass of Potable Water	sej/g	1.45E+08	(sej/yr)/(g/yr)

15 Potable Water Produced without services

Emergy of Potable Water w/o Services	sej/Year	4.27E+14	(total emergy-services)=Y-S
Energy of Potable Water	J/Year	2.16E+07	(same as note 13)
Transformity without services	sej/J	1.97E+07	(sej/yr)/(J/yr)

16 Emergy Investment Ratio

P = items (5 -10)	sej/Year	4.02E+14	(P = Electricity, Fuels, goods & materials)
S = items (3-4)	sej/Year	2.07E+14	(S = services-all money flows-)
N =	sej/Year	0	(N = local non-renewable resources)
R =	sej/Year	2.54E+13	(R = renewable resources)
EIR =		24.01	(P+S)/(N+R)

17 Emergy Yield Ratio

Yield, Y =	sej/Year	6.34E+14	(Y = total emergy of potable water)
EYR =		1.04	(Y)/(P+S)

18 Percentage of Renewable Emergy

Yield,Y =	sej/Year	6.34E+14	
R =		2.54E+13	
% of Renewable Energy =		4.00E+00	100x(R/Y)

19 Ratio of Emergy benefit to the Purchaser

Em$ value of Water	Em$/Year	1174.20	(Y)/(sej/2009$ratio)
Annual Cost of desalinating	$/Year	127.46	(sum of all the operating costs in $ / ye)
Emergy Benefit to the Purchaser	EM $/$	9.21	Em $/$

20	**Em \$ Value of potable Water per m^3**			
	Em $/Cu.m		268.08	(Y)/[(sej/2009\$ratio)(potable m^3/yr)]
21	**Transformity of potable Water,sej/J**			
	Transformity of Potable Water	sej/J	2.93E+07	(see note 13)
22	**Emergy per Cu.m of Potable Water**			
	Emergy per Cu.m of Potable Water	sej/Cu.m	1.45E+14	(Y)/(m^3 produced /yr)

Table A-5: Notes for the Emergy Evaluation of Drinking Water Produced from System 5 (Footnotes for Tables 9 and 10)

1	**Solar Radiation,J**			
	Avg Surface Solar Radiation in Las Cruces:	Kcal/m^2/year	6.03E+09	(Gude,2007)
	Average Surface Solar Radiation in LC:	J/m^2/Year	2.52E+13	(Avg surface solar radiation)(4186.8J/Kcal)
	Evaporating Surface Area per Distiller:	m2	1	(Gude,2007)
	Avg Solar Radiation per unit per year	J/Yr	2.52E+13	(avgsurface solar radiation)(evapt area)
	Transformity	sej/J	1	(Gude,2007)
2	**Salty Water,J**			
	Average Fresh Water Produced per Day	L/m^2-day	4.9	(Gude,2007)
	Evaporating Area per Distillation System	m^2	1	(Gude,2007)
	Fresh Water Produced per Unit per Year	L/Yr	1788.5	(L/day)*(365days/yr)
	% Efficiency of the System	%	61%	(Gude,2007)
	Salt Water Used Per Year	L/Yr	2931.967213	(L/day)(% recovery)x100
	Mass of Salt Water Used per Year	g/Yr	2.99E+06	(L/yr)(1020 kg/m^3)(1e-3 m3/L)(1000g/Kg)
	Avg TDS of Salt Water Used	ppm	30000	measured
	Avg. Gibbs Free Energy of Water	J/g	7.13E-01	[(8.33J/mol/C)(290K)/(18 g/mol)] *ln(1E6-TDS in ppm/965,000ppm)
	Energy of Salt Water Used	J/Year	2.13E+06	(g/Yr)(J/g)
	Transformity	sej/J	3.19E+04	(Buenfil,2001)
3	**Constructional & Operational Costs:**			
	Total Cost of Water Production	$/L	0.017	(assumed)
	Fresh Water produced per unit /Year	L/Year	1788.5	(same as 1)
	Annual Cost of Water Production	$/Year	30.4045	(Cost of water prod)(Fresh water prod/ yr)
	Emergy per Dollar Ratio in 2000	sej/$	5.40E+11	(Projected from 1993 sej/$ ratio in) Odum(1996,p.314 using 5.7 % decrease/yr)
4	**Work To Carry Sea Water To Distiller**			
	Salt Water Required Per Week	L/Week	56.38	(same as 1)
	Weekly Time to Carry Sea Water	min/Week	45	(assumed)
	Calories required for Sea Water Transport	Kcal/Day	13.39	(3000 kcal/day)(min/week)/(10080 min/wk)
	Work Required for Sea Water Transport	J/Year	2.05E+07	(kcal/day)(4186J/kcal)(365 days/year)
	Transformity	sej/J	6.76E+06	(Buenfil,2001)
5	**Stainless Steel**			
	Total Steel and Iron in Assets	Kg	1500	(assumed)
	Useful Life of Aqueduct Assets	years	15	(assumed)
	Prorated Steel and Iron Assets	kg/Year	100	(Total assets in Kg)/(Yrs)

	Emergy per Mass of Steel	sej/Kg	1.80E+12	(Odum,1996;p.192)
6	**Aluminum**			
	Total Aluminum in Assets	Kg	100	(assumed)
	Useful Life of Aqueduct Assets	years	15	(assumed)
	Prorated Aluminum Assets	kg/Year	6.67	(Total assets in Kg)/(Yrs)
	Emergy per Mass of Aluminum	sej/Kg	1.25E+10	(Buranakarn,1998)
7	**Glass**			
	Average Area of the Glass Used	m^2	1	(Gude,2007)
	Thickness of the Glass used	m	0.01	(Gude,2007)
	Volume of the Glass Used	m^3	0.01	(area*thickness)
	Density of the Glass	Kg/m^3	2200	
	Useful Life of Assets	years	15	(assumed)
	Weight of the Glass	Kg	1.47	(volume)(density)
	Emergy per Unit	sej/Kg	8.40E+08	(Odum et al.,1987b)
8	**Concrete & Cement**			
	Weight of Concrete Used	Kg	2700	(Vol of concrete * density of ready mix)
	Useful Life of Aqueduct Assets	years	15	(assumed)
	Weight Used per Year	Kg/Yr	180.00	(Total assets in Kg)/(Yrs)
	Emergy per Unit	sej/Kg	1.23E+12	(Buranakarn,1998;p.175)
9	**PVC**			
	Volume of PVC Used	m^3	0.14	measured
	Density of PVC Pipes Used	Kg/m^3	1800	
	Useful Life of Assets	years	15	(assumed)
	Weight Used per Year	g	16.96	(volume)(density)/(useful life)
	Emergy Per Unit	sej/g	5.85E+09	(Buranakarn,1998)
10	**Solar Heaters And Other Auxiliary Equipment**			
	Purchase Price of the Auxiliary Equipment	$	0	purchased value
	Replacement Time	Years	10	(assumed)
	Annual Cost	$/Year	15	(Price of equipt)/(Replacement time)
	Emergy per Dollar Ration	sej/$	5.40E+11	(Projected from 1993 sej/$ ratio in Odum(1996,p.314) using 5.7 % decrease/yr)
11	**Land Lease, $**			
	Land Required	m^2	5	area required is 5 times the distiller area
	Land Leasing rate	$\$/m^2/Year$	10	(from an average rates in NM)
	Land Lease	$/Year	50	(area)(leasing rate)
	Emergy per Dollar Ratio in 2000	sej/$	5.40E+11	(Projected from 1993 sej/$ ratio in Odum(1996,p.314)using 5.7 % decrease/yr)

12 Potable Water Produced, m^3:

Total Potable Water Produced	m^3/year	1.7885	(L/yr)/1000
Total Emergy Yield	sej/Yr	6.17E+14	(sum of items 1-11)
Emergy per Volume of Drinking Water	sej/m^3	3.45E+14	(sej/yr)(m^3/yr)

13 Potable Water Produced,J:

Total Drinking Water Produced	m^3/year	1.7885	(same as 12)
Total Energy Content of the Water	J/Year	8.84E+06	(m^3/yr)(4.94 J/g)(1E6 g/ m^3)
Total Emergy Yield	sej/Yr	6.17E+14	(sum of items 1-11)
Transformity of Potable Water	sej/J	6.98E+07	(sej/yr)(g/yr)

14 Potable Water Produced,g:

Total Potable Water Produced	m^3/year	1.7885	(same as 12)
Mass of Potable Water produced	g/Yr	1.79E+06	(m^3/yr)(1E6 g/ m^3)
Total Emergy Yield	sej/Yr	6.17E+14	(sum of items 1-11)
Emergy per Mass of Potable Water	sej/g	3.45E+08	(sej/yr)/(g/yr)

15 Potable Water Produced without services

Emergy of Potable Water w/o Services	sej/Year	4.27E+14	(total emergy-services)=Y-S
Energy of Potable Water	J/Year	8.84E+06	(same as note 13)
Transformity without services	sej/J	4.83E+07	(sej/yr)/(J/yr)

16 Emergy Investment Ratio

P = items (5 -10)	sej/Year	4.02E+14	(P = Electricity, Fuels, goods & matrls)
S = items (3-4)	sej/Year	1.90E+14	(S = services-all money flows-)
N =	sej/Year	0	(N = local non-renewable resources)
R =	sej/Year	2.53E+13	(R = renewable resources)
EIR =		23.38	(P+S)/(N+R)

17 Emergy Yield Ratio

Yield, Y =	sej/Year	6.17E+14	(Y = total emergy of potable water)
EYR =		1.04	(Y)/(P+S)

18 Percentage of Renewable Emergy

Yield,Y =	sej/Year	6.17E+14	
R =		2.53E+13	
% of Renewable Energy =		4.10E+00	100x(R/Y)

19 Ratio of Emergy benefit to the Purchaser

Em$ value of Water	Em$/Year	1142.03	(Y)/(sej/2009$ratio)
Annual Cost of desalinating	$/Year	95.4045	(sum of all the operating costs in $ / ye) Em $/$
Emergy Benefit to the Purchaser	EM $/$	11.97	

20 Em $ Value of potable Water per m^3

Em $/Cu.m		638.54	(Y)/[(sej/2009$ratio)(potable m^3/yr)]

21 Transformity of potable Water,sej/J

Transformity of Potable Water	sej/J	6.98E+07	(see note 13)

22 Emergy per Cu.m of Potable Water

Emergy per Cu.m of Potable Water	sej/Cu.m	3.45E+14	(Y)/(m^3 produced /yr)

Table A-6: Notes for the Emergy Evaluation of Drinking Water Produced from System 6 (Footnotes for Tables 11 and 12).

1 Salty Water,J

Salt Water Used	Gal/Day	4.17E+07	(gal/day)(%recovery)x100
Recovery rate to produce 25 MGD	%	60%	(Buenfil,2001)
Fresh Water Produced	Gal/Day	2.50E+07	(Buenfil,2001)
Mass of Salt Water Used per Year	g/Year	5.87E+13	(gal/day)(365 days/yr)(3.785L/gal)(1020g/L)
Avg TDS of Salt Water Used	ppm	26000	(Buenfil,2001)
Avg. Gibbs Free Energy of Water	J/g	1.25	[(8.33J/mol/C)(290K)/(18 g/mol)] *ln(1E6-TDS in ppm/965,000ppm)
Energy of Salt Water Used	J/Year	7.32E+13	(g/Yr)(J/g)
Transformity	sej/J	3.19E+04	(Buenfil,2001)

2 Constructional & Operational Costs:

Total $ for Operation and Maintain ace	2002$/Year	2314138	(Buenfil,2001)
Emergy per Dollar Ratio in 2002	sej/$	8.10E+11	(Projected from 1993 sej/$ ratio in Odum(1996,p.314)using 5.7 % decrease/yr)

3 Total Steel & Iron

Total Steel and Iron in Assets	Kg	2.10E+06	(Buenfil,2001)
Useful Life of Aqueduct Assets	years	30	(Buenfil,2001)
Prorated Steel and Iron Assets	kg/Year	7.00E+04	(Total assets in Kg)/(Yrs)
Emergy per Mass of Steel	sej/Kg	1.80E+12	(Odum,1996;p.192)

4 Chemicals,$

Total Annual $ paid for Chemicals	2002$/Year	679173	(Buenfil,2001)
Emergy per dollar ratio in 2002	sej/$	8.10E+11	(Projected from 1993 sej/$ ratio in Odum(1996,p.314)using 5.7 % decrease/yr)

5 Chemicals.Kg

a) Total chlorine to be used per Year	kg/Yr	104025	(Buenfil,2001)
b) Total Ammonia to be used per year	kg/Yr	34675	(Buenfil,2001)
c) Total Sulphuric Acid to be used	kg/Yr	294738	(Buenfil,2001)
d) Total sodium Hydroxide	kg/Yr	208050	(Buenfil,2001)
e) Total Fluoride to be used	kg/Yr	83220	(Buenfil,2001)
Total Weight of Chemicals	kg/Yr	724708	(a+b+c+d)
Emergy per Unit	sej/Kg	1.00E+12	(Buenfil,2001)

6	**Total Concrete (without services),kg**			
	Weight of Concrete Used	Kg	2.77E+07	(Buenfil,2001)
	Useful Life of Aqueduct Assets	years	30	(Buenfil,2001)
	Weight Used per Year	Kg/Yr	9.23E+05	(Total assets in Kg)/(Yrs)
	Emergy per Unit	sej/Kg	1.23E+12	(Buranakarn,1998;p.175)
7	**Assets**			
	Total Annual Cost	2002$/Year	8162150	(Buenfil,2001)
	Emergy per Dollar Ratio in 2002	sej/$	8.10E+11	(Projected from 1993 sej/$ ratio in Odum(1996,p.314) using 5.7 % decrease/yr)
8	**Money Spent for Electricity**			
	Money to be spent for Electricity	2002$/Year	4472877.00	(Buenfil,2001)
	Emergy per dollar ratio in 2002	sej/$	8.10E+11	(Projected from 1993 sej/$ ratio in Odum(1996,p.314) using 5.7 % decrease/yr)
9	**Electricity,J**			
	Energy requirements/ 1000 gal Water	kWh	11.60	(Buenfil,2001)
	Total Drinking Water Produced	mgd	25	(Buenfil,2001)
	Total Drinking Water Produced	gal/Year	9.13E+09	(mgd)(365 days/yr)(1E6)
	Electrical Energy to be Used	J/Year	3.81E+14	(total KWh/1000gal)(gal/yr)(3.6E6J/KWh)/1000
	Transformity	sej/J	1.60E+05	(Odum, 95;p.305)
10	**Potable Water Produced, m^3:**			
	Total Potable Water Produced	mgd	25.00	(Buenfil,2001)
	Total Drinking Water produced	m^3/year	3.45E+07	(mgd)(365 d/Yr)(1E6)(0.003785 m^3/gal)
	Total Emergy Yield	sej/Yr	7.79E+19	(sum of items 1-9)
	Emergy per Volume of Drinking Water	sej/m^3	2.26E+12	(sej/yr)(m^3/yr)
11	**Potable Water Produced,J:**			
	Total Drinking Water Produced	m^3/year	3.45E+07	(same as 10)
	Total Energy Content of the Water	J/Year	1.71E+14	(m^3/yr)(4.94 J/g)(1E6 g/ m^3)
	Total Emergy Yield	sej/Yr	7.79E+19	(sum of items 1-9)
	Transformity of Potable Water	sej/J	4.57E+05	(sej/yr)(g/yr)
12	**Potable Water Produced,g:**			
	Total Potable Water Produced	m^3/year	3.45E+07	(same as 10)
	Mass of Potable Water produced	g/Yr	3.45E+13	(m^3/yr)(1E6 g/ m^3)
	Total Emergy Yield	sej/Yr	7.79E+19	(sum of items 1-9)
	Emergy per Mass of Potable Water	sej/g	2.26E+06	(sej/yr)/(g/yr)

13 Potable Water Produced without services

Emergy of Potable Water w/o Services	sej/Year	6.53E+19	(total emergy-services)=Y-S
Energy of Potable Water	J/Year	1.71E+14	(same as note 11)
Transformity without services	sej/J	3.83E+05	(sej/yr)/(J/yr)

14 Emergy Investment Ratio

P = items (5 -9+12)	sej/Year	6.30E+19	(P = Electricity, Fuels, goods & materials)
S = items (3-4+10+11+13)	sej/Year	1.27E+19	(S = services-all money flows-)
N =	sej/Year	0	(N = local non-renewable resources)
R =	sej/Year	2.33E+18	(R = renewable resources)
EIR =		32.40	(P+S)/(N+R)

15 Emergy Yield Ratio

Yield, Y =	sej/Year	7.79E+19	(Y = total emergy of potable water)
EYR =		1.03	(Y)/(P+S)

16 Percentage of Renewable Emergy

Yield,Y =	sej/Year	7.79E+19	(sum of items 1-9)
R =		2.33E+18	(same as note 14)
% of Renewable Energy =		2.99	100x(R/Y)

17 Ratio of Emergy benefit to the Purchaser

Em$ value of Water	Em$/Year	9.62E+07	(Y)/(sej/2002$ratio)
Em $ / 1000 gals	EM $	10.55	(sum of all the operating costs in $ / yr)
Market Price of Water / 1000 gals	$	2.15	(Buenfil,2001)
Emergy Benefit to the Purchaser	EM $/$	4.91	Em $/$

18 Em $ Value of potable Water per m^3

Em $/Cu.m		2.79	(Y)/[(sej/2002$ratio)(potable m^3/yr)]

19 Transformity of potable Water,sej/J

Transformity of Potable Water	sej/J	4.57E+05	(see note 11)

20 Emergy per Cu.m of Potable Water

Emergy per Cu.m of Potable Water	sej/Cu.m	2.26E+12	(Y)/(m^3 produced /yr)

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