Energy Conversion and Management 110 (2016) 419–427

Contents lists available at ScienceDirect

Energy Conversion and Management

journal homepage: www.elsevier.com/locate/enconman

Exergy costs analysis of groundwater use and water transfers

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ARTICLE INFO

Article history:
Received 22 July 2015
Accepted 13 December 2015
Available online 31 December 2015

Keywords:
Water costs
Water transfers
Groundwaters
Exergy analysis
Exergy cost
Transfer function

ABSTRACT

In the search for new alternatives to meet the water demands, it is interesting to analyze the cost of using alternatives different from those such as desalination and pumping. The exergy cost analysis can be a useful tool to estimate costs of those alternatives as a function of its energy efficiency and its relative abundance with respect to existing resources in their surroundings. This study proposes a methodology for assessing the costs of groundwaters and water transfers from surplus basins within the exergy perspective. An equation to assess the exergy costs of these alternatives is proposed. System boundaries are first identified to the assessment of input and output currents to the system in exergy values for the design and certain operating conditions. Next, an equation to assess water supply costs depending on design and operational parameters is proposed, from the analysis of different examples. Pumping efficiency, altitude gap and flow among other features are introduced in the calculations as those characteristics parameters. In the developed examples, unit exergy costs of groundwaters go from 1.01 to 2.67, and from 1 to 4.06 in case of water transfers. Maximum values, as expected within this perspective, are found at high pumped/transferred flows and high pumping levels and/or low pumping efficiency if pumping is required.

1. Introduction

Water resources are degraded by human actions as well as by natural processes. Consequently, energy is needed to restore their quantity and quality. In case of diverse feasible water restoration alternatives, comprehensive methodologies are required in order to make decisions about the most suitable one. Exergy cost analysis is one of those methodologies.

In last years, exergy analysis has been focused with the aim of improving the energy efficiency in their processes. The exergy analysis considers the irreversibilities and potential optimization of the processes in their evaluation. Exergy efficiency can be assessed as the ratio between exergy of obtained products and exergy of demanded resources, as has been shown in different studies including the evaluation of industrial processes [1,2], specific technologies [3,4] and sometimes having in regard the full life cycle of the products [5]. The original field of exergy analysis consisted on the application to power engineering within the evaluation of thermal and potential components of the system. Together with these components, the chemical exergy is being more and more important in exergy analysis in industry and industrial technologies as well during last years. It is clearly shown in some of the previous mentioned works [1]. In this respect, chemical exergy component takes importance in water supply and treatment technologies as well, as it pointed out in several reviewed studies showed next. This chemical exergy component is especially important in the assessment of the exergy of water flows.

In regard to the exergy analysis of water supply technologies, and specifically desalination, works focused on exergy losses and irreversibilities in diverse seawater desalination units [6,7]. Vapor compression seawater desalination systems were analyzed by some authors such as Jin et al. [8]. Apart from the analysis of irreversibilities of the system, other researchers such as Al-Nory et al. [9] aimed their studies to the search of strategic investment decisions related to plant locations and capacity the selection of the desalination technology, and plant design and operation parameters. Esfahani et al. [10] and Piacentino [11] focused their evaluations on multi-effect distillation (MED) units. Additionally, El-Emam and Dincer [12] developed thermoeconomic analysis of reverse osmosis desalination plants. Those works shows a great variability among values of exergy efficiency and energy consumption, depending on the type of process, plant capacity and water composition. Values in distillation systems varied from 3–6% to 10% [7,10]. Values of exergy efficiency found in literature are usually higher in RO systems, and varied greatly as well, from 6% [11] to 30% [7]. Monetary costs of RO according to those authors are around 0.5–1 €/m^3, and energy consumption around 2.5 kW h/m^3.

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http://dx.doi.org/10.1016/j.enconman.2015.12.022
0196-8904/

Nomenclature

a	activity (mol/kg)
b	specific exergy (kJ/kg water)
B	exergy (kW h)
C	concentration (ppm)
COD	chemical oxygen demand (ppm)
F	fuel
h	altitude (m)
k^*	unit exergy cost
LCA	life cycle assessment
P	product
Q	flow (m^3/s)
R	ideal gas constant (J/mol K)
RE	reference environment
T	temperature (K)
TF	Transfer Function
TOC	Total Organic Carbon (ppm)
x	molar concentration (mol/l)
ΔB^*	total exergy costs (kW h)

Subscripts and superscripts

aqu	aquifer
cat	catchment
ch	chemical
deg	degraded
deliv	delivered
down	downstream
ext	extracted
i	substance *i*
IM	inorganic matter
OM	organic matter
0	reference
p	potential
pump	pumping
rest	restored
trans	transferred water flow
up	upstream
W	energy consumption

This value is higher in distillation units, even higher than twice compared to RO. Not so much work has been developed in the framework of exergy analysis of other water supply methods apart from desalination. However, some researchers such as Razzaghmanesh [13] focus their research on green technologies that could be useful in diminishing our dependence on desalinated or treated water and the associated energy requirements, such as rainwater harvesting. Vargas-Parra et al. [14] used the exergy efficiency analysis to evaluate the performance of different scenarios of urban rainwater harvesting systems by a life cycle approach.

Different authors aimed their research to link the mentioned exergy concept with economy; this is called thermoeconomics discipline. It is based on the Second Law of Thermodynamics and the exergy concept, but linked with terms of economic criteria (productivity, efficiency, costs and benefits). Exergy is gradually destroyed by irreversibility along the productive chain, or process. Therefore, the monetary value of those streams of materials is increased. In this regard, the general theory of exergy costs was presented by Valero et al. in [15,16] and used in works of authors such as Silva and Oliveira [17]. The methodology was extended also to the minimization of pollutants emissions and waste disposals, through the residues costs formation developed from Torres et al. [18]. The thermo-economic concept was also applied by Frangopoulos [19], and Lazzaretto and Tsatsaronis [20] who proposed the specific exergy costing method (SPECO). Examples of evaluated energy systems within the principles of thermoeconomics are cement plants [21], geothermal plants [22,23], combined cycle power plants [24], solar energy systems [25,26], and other systems having in regard the variation of main operation parameters [27–30].

Within the general theory of exergy cost it was demonstrated in some studies [15] that the difference between the exergy of fuels and products determines the irreversibility in a system. In this respect, the unit exergy cost (k^*) was defined there as the inverse of the exergy efficiency, as the ratio between the exergy needed to produce a resource (fuel, F) and the exergy of the resource in which the interest is focused (product, P). This definition started to be extended to waters restoration in [31]. The exergy cost assessment in this work is framed from a wider perspective focused to the assessment of a generic k^*. First, by the estimation of unit costs at different design and operating conditions (in real terms), it is possible to set a function that relates these parameters with unit exergy costs. Secondly, the assessment of this work focusses not only on energy issues, but also on chemical concerns in regard to water quality and water consumption. The criteria of water supply have been extended by introducing the remaining available water in their surroundings in order to choose the most adequate water supply alternative. Then, energy consumption, resources consumption and degradation are all considered in the estimation of cost of the supply alternatives and, indirectly, in the assessment of the value of water resources. Alternatives to water supply technologies such as desalination with lower energy consumption and economic costs, around 50% lower than desalination [32,33] are analyzed in this paper from this perspective. The exergy costs of groundwaters and water transfers are presented.

2. Methodology

The exergy value of a water course (B) is assessed as the product of flow, Q (l/s) and the specific exergy (b) of a liter of water (kJ/l).

$$B = Q \cdot b \tag{1}$$

Specific exergy of water exergy is a function of its internal characteristics. In this respect, Zaleta, Ranz and Valero defined the exergy of water from six measurable parameters: composition, temperature, pressure, concentration, speed and altitude, according to Martínez et al. [31]. Each of them constitutes a different exergy terms.

The potential specific exergy term (b_p) and the chemical specific exergy component (b_c) take importance to the total exergy value. Thermal, kinetic, and mechanical components, are only representative in industrial processes, thus they are not included in the analysis performed here.

The potential specific exergy term is characterized by the natural slope of the river. It is calculated from the altitudes in the initial and final point in a given stretch of the river.

The sum of all the specific exergy expresses the specific exergy of the given water resource. Since that concept of exergy is related to the disequilibrium with the environment, it is necessary an adequate reference environment, RE, to perform the assessment; sea water was the chosen one [34].

Focusing on the exergy related to the composition of water, it includes two different components depending on the presence or not of the water components in the RE: the concentration term