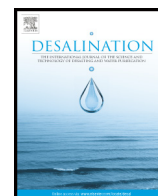




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Sustainability as the quantitative norm for water desalination impacts

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HIGHLIGHTS

- Environmental, economic, and social impacts of water desalination
- Quantitative holistic sustainability analysis should be the norm for assessing water desalination.
- Sustainability metrics for water desalination
- A methodology for sustainability analysis of water desalination
- Calculation of composite sustainability indices

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ABSTRACT

Water desalination continues to evolve exponentially in magnitude and importance to a currently mature stage that, like all large human endeavors, must be planned, designed and operated according to the quantitative holistic sustainability paradigm and criteria that are defined by the interrelated aspects of the environmental, economic and social pillars of the endeavor. This integrates but also transcends the currently separately employed and analyzed methods such as Environmental Impact Assessment (EIA), Life Cycle Analysis (LCA), and Best Available Technology (BAT), for selection, design, economic analysis, social impact analysis, and regulation planning. This paper quantitatively introduces the sustainability paradigm and its application to water desalination. It includes a critical review of the state of sustainability analysis as related to desalination, and proposes a methodology for such evaluation that results in calculation of composite sustainability indices, which is much better as a quantitative measure for the evaluation of desalination processes than the current practice of addressing the economic, environmental, and sometimes social aspects separately without their coherent integration. The method and equations for formulating a composite sustainability index as a function of relevant parameters, which thus allows mathematical analysis in general and sensitivity analysis and optimization in particular, are described.

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1. Introduction

1.1. Objectives, growth and the vital need for sustainable development

The main purpose of this paper is to introduce and critically review the sustainability paradigm, which integrates the evaluation of environmental, economic and social impacts (the sustainability pillars) that are also strongly interconnected, as a quantitative measure for the evaluation of water desalination processes. It is increasingly recognized by global, national, regional and institutional that the sustainability concept should be employed for all large physical and social development endeavors (developments, projects, production and so on), including both big centralized single ones and those including a large number of small ones. It thus would extend and make complete the current

practice of addressing the economic, environmental, and social aspects (called the *sustainability pillars*, noting that other or more than three pillars were recommended by some) separately without their coherent integration. Water desalination is at a stage where it is widely used commercially, has an important impact, and is thus mature and ready enough for evaluation and advancement by the scientific use of sustainability [1]. The paper also outlines the methods for the quantitative evaluation of the sustainability based on holistic scientific sustainability principles, and presents a fairly comprehensive set of references for those interested in the topic.

The detailed mathematical definition of sustainability is presented in Section 4 below, but to make the paper clearer from the start, a brief summary of the basic concept [2–5] follows:

- First, a sufficient number, i , of metrics, M_i (most often called indicators) that measure the environmental, economic and social impacts of the considered project/development are chosen.

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- Second, their relative importance, expressed by their weights, w_i is determined.
- Third/finally, the used $M_i w_i$ products are aggregated into a single composite sustainability index (CSI) as illustrated in Fig. 1. The CSI are in their simplest form and way expressed as

$$CSI = \sum_i M_i (\bar{x}_{ij}) w_i (\bar{y}_{ik}) \text{ or some other aggregation method of the } M_i w_i \text{ products.} \quad (1)$$

CSI can then be used as the quantitative sustainability measure of the considered project/development, and, being in mathematical function form, can also serve as the objective function for mathematical sensitivity analysis and optimization, down to the level of component variables, or be part of it. It is noteworthy that even just the described methodology of developing the metrics, weights and aggregation are very enlightening for the understanding and improvement of desalination processes.

The economic pillar has historically dominated decision making, and still does due to both inertia and human nature, but the last several decades have produced a rapidly increasing vitally needed concern for increasing the weight and influence of the environmental and social pillars. This concern is driven by mounting public concern about local and global sustainability as well as by correspondingly increasingly stricter regulations.

It is amply documented (for data see [6,7]) that the world on the average and most of its individual countries experience an exponential increase in consumption of nonrenewable resources of all kinds, including water, and in generating pollution in magnitudes that in many aspects cause practically irreparable damage to our environment and long-term survivability. A simple but telling example is that the world's ecological footprint has grown at this time to a value that requires resources 60% higher than our planet could continuously provide [8,9], concluding that we are already consuming the natural reserves, or in other terms consuming the seeds needed for continued growth. Leaders in magnitude of the ecological footprint, expressed as the number of earth planets that would be required if the per-capita consumption and emissions in these countries were by every person in the world, include Qatar at 6.2 planets, Australia at 5.4, UAE at 5, and the US at 4.8, but even much more modestly consuming countries such as China, the world's most populated one, already has an ecological footprint that would require 2.0 planets (and rising). For comparison, for EU-27 it is 2.8, and for India 0.7.

The representativeness of the Ecological Footprint criterion for human demand and resources exploitation may not be perfect, but there are many other indicators of the world population's excessive

anthropogenic intervention and damage in this era that was thus named the Anthropocene, in which humankind has a significant global effect on nature. Adding to the excessive consumption and damage is the increase in population, predicted to rise from the current 7 billion to 9.5 billion by 2050 [10] (or more as China relaxed its one child per family policy and as some developed countries started encouraging family growth), from which it is rather obvious that it would increasingly be impossible to engage in large scale development/activities of any sort without insuring their sustainability. This also holds even for developing countries in which there is a perceived priority of development over the environment and society in the longer term.

The ongoing climate change has introduced a new and ominous dimension as its impacts will make the availability of water resources more unpredictable. This includes droughts and floods, as well as significant precipitation changes that are foreseen to increase their frequency, duration and magnitude, increased sea levels, including storm surges, and extreme weather events, which can cause salt water intrusion into groundwater reserves and also incapacitate desalination plants [11–15].

A poignant local example of the desalination-related Anthropocene is the world's largest concentration of water desalination plants in the Arabian Gulf. Exacerbated by the World-leading consumption of water made cheap by government policy and wealth, cheap fuel, and weak environmental and consumption regulations, it has a very detrimental environmental regional effect on the Gulf and its states [16]. Sharing the same relatively shallow and narrow sea (choking down to 55 km in the Strait of Hormuz), and air, the environmental impacts of the desalination activities in practically each of the Gulf states increasingly affects the others, thus making the problem regional. It is an example, albeit of relatively small global extent, of the urgent need for regional cooperation.

An example of larger geographic and international scale, which requires cooperation and regional integrated governance, is watershed management for human health and well-being [17]. Further extending the scope and boundaries to the limit, the ongoing global environmental deterioration has identified the need for some form of earth system governance to protect the entire system earth, including most of its sub-systems. This would require building of stable and effective institutions that would guarantee a satisfactory transition and a co-evolution of natural and social systems at the planetary scale [12,18,19]. The United Nations can be regarded as one of the institutions that is oriented for helping with this transition, but is far from able to provide such earth system governance. It is noteworthy that implementation of sustainability principles and criteria would apply to a system of any extent and mode of governance, and that this implementation is synergistically supportive to the establishment of earth system governance but needs not wait for it.

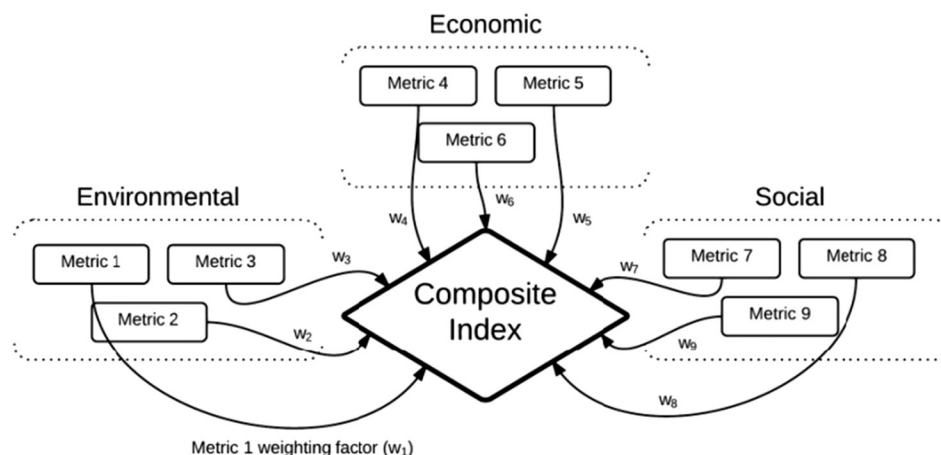


Fig. 1. A diagram for Composite Sustainability Index (CSI) construction.

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