Desalination 401 (2017) 99–111

Contents lists available at ScienceDirect

Desalination

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

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

ARTICLE INFO

Article history:
Received 17 April 2016
Received in revised form 3 August 2016
Accepted 5 August 2016
Available online 15 August 2016

Keywords:
Water desalination
Sustainability
Water desalination sustainability
Water supply

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. A 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.

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 entities 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 [1-5]. The paper also outlines 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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http://dx.doi.org/10.1016/j.desal.2016.08.008
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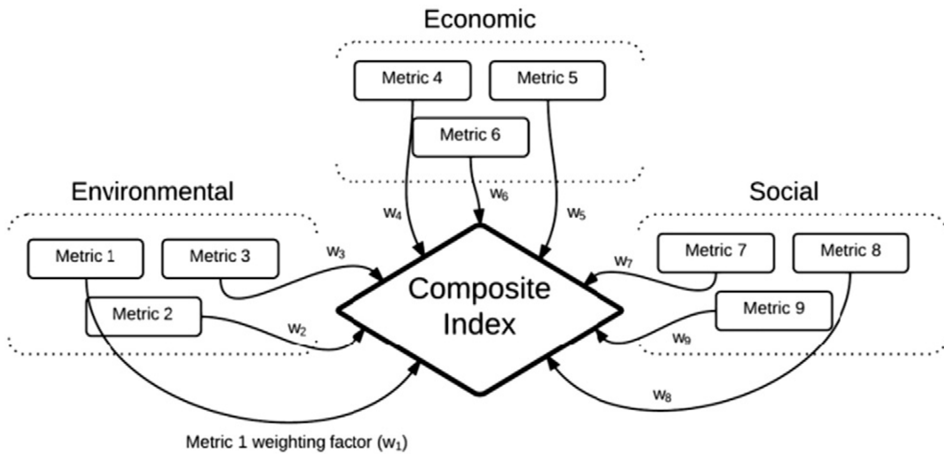

Fig. 1. A diagram for Composite Sustainability Index (CSI) construction.

- 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

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

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 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 have an ecological footprint that would require 2.0 planets (and rising). For comparison, for EU-27 it is 2.8, ad 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.

A relatively new and ominous issue is the ongoing climate change, causing droughts and floods, significant precipitation changes that are foreseen to increase their frequency, duration and magnitude, rising sea levels and storm surges that can also cause salt water intrusion into groundwater reserves, increased sediment, nutrient and pollutant loadings in the seawater, and extreme weather events, all of which will make the availability of water resources more unpredictable and thus very likely to increase the need for desalination in many parts of the world (especially in most dry subtropical regions). The desalination plants' operation will also be subject to these consequences of climate change. It is noteworthy that significant precipitation changes also destabilize the economic viability of desalination plants, and experience has shown that unexpectedly high precipitation at some periods has idled or even retired some. Furthermore, desalination causes significant concentrated brine discharges, and since it is energy intensive, it will be associated with undesirable emissions if hydrocarbon fuels are used. Plans for desalination plants must therefore include the evaluation of the long-term climate change risks and benefits, with the former being subject to regulation [11,13-15].

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 subsystems. 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.

1.2. Growth in desalination capacity, in associated impact, and in obligation for accountability

The rapidly deteriorating large scale imbalance between fresh water supply and demand, aggravated by massive pollution of water resources of any kind is one of the demonstrated effects of the Anthropocene, and created a significant growth in water desalination. Having started on large commercial scale only around 1965 and having had a worldwide capacity of only about 8000 m^3/day in 1970, water desalination now produces worldwide about 86.5 million m^3/day of desalted water by about 16,000 plants, with some forecasts of capacity perhaps tripling within 10 years [20,21]. It had exponential growth of ~14%/year by commissioned plants from 2007 to 2012 (during 2012 to 2015 the rate declined to ~3%/year). The amount of desalted water is now of vital impact in several regions of the world, but it globally remains only ~0.6% of global abstracted fresh water, or 3% of domestic/municipal use [20,22].

Globally, about 59% of the feed for desalination is seawater, the rest being brackish, river/lake, fresh (<500 ppm), and waste waters [20]; waste water amounts to about 6% of the desalted total but the rate is foreseen to rise rapidly.

Sustainability of desalination depends to important extent on the type of the desalination process. Distillation processes (dominated by multi-stage flash evaporation, MSF) use mostly heat, and some electrical energy, both generated by burning fuel. Air pollutant emissions rate rises with the amount of fuel used, and is hence reduced by increasing plant energy efficiency. In many large-capacity distillation plants the efficiency is raised by using dual-purpose (cogeneration) designs that produce both electricity and desalted water. While distillation processes dominated desalination until about 1997, reverse osmosis (RO) desalination has by 2015 grown to 65% of the installed desalination capacity, primarily because of much higher energy efficiency, with distillation dropping to 28% [23].

The viability of desalination plants and processes was at first judged primarily on economics and production reliability with minimal concern about externalities. The cost of externalities was internalized only when government regulations existed (and were enforced), but production of water was so overwhelmingly important, and plant capacity so relatively small, that regulations and their interpretation and enforcement were often of secondary importance. The feeling of the industry and most customers was probably reflected in the 1996 statement that "The authors consider that the benefits of water production by desalination far outweigh the relatively small negative impacts of properly sited and designed plants." [23], a view that still seems to prevail in many parts of the world. It is also noteworthy that in 1995/6 the desalination capacity was just <20 million m^3/day, less than a quarter of the current one.

The current large scale of water desalination and its rapidly increasing rate brings up, just as for any large scale project in any domain, various important local and global sustainability concerns. These concerns include environmental damage from the process itself, the energy needed for it, the production of the materials needed for its construction, resources depletion, economic impacts on local, national and global levels, sometimes undue competition with more sustainable water supply methods, and various social consequences ranging from concerns about desalted water quality and health, to employment and education and general quality of life.

These important sustainability issues may start dominating the conditions for desalination use, as stated by Darwish Al-Gobaisi's opening of the International Desalination Association (IDA) World Congress in 1995 in his "Water Desalination Manifesto" [24]: "We as a community of engineers, technologists, and managers of desalination plants have to consider the call of the next century for sustainable development which implies economization of material and energy resources utilization and reduction of wastes with a view to conserve the environment". Several reports pointing to unsustainable aspects of desalination and urging attention to problems were indeed recently published, such as those by the WWF [25], WHO [26,27], the US Academy of Sciences National Research Council [28], and journal papers including [23,29–39], and IDA recognized it as an important problem to deal with. Furthermore, increasing government regulations are being imposed on water desalination plants to reduce environmental impact.

1.3. Sustainability: the best measure for the integrated impacts of large endeavors

Sustainable activities have many definitions, but simply, ***they describe a logical process that takes carefully into account all relevant consequences within time and space boundaries that are large enough to ensure satisfactory existence for us and other humans, and of our and their descendants***. These "all relevant consequences" are primarily **economic, environmental and social**, the three pillars of sustainable development[1] [5,43]. It is generally and increasingly believed that humanity's survival depends on adoption of sustainable development (SD) practices, which are based on adequate construction of these quantitatively defined and inter-related sustainability "pillars", within appropriate space and time boundaries. In contrast with approaches like EIA, LCA, and BAT that were mostly focused on the environmental ("green") pillar, the sustainability paradigm, supported by a quantitative definition of these pillars and their weights, and by a mathematical methodology of their aggregation (see Section 4 below), accounts for all three pillars and their interactions, and results in the most needed, inclusive and holistic index for SD choices. Approaches like EIA, LCA, and BAT did at times attempt to add consideration of economic and social issues to the environmental ones (e.g. [45]) but a superior approach is to apply the holistic/inclusive sustainability analysis methodology that includes the environmental pillar rather than the other way around.

An important side-note here is that human focus should be to achieve sustainability and not "green-ness" per se. While "green" is generally desirable, it must be considered as only a part of sustainability, alongside with economic and social aspects, and even the most "green" approach may not be the most sustainable.

"Sustainability" is a positive and popularly well-liked term, however without a widely well-recognized definition, and is consequently more and more extensively used erratically and often improperly and even fraudulently, posing thereby a serious problem for implementation. A description of this menace and some suggestions for its curtailment

[1] This, and the various path-breaking sustainability statements (e.g., Thomas Jefferson: "Then I say the Earth belongs to each generation during its course, fully and in its right no generation can contract debts greater than may be paid during the course of its existence" [40] (September 6, 1789; interestingly, he also invented a water desalination system [41]) and much later by the UN Brundtland Commission's [42] of "Meet the current needs without destroying the ability of future generations to meet theirs" provide the correct intent but require quantification; they are very qualitative and tolerate any population growth and unsustainable behavior by future generations, and exclude concern about destruction of the ability of the less fortunate members of the current generation to meet their reasonable needs (e.g., [43,44]).

are given in [46]; [47,48] are some of the many examples of somewhat incorrect use related to desalination.

Water desalination is of critical importance to humanity, and proper attention to its sustainable conduct is of urgent and vital importance to its continued success. While the need for sustainability analysis has been recognized and the state of knowledge has been advanced (e.g. [5,48–67]), an inclusive and uniform methodology has not been fully established yet, and this paper is aimed to contribute to the establishment of such methodology as related to water desalination.

2. Selection of desalination sustainability issues and criteria

2.1. A brief review of the desalination sustainability pillars

The key desalination sustainability issues must be considered in adequate spatial and temporal boundaries. For example, they must include all directly related activities: planning, design, construction, commissioning and operation, and decommissioning, but also indirect ones such as the used utilities and service systems and their impacts as well as the associated materials with their embodied energy and emissions. Spatially, it clearly must address at least the area directly affected by the plants, including the further aggravation when other plants are installed in the same area. Some emissions, such as CO_2, may have a global extent effect.

Temporally, it must be of multi-generational duration, by definition, and not confined only to the life of the plant.

The **economic pillar** of sustainability obviously contains the total unsubsidized cost of the desalted water, including the rising cost of permitting (that can reach 60% of a major project cost, [68]) and of permitted chemicals, but also the impacts of that water on the local and national economy, land development, and consideration of alternative ways for supplying the needed water, including reduction of water demand by investment into more efficient ways for water use, and water pricing policy that should encourage efficient resource utilization leading to pollution reduction and resource protection (e.g., when subsidies applied previously on the water prices were removed in many of the European Union states, water prices increased by 5 to 20 fold).

The current price of desalted water produced by large plants is between about \$0.45 and \$6 [69].

There are many tools for pricing desalted water, but most of them are just for the plant itself [70]. The existing cost estimation methodologies are proprietary, so more transparent methods would help researchers and users develop tools for optimal configuration of plants and for comparisons.

Perhaps the biggest barrier to reliable pricing is the high uncertainty in the future price of the needed energy.

The **environmental pillar** contains all the effects on the feedwater and its domain (including the coast), emissions from the energy supply for the desalination, and environmental impacts on the existing fresh water resources and on the water consuming sectors, such as agriculture. This pillar has high complexity, including the fact that the feed is most often also a habitat containing an entire ecosystem which desalination disturbs due to withdrawal of large volumes, and discharge of large volumes of highly concentrated brine with many chemical additives, and at elevated temperatures.

Just to present an idea of some of the environmental impacts, Table 1 contains a very rough estimate of the global desalination-associated saline feedwater flow rates and gaseous emissions in 2011. It shows that the rate of CO_2 emissions is high (although only 0.8% of the World's total in 2011). The emissions of SO_2 and NO_x are very high too. The associated saline feedwater flow rate is 63% larger than that of the Nile River, and 83% larger than that of the Yellow River. These values become much more significant as a regional amount of desalination becomes larger per unit area. These gross environmental impacts must be addressed.

Current state-of-the-art seawater reverse osmosis (SWRO) plants consume between 3 and 4 kWh/m^3 energy (noting also that energy is a major component of their desalted water cost), and emit between 1.4 and 1.8 kg CO_2/m^3 and between 10 and 100 g NO_x/m^3 of produced water.

Table 1
Year 2011 global annual desalted water production [20] and estimated associated saline feedwater flow rates and gaseous emissions (the emissions data are an average for advanced desalination plants from [29]).

Process	Produced water, billion m^3/y[a]	Emitted CO_2[b]		Emitted SO_2		Emitted NO_x		Saline water flow rate, m^3/s
		kg/m^3	Mt/y	kg/m^3	Mt/y	kg/m^3	Mt/y	
RO[c]	18.51	2.27	42	0.02	0.37	0.0075	0.14	2329
MSF	10.87	19.9	216	0.16	1.74	0.06	0.65	2298
Total	29.38	23.17	258	0.18	2.11	0.0675	0.79	4627

[a] [16].
[b] Only from power generation, does not include the CO_2 released from the saline feedwater.
[c] The emissions were estimated as half of the values emitted by advanced seawater RO plants.

Most studies of environmental impacts of desalination claim that the energy used for the process is one of the most important contributors to its environmental impact, including global warming, if it is derived by using fossil fuels for its heat or electrical energy input [29,67]. While this opinion depends on the method for valuation of the biological/ecological impacts caused by all the other desalination drivers/pressures, energy is indeed an important contributor, and studies of desalination plants using renewable energy show that their environmental impact is much lower [29,72–79]. Some of these studies include the important role of embodied energy and emissions, which are relatively large when the used renewable energies are such as solar and wind. It should be kept in mind though that the use of renewable energy raises the cost of water, especially when conventional energy is relatively cheap (as it is now), including the need for additional investments to deal with the consequences of its intermittency.

Use of nuclear energy (electricity and/or heat) is also touted as a way to minimize greenhouse gas emissions and offer an alternative energy source for desalination. While the use of nuclear power alleviates the global warming problem significantly, some of the leading problems associated with generating nuclear power haven't gone away [7,80]. Hundreds of thousands of tons of spent nuclear fuel and other long-life nuclear waste are accumulating rapidly world-wide in temporary storage sites (many near the reactors that produce them), and hundreds of million tons of low-level waste from uranium mining and milling are being left at mine sites and there is no solution yet for long term radioactive waste storage or destruction. The Fukushima disaster has also significantly raised worldwide concern about the safety of nuclear energy, which led to reduction of reactor construction. On top of that, the risk of proliferation of hazardous nuclear materials has become a much more serious problem (in some views the dominant one) in the past few decades or so. All of this has also led to sharp rise in nuclear power costs. If nuclear energy is planned to be used for desalination anyway, a comprehensive analysis that considers all these concerns, with an appropriate set of indicators, must of course be conducted to start.

Comprehensive discussion of desalination environmental issues is also available in [81–87].

The **social pillar** contains impacts on health; employment including safety and treatment of employees; developments, land use, and local growth: rapid, unplanned growth resulting from new desalted water supply can damage local environmental resources as well as the community's social fabric, e.g., new construction without investing in infrastructure can cause overcrowded schools, traffic, and water shortages, and urban and agricultural runoff would increases wastewater flows, may create water-quality problems in local rivers, streams, and/or the ocean; social acceptance; confidence in quantity and quality of the water sources and their demands; acceptance of desalination technologies and trust in the water providers; esthetics of landscape and

Table 2
Water desalination sustainability issues and impacts (most of the information is from [11,45,71,76,77,81,82,87–94]).

2.1 The economic pillar
Cost of water, without externalities
Cost of water, with externalities
Affordability
Pricing policy
Capital investment cost (including possible financial incentives)
Operating cost (including also taxes, insurance, warranties)
Impact on economy; economic growth and development
Commercial conflicts (e.g., immediate and surrounding land use and values, water navigation, access to harbors, commercial fishing, Aquaculture)
Pretreatment and post-treatment requirements
Production reliability
Water distribution
Water supply alternatives
Water conservation
Impact on energy use and security
Construction materials consumption
Consumption of fuel, chemicals
Chemicals consumption
Corrosion cost and prevention
Embodied energy
R&D cost
2.2 The environmental pillar (incl. ecological)
During planning and construction
PLANNING
Water conservation
Water resources planning and use, water supply alternatives
Water resources impact indices: the Water Impact Index, the Freshwater Ecosystem Impact (FEI) index, the Freshwater Withdrawal Impact (FWI) index, the Water Footprint [90,95–100]
The carbon footprint [100–103]
CONSTRUCTION
Impacts of construction wastes and excess soil
Soil and groundwater pollution (fuels, oils, etc.)
Air pollution (fugitive dust emission)
Noise emission
Damage to antiquities and heritage
Alteration of the seabed
Sediment resuspension (impacts on marine water quality and ecology)
Oil pollution
Alteration of the coastal zone and obstruction of passage along the seashore
During operation – Potential impacts on the marine/source environment
Habitat alteration and changes in sediment transport
Entrainment and impingement of marine biota
Debris pollution (from intake screening)
Biological effects of residual chemical additives (e.g. chlorine, pH modifiers) and their by-products
Brine discharges (outfall) and impact on marine habitat: salinity. pH, dissolved oxygen, CO_2, nitrogen, temperature, density, residual chemicals (iron-hydroxide, metals, polymers, antiscalants, biocides, *anti*-foamants, acids, coagulants, cleaning chemicals, coliform and other organics, TOC, floatables and suspended solids, turbidity) and particulate matter in the concentrate (biological & aesthetic impacts)
Intake/outfall velocity and buoyancy effects, incl. those on natural currents and waves, volumetric flow rates
Sea level changes, coloration
Product water Recovery Ratio
Protection of wildlife and biological diversity, rare and endangered species, sensitive habitats
During operation – Potential impacts on the terrestrial environment and atmosphere
Alteration of the coastal environment and obstruction of free passage along the seashore
Emission (direct and indirect) of greenhouse gases (carbon footprint due to both the energy use and release from the feedwater), and air pollutants, and gas-carried particulates
Corrosion products
Noise emission (effect on marine organisms and humans)
Light “pollution”
Membrane end of life treatment [104]
Accidental spillage or leakage of hazardous chemicals
Solid waste and sanitary sewage
Soil (surface sealing and compaction, erosion, excavated material, accidental spills, contamination, surface water runoff, barrier effects, pipelines)
Ground water and hydrology, salination
Protection of wildlife and biological diversity, rare and endangered species, sensitive habitats
Nature conservation conflicts
Aesthetic impacts (landscape and natural scenery)
Recreation, tourism
Embodied emissions

(*continued on next page*)

Table 2 (*continued*)

2.3 The social pillar
Health and sanitation; e.g., indices of the populations at risk of being affected by the project; Product water quality must ensure adherence to limits of unhealthy ingredients and inclusion of those that should be in the water at some level
Life quality
Effective and equitable employment, local and regional
Impact on food (cost, availability, quality)
Education and training
Land footprint
Present land-use and planned development activities
Visual amenity
Equitable water security for all
Poverty
Trans-border relations
Gender effects
Demographic development
Community structure
Recreation
Cultural aspects incl. tribal and indigenous people
Characteristic landscape and natural scenery
National water security

structure ("Visual Amenity"); and on general satisfaction with the quality of life [11,88].

In addition to the impacts and criteria directly related to the desalination sustainability pillars (also see Table 2), there exist important issues related to water use and planning. Reduction of water demand reduces the need for water and all its associated processes, whether desalination, treatment, or conveyance, and this is usually a good and first path to sustainability. It is also clear that water uses that have high cost-benefit ratios, or low sustainability metrics (already normalized/integrated with the benefits), is less desirable. A case in point is the use of potable desalted water for agriculture, and this becomes even more problematic if the agriculture is subsidized.

2.2. A more detailed inventory of desalination sustainability impact metrics

Just to demonstrate the sustainability analysis approach more specifically, key economic, environmental and social elements/pillars of desalination sustainability are identified in Table 2 (although the list is incomplete and, of course, must be adapted individually to each considered project). Each issue is characterized by many indices and metrics, too numerous to list here, which is typical of most projects. Aggregation of these indicators into a single composite metric (or at most a few metrics) requires weighting factors, and the entire mathematical procedure is described in Section 4 (an example of an existing methodology is described in [2]). It is noteworthy that the pillars are interrelated.

Table 2 data are the basis for constructing metrics/indicators for sustainability analysis.

The economic, environmental and social impacts take place during the financial investment planning, the construction, the operation, decommissioning, and after the plant has been taken out of operation, and the planning must include foreseeable climate change effects.

Since a fair amount of chemicals is used in desalination, and they create some of the environmental problems, it is important to note that it is important to employ "Green" chemistry ("sustainable chemistry"), i.e. to design chemical processes and formulate products in ways which reduce or eliminate the use of hazardous substances [94]. This effort is, for example, supported and prescribed by the United States Environmental Protection Agency (EPA) [105], with participation by the American Chemical Society (ACS). It is obviously most advisable to prevent pollution rather than cleaning it after it has occurred.

3. Current approaches to assessment of desalination impacts

3.1. The Environmental Impact Assessment (EIA)

The desalination-associated environmental issues are typically dealt with the well-known Environmental Impact Assessment (EIA), which is sometimes combined with Life Cycle Assessment (LCA) and often including a request to use Best Available Technology (BAT). Not unique to desalination, EIA, LCA and BAT are commonly legislated by government and employed by the industry for most applications. All these are a significant step towards overall sustainability, but not a substitute for it because they primarily focus on environmental impacts only. A very brief description of impact assessment methods follows.

As defined by UNEP [31,45], an EIA is a systematic process for identifying, evaluating and developing means of mitigating the potential impacts of a proposed project on the environment. Its main objectives are to provide information on the environmental consequences of a project for decision-making, and to promote environmentally sound and sustainable development through the identification of appropriate alternatives and mitigation measures. EIA studies are often based on an "ecological risk assessment" approach, aimed to systematically identify and evaluate the relationships between *stressors* as caused by anthropogenic activity (*exposure analysis*), and subsequent impacts on *receptors* [30]. Besides regular circumstances, it should also consider potential effects of disasters, such as earthquakes, fire, flooding, and war. Some of these were indeed experienced in water desalination and caused temporary water shortages and impairment.

Significantly, the United Nations Environment Programme (UNEP) released an EIA guidance manual for desalination projects in 2008 [45]. In [26], Lattemann (the lead author of [45]) points out that the WHO water desalination guidance document recommends following a ten-step process to systematically identify, investigate and mitigate all potential impacts:

1) Decide, on the basis of a screening process, whether or not an EIA is required;
2) Conduct scoping to determine the contents and extent of the EIA;
3) Identify policy and administrative aspects relevant to the project and the EIA;
4) Describe the technical design and process of the proposed desalination project;
5) Describe and assess the environment baseline of the project site;
6) Describe and evaluate the potential impacts of the project on the environment;
7) Identify approaches for mitigation of negative impacts;
8) Provide a summary of the major findings and develop conclusions;
9) Establish a programme to monitor impacts during construction and operation; and
10) Review the EIA process for decision-making purposes.

Conduct of EIA-s is best guided by the increasingly used standard ISO 14001:2004 "Environmental management systems – Requirements with guidance for use" procedures [106,107].

3.2. Life Cycle Assessment (LCA)

The widely used Life Cycle Assessment (LCA) procedures are basically part of the ISO 14000 environmental management standards [106]: in ISO 14040:2006 and 14044:2006. (ISO 14044 replaced earlier versions of ISO 14041 to ISO 14043.)

LCA is a method for considering the design, manufacture, and use of a product across its entire life cycle: from raw material extraction and conversion; to manufacture and distribution; through use, re-use, and recycling; to ultimate disposal. The U.S. Environmental Protection Agency (EPA) defines LCA as "the investigation and valuation of the environmental (and often economic and social) impacts of a given product or service caused or necessitated by its existence" [108]. The technique includes compilation of an inventory of relevant energy and material inputs and environmental releases, evaluation of the potential environmental impacts associated with identified inputs and releases, and interpretation of the results to help make a more informed decision. The time period for the analysis can be cradle-to-gate, cradle-to-grave, and cradle-to-cradle. The spatial extent (boundaries) depends on regulations or choice.

In addition to uncertainties common to all impact assessment methods, LCA suffers from a number of important uncertainties, principally due to its dependence on time:

○ "The art of prophecy is very difficult, especially with respect to the future", which is a serious problem for all planning endeavors; a case in point are the extraordinary fluctuations in the price and availability of fossil fuels,
○ The space-time relationship: the extent of the space of interest and its content/purpose may change with time
○ The life cycle impact may vary with time due to legislation, discovery of new information, changes in attitudes, population, events….

One should start LCA with comprehensive realization that it contains many possible error sources. Several approaches for understanding and reducing the uncertainties, the latter including stochastic modeling, Monte Carlo simulation and fuzzy set theory, have been proposed and implemented (e.g. [109,110]), nevertheless, the serious inevitable uncertainties in LCA and the difficulties in evaluating them make the value of absolute quantitative results meaningless. The process and methodology are by themselves very valuable however, in learning about the object of LCA, about areas that need better information, and about ways that it affects the sustainability pillars of environment, economics and social impact. LCA is also useful for considering alternative approaches if all the inputs and scenaria are the same and reasonable. LCA was applied to evaluate water treatment and desalination processes, such as in [72,77,78,90,111–113].

3.3. Best Available Technology (BAT)

Specifications and contracts, including those requiring some environmental compliance, often recommend the use of "Best Available Technology" (BAT) in lieu of (or in addition to) specific limits. The techniques that are considered as BAT should have been proven to be economically and technically feasible on an industrial scale, and should have employed or taken into account technological advances. Special consideration in the development of BAT is typically given to the consumption of raw materials, water and energy, and the possibility for recovery and recycling of used resources or generated wastes. Identification of zero- or low-waste techniques is based on the nature and volume of the emissions resulting from the process and the use of less hazardous substances in the process.

As described in [81,114], the concept of BAT was adopted by different legislative systems, and was applied to environmentally-related projects, such as coastal based power plants and seawater cooling water systems [e.g., the EC Directive 96/61/EC on Integrated Pollution Prevention and Control (IPPC), the Conventions for the Protection of the Marine Environment of the North-East Atlantic (OSPAR), of the Baltic Sea Area (HELCOM), and the Protocol for the Protection of the Mediterranean Sea against Pollution from Land-Based Sources of the Mediterranean Action Plan (LBS protocol)].

Significantly, Lattemann and co-workers made a generalized introduction of the BAT approach to water desalination [114].

While BAT is a useful and necessary approach, it is not quantitative goal oriented, is somewhat arbitrary in the definition of what best technologies for a certain purpose are (the USEPA, for example, states "The best technology treatment techniques, or other means which the Administrator finds, after examination for efficacy under field conditions and not solely under laboratory conditions, are available…" [115]) and it is rather difficult to define, and does not strictly guide how to introduce all possible useful innovations, and thereby supports inertia.

3.4. The Driver-Pressure-State-Impact-Response (DPSIR) method

The Driver-Pressure-State-Impact-Response (DPSIR) framework was developed in the late 1990s to structure and organize indicators in a way that provides meaningful explanations of cause and effect relationships. It is best employed by using inputs from a broad range of stakeholders, and thus also leads to the presentation of their values and alternative decision options. Its application provides a basis for policy relevant research, and was mostly used in research to support decision-making by policy makers. It has been used in the investigation of environmental governance addressing sustainability challenges of seawater desalination in the Arabian Gulf [16], regional water governance frameworks [116]), categorization of socioecological aspects of marine ecosystems management [117], and in general to facilitate and guide the development of policy indicators in complex systems [118].

Unlike the other methods described in this section, DPSIR is more oriented to research on policy making, but is a very useful complement to the development of policy-related sustainability criteria that are a critical component of the social pillar.

3.5. Some closing comments about the current approaches to assessment of desalination impacts

An important matter is that any environmental assessment process for satisfying national and local regulations is very intricate, time-consuming and costly, requiring hundreds [119] (or at least scores) of analyses and reports. Furthermore, it therefore tends to freeze the original designs during the process that may take a couple of years, and thus discourage opportune improvements and innovation during that time. A solution proposed in [86] for the Victoria Desalination Project (Australia's largest desalination plant) was to develop a performance based environmental assessment process, focusing on outcomes rather than on inputs, by using a reference design with a series of optional variations to develop performance requirements during the tender process. This allowed design flexibility and completion on schedule, but of course requires much more work to prepare, as well as adequate foresight for good a-priori choice of the variations.

Considering that desalination plants have long-term and possibly significant impact, and must not only meet regulations but also be sustainable when regulations are not sufficient for that, an adequate investment must be made in their design and assurance of government and community acceptance. Clearly, any such method, including sustainability analysis, must be made simple and flexible enough to allow reasonable expenditure of time, effort, and money, without sacrificing the objective.

Perhaps a proper conclusion of this Section is Manuel Schiffler's from the World Bank who stated in 2004 that an "internationally agreed environmental assessment methodology for desalination plants does not exist so far and its development would be desirable" [34]. An addendum to it could be that **no** satisfactory assessment methodology exists yet either, and the focus proposed in this paper is on one that is based on sustainability as the right direction for its development.

It is also noted that even the current analyses of such separate sustainability aspects are neither complete nor standardized, and that such standardization is recommended even just for the satisfactory conduct of these individual analyses, and at last for the complete sustainability analysis. That would, at least, simplify the process very significantly.

The current approaches to assessment of desalination impacts mostly address environmental ones, as well as costs, but not, or very weakly, the socio-economic aspects nor the interactions between the three pillars of sustainability.

Any development of desalination (and for any project for that matter), loses much, or even fails, if the plant operation and performance, are not effectively and comprehensively monitored after project commissioning. Furthermore, absence of such monitoring, including implementation of corrective measures as needed, seriously diminishes learning and improvement. A critical review of existing monitoring programs for desalination plants, which also describes shortcomings of current practices and identifies aspects relevant to the design of marine monitoring programs, is in [120].

4. The scientific sustainability analysis methodology and process

4.1. Sustainability quantification [2–5,54–56,61,64–66]

Rational sustainable development requires the advancement of quantitative sustainability science, which, as introduced in Section 1 above, is indeed evolving through the efforts of the multi-disciplinary sustainability science community. A first important part of this is the definition, and adaption of the sustainability metrics/indicators[2] that characterize each pillar, the second is the determination of the relative weights of the pillars, and the third is the normalization and aggregation of these weighted metrics to a "composite sustainability index" (*CSI*) that can be used for assessing and comparing process sustainability. To render the *CSI* useful for sensitivity analysis and optimization, the functional dependence of the metrics, and sometimes of the weighting factors, on the process parameters must be formulated. Since the definition of metrics and weights is not completely deterministic, partially because it depends on local physical and social conditions, the sensitivity of the results to the assumptions and choices must also be analyzed. The reminder of this section presents a brief introduction to these issues.

4.2. The fundamental equation for sustainability assessment

The metrics M_i can be used individually to address the impact of each, but most useful is their aggregation into a single composite sustainability index (*CSI*) using weights (w_i) for each (introduced partially by eq. (1)), in their simplest way expressed as

$$CSI = \sum_i M_i\left(\vec{x}_{ij}\right) w_i\left(\vec{y}_{ik}\right) \quad \text{or} \quad = \prod_i M_i\left(\vec{x}_{ij}\right) w_i\left(\vec{y}_{ik}\right) \text{ or some other agggregation} \tag{2}$$

where

$\vec{x}_{ij}$ the j system parameters that affect the metric M_i; Example: if a metric is environmental, the "system parameters" may be impact on biota, gaseous emissions, etc.

$\vec{y}_{ik}$ the k system parameters that affect the weight w_i; Example: if a weight is related to an environmental metric, the "system parameters" may be the relative importance of the impact on biota, gaseous emissions, etc.

i index of a metric-weight pair (M_i-w_i)

j index of a metric (M_i) - dependence parameter $\vec{x}_{ij}$

k index of a weight (w_i) - dependence parameter $\vec{y}_{ik}$.

As shown in Eq. (2), the metrics and their weights are usually functions of some system parameters, marked here as $\vec{x}_{ij}$ and $\vec{y}_{ik}$, respectively, and each one of these, in turn, can be expressed as a function of the system's component variables,

$$\vec{x}_{ij} = \vec{x}_{ij}\left(\vec{c}_{x,il}\right) \tag{3}$$

$$\vec{y}_{ik} = \vec{y}_{ik}\left(\vec{c}_{y,im}\right) \tag{4}$$

where

$\vec{c}_{x,il}$ the l component variables affecting the $\vec{x}_{ij}$; Example: if a "system parameter" is gaseous emissions, the "component variables" may be the type of power generation system, its fuel, etc.

$\vec{c}_{y,im}$ the m component variables affecting the $\vec{y}_{ik}$; Example: if a "system parameter" is gaseous emissions, the "component variables" may be the relative importance of the impact of the type of power generation system on the relative importance of gaseous emissions, etc.

l index of the component variables affecting the $\vec{x}_{ij}$

m index of the component variables affecting the $\vec{y}_{ik}$.

Eqs. (2)–(5) create a composite sustainability index (*CSI*),

$$CSI = CSI\left\{M_i\left[\vec{x}_{ij}\left(\vec{c}_{x,il}\right)\right], w_i\left[\vec{y}_{ik}\left(\vec{c}_{y,im}\right)\right]\right\} \tag{5}$$

related by a system of equations expressing its dependence on all the chosen 'system parameters' and their 'component variables'. Thus established, *CSI* can serve as the objective function for mathematical sensitivity analysis and optimization, down to the level of 'component variables', or be part of it.

Some models are in development for sustainability, for example the EU recently funded project "INSURED" to develop a flexible methodology for representation, analysis and evaluation of sustainability at the regional level. "INSURED" was aimed to develop a practical and ready-to-apply method and toolkit for working with regional sustainable development indicators [121]. Validity of these evolving models is still unknown.

4.3. Sustainability indicators/metrics

Regardless of the specific definitions, and their complexity, the sustainability metrics (Section 2) must satisfy some commonsense criteria, to be: inclusive of economic, environmental and social concerns (the three pillars of sustainability); relatively simple, and widely understandable; normalized to allow easier comparisons; reproducible; and satisfy the laws of nature.

Perhaps the most daunting obstacle to sustainability analysis is not just the definition and quantification of the appropriate metrics and weights, which is a very significant problem and burden for even "just" environmental impact statements (see Section 3.1 including [45, 63,81,82]) but also the significant increase in their number, complexity and indeterministic nature (plurality). While many of the environmental metrics, such as concentrations of chemicals relative to desire values, are relatively simple and deterministic, others such as those dealing with ecology are much more complex and unclear, and so are many of those associated with social impacts. Disciplinary and interdisciplinary work are, however, progressing rapidly to characterize sustainability as a science, and to that end quantitative scientific definitions of its

[2] The terms "Indicator" and "Metric" are used in the literature quite interchangeably and there is no universally accepted usage of the two terms. "Metrics" are, however, often defined as measures of things like weight of emissions, kWh electricity, km^2 land area use, etc., whereas" indicators" most often refer to a score that aggregates multiple metrics.

metrics are evolving and gradually becoming a part of standards and regulations (e.g., [33,42,48,52,53,63,65,85,122,123]). Since there are many definitions of sustainability indices and metrics, work is underway to establish easily-usable, appropriate and commonly accepted criteria but much remains to be done, which also constitutes an exciting challenge for all stake holders, from the global public, to users and scholars.

Arbitrary examples of some of the difficulties to quantify environmental and social metrics follow. One classical problem for the former is how to monetize the value of biodiversity [124,125], and with the latter the tight relation to human values, which also vary widely by geography, customs, religion, etc. if there are no regulations that monetize them. Another example is that corporate social responsibility is defined as an attempt to achieve "commercial success in ways that honor ethical values and respect people, communities and the natural environment" [126], or "A sustainable corporation is one that creates profit for its shareholders while protecting the environment and improving the lives of those with whom it interacts" (Savitz [127]) and many others in the same vein, but these statements are extremely qualitative and not a metric yet. At the same time, progress towards development of social sustainability understanding and metrics is advancing (e.g., the work in [57] and [60] on quantifying the link between sustainability and human resources management, and in [51] on managing corporate sustainability). It is noteworthy that the social pillar is not only for the society external to the corporate entity but also for treatment of its own employees. An incidental but good example of the ambiguity of even the simplest qualitative social sustainability understanding and definitions is that the acronym CSR is arbitrarily used to mean Corporate Social Responsibility, or Corporate Social Reporting or Corporate Sustainability Reporting, three very different concepts, where, for example, the second is actually only a part of the third.

A frequent problem beyond science and technology is the lack of transparency associated with metrics and indices used in many projects, since many environmental studies remain confidential for alleged commercial or security reasons, and that there is too little sharing of information, on the Gulf for example [39]. This defies principles of sustainable development and the essentially important public participation.

4.4. Normalization of the indicators

The indicators (M_i in Eq. (2)) must be normalized before they are aggregated to form a composite index. This is needed to allow rational comparison among the different indicators having different units, to prevent the absolute magnitudes of the metrics from biasing the results, and to assign a consistent directionality to all the indicators (i.e. directionality indicates if a higher value corresponds to a more desirable/sustainable state or a less desirable/sustainable one).

Various normalization methods are used, such as "Distance-based" [2], "Min-Max" [2], "Z-score transformation" and "T-Score" [128], and "Decimal scaling" [129]. The choice of normalization methods is highly dependent on the nature of the specific indicator that is being normalized, as well as the size of the metric data set that is being considered.

4.5. Sustainability indicators' weights

Weights (w_i in Eq. (2)) are a quantitative expression of the importance of a metric (M_i) relative to the other metrics used. In some cases they are calculated using some quantitative analysis, but often via polling, with some statistical significance, of the opinions of experts and stakeholders, including decision makers that may include politicians. Weights can be established directly, or indirectly following a formal method, such as "Equal Weighting", "Ranking", "Pairwise Comparison", "Swing weight method", "Direct Rating & Point Allocation", "Conjoint Analysis Tradeoff", and "Analytic Hierarchy Process (AHP)" [130–140]. The determination of weights, whom to ask and by which method to calculate them, is likely to cause more controversy than other parts of sustainability analysis.

4.6. Aggregation methods ([2,141–143])

The most used are "Additive Aggregation" and "Geometric Aggregation" as shown in Eq. (2), and other methods such as those used in [142].

4.7. Solution methods for evaluating the composite sustainability indices

The *CSI* characterized by Eq. (5) is most often calculated by using multi-criteria analysis (MCA) techniques. An interesting yet simplified approach is outlined in [27] using decision theory and based on the General Indices Method. Case studies of EIA for pretreatment methods are calculated in [81] by using the MCA *DEFINITE* software tool [144]. Further mathematical treatments are shown in [50,54,63], discussion of multi-criteria sustainability evaluation in [57,144–153], and fuzzy evaluation in [62].

4.8. The sustainability analysis procedure

The recommended quantitative procedure steps should be [5,43]:

1. Definition of the system and its spatial and temporal extent
2. Preliminary definition of the sustainability objective function and its units
3. Definition of all sustainability metrics and their system-variable dependence quantification (considering spatial effects and temporal evolution)
4. Reduction of their number to a necessary minimum
5. Normalization of the metrics and unification of their units
6. Final definition of the sustainability objective function and its units
7. Definition of the metrics' relative weights
8. Decision on the method of the aggregation of the metrics, considering space and time
9. Aggregation
10. Error analysis
11. Sensitivity analysis
12. Optimization
13. Testing under practical conditions
14. Repeat of the procedure for an established alternative process for the same water supply objective: this allows generation of relative rather than absolute quantitative results and is very important for comparison and further validation.
15. Iteration and development of learning experience for this and future projects.

It is very noteworthy that each step in the procedure is very beneficial in improving the detailed understanding of the whole process, of its impacts and in consideration of ways to deal with them.

A necessary and encouraging progress towards sustainable development would be standardization. This is already increasingly used for environmental impact statements (a subset of the needed sustainability impact statements) preparation, such as by implementation of ISO 14001:2004 (environmental management system standard, [106]) and similar guidelines.

4.9. Use and interpretation of composite indices (CSI)

As discussed, the composite (aggregated) index (*CSI*) joins together the indicators/metrics that quantify the pertinent aspects of sustainability to consolidate them into a single value for straightforward appraisal and easy comparison among the various planning alternatives. While these are extremely desirable advantages of this scientific sustainability analysis method, it is critically important to always maintain clear detailed understanding of how the aggregated indices were constructed and how they are interpreted and used, so as not to lose sight of the forest for all the trees.

To avoid such problems, the values of the metrics and weights that were used to construct the *CSI* must be retained and displayed during its use, for example by "spider plots" similar to the way shown in [154], to provide easy real-time inspection.

Further, to avoid unacceptable aggregation mistakes in cases where certain values of one or more of the component metrics may cause catastrophic consequences despite desirable values of the other metric-weight combinations, the mathematical aggregation method and the weights must ensure that such unacceptable mistakes become clearly apparent. For example, use of the product version of the aggregation Eq. (2) and assignment of zero value to a weight of a metric that may have a catastrophic consequence, would annul *CSI*, which can be seen even before conducting the aggregation process.

It is known that while use of any sustainability-related indicators without their adequate understanding is easy but prone to wrong conclusions, as evidenced by the experience with the widely used GDP, ecological footprint, and human development index (HDI), to name a few. The use of all indicators should not be left to 'bean counters' who use only the values of the indicator.

An example applicable to some real desalination plant data, which would demonstrate the development process of the sustainability analysis, including metrics, weights and aggregated index, and discuss the ways, advantages and shortcomings of using such an indicator, is being prepared and would be submitted for publication after its completion.

4.10. Realization of the sustainability principles

It is obvious that it is much easier to implement the necessary sustainability criteria into the planning and design of the desalination project (and any project) rather than after it is already under construction or in operation.

Just as the sustainability pillars of economics, environment and society, the path to sustainability will have to address all three topics, as follows.

The economic challenge, at least at start of the path, is that both the satisfactory development and specification of the sustainability criteria and processes, and of their implementation, will raise the effort, duration and cost for producing the water. All that is likely to be significantly ameliorated with experience and standardization.

The environmental challenge in the Anthropocene is that, in addition to both regular and unpredictable natural events, the humans have a strong and increasing effect on the environment, which is going to keep changing the basic conditions, hence requiring continuous update of the methodology and sustainability criteria. Just like, for example, the global efforts for reducing emissions of greenhouse gases to decelerate global warming, more sustainable desalination is going to help, even though in a modest degree, decelerate the anthropogenic ally caused damage.

The social challenge is the greatest barrier. In view of the needed higher investments, uncertainties about the future, and some possible delays, society must be globally convinced that the most reliable, or perhaps only, path to a satisfactory future for humanity is by sustainable development as defined in its principles, and that time is running out. Such conviction is also typically effective for creating political leaderships that would be willing to invest in the needed efforts and see them realized. Knowledge and education at all levels are critically important for developing such conviction.

5. Conclusions and recommendations

A. Sustainability analysis integrates the evaluation of environmental, economic and social impacts (the sustainability pillars), and an index based on it is thus much superior and inclusive as a quantitative measure for the evaluation of water desalination processes than the current practice of addressing or failing to address the economic, environmental, and sometimes social aspects separately without their coherent integration.

B. Desalination has evolved over the past six decades into a regionally important fresh water source, with an exponential growth rate, and like all large human endeavors is accompanied by significant economic, environmental and social impacts, and is at an amply mature and needed stage to be planned, designed and operated by using quantitative sustainability analysis and criteria

C. A critical review of the state of the art of sustainability analysis and its comparison to other methods such as EIA, LCA, and BAT, and DPSIR is presented.

D. Even the current analyses of the separate aspects are neither complete nor standardized, and such standardization is urgently recommended for the sustainability analysis, which would, at least, simplify the process very significantly.

E. The mathematical model for formulating a composite sustainability index (*CSI*) as a function of all relevant parameters and variables, which thus allows mathematical analysis in general and sensitivity analysis and optimization in particular, is outlined.

F. While the *CSI*, which provides a single function/value for straightforward appraisal and easy comparison among the various planning alternatives, is extremely useful for scientific sustainability analysis, it is critically important to always maintain clear detailed understanding of its components and its construction method, and then of its interpretation and use.

G. Information about the needed metrics and their normalization and weights is outlined, and calculation methods are presented, and an analysis procedure is recommended.

H. In view of the very large set of indicators and metrics that characterize the sustainability of water desalination, a compact but adequate set must be carefully chosen.

I. It is obvious that the necessary sustainability criteria should best be implemented into the planning and design stages rather than after the project is already under construction or in operation.

J. In view of the required higher investments required for sustainability-based development, uncertainties about the future, and some possible delays, society must be globally convinced that the most reliable, or perhaps only, path to a satisfactory future for humanity is by sustainable development, and that time is running out; such conviction should also be effective for creating political leaderships that would be willing to invest in the needed efforts and see them realized. Knowledge and education at all levels are critically important for developing such conviction.

Acknowledgment

The author acknowledges the important help in this study by his former M.S. student David D. Kim, and the good suggestions by the anonymous reviewers that improved the paper.

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