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Assessment of methodologies and data used to calculate desalination costs

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Abstract:

In desalination, similarly with other industries, the cost of the final product is one of the most important criteria that define the commercial success of a specific technology. Therefore, when new projects are planned or new technologies are proposed, the analysis of the expected costs attracts a lot of attention and is compared to (perceived) costs of state-of-the-art desalination or costs of alternative fresh water supply options. This comparison only makes sense if the cost assessment methodologies are based on the same principles and use common assumptions. This paper assesses: (i) the methodologies used to calculate the water cost; (ii) the boundary conditions and (iii) the input data and assumptions. It has been found that most papers in the literature use suitable equations and boundary conditions. Also certain elements like land costs are ignored, but in most cases this is duly acknowledged and justified. However, the quality of the input data for the hardware costs, the operating costs, and the financial parameters are not always appropriate. Guidance for the methodology, data and assumptions that should be used is provided depending on the purpose for which the cost of the desalinated water is calculated.

Keywords: Desalination costs, energy source, methodology, boundary conditions, input data

1. Introduction

The combined effects of global population growth, industrialisation and urbanisation drive an increasing demand for water. UNEP predicts that by 2025 more than 2.8 billion people in 48 countries will face water stress or scarcity conditions [1]. In many regions of the world, desalination is one of the strategies adopted in order to deal with this issue. As a result the relevant market is growing rapidly. The global desalination capacity in 1980 was about 5 million m^3/year [2] increasing to about 90 million m^3/year by 2016 [3]. Between 2005 and 2015 alone the desalination capacity in the world has more than doubled and this trend continues [3].

The preferred type of desalination process and the sources of energy used change over time depending on technological developments, which affect both the performance and the cost of the desalination and energy generation technologies. In addition, the technological preferences are greatly affected by the local conditions in the regions where the plants are installed because parameters such as the cost of fuel and the typical feed water composition can vary widely, affecting the performance and feasibility of the plant.

In most countries water supply is the responsibility of municipalities, or some other kind of governmental agencies. Therefore, these agencies and the companies that are supporting them in the process face the following choices:

- Shall they employ desalination, or is there a better alternative for securing the necessary resources for their water supply needs?
- If desalination is employed, which is the most suitable technology for their specific conditions?
- Which source(s) of energy should be used to power the inherently energy intensive desalination process?

The issue of cost is central in dealing with these questions. Of course other parameters are also taken into account in the decision process, such as environmental impacts, social acceptance and strategic choices defined by governmental policies. But in any case, no decision can be taken without full clarity on the economics of each choice.

The importance of the desalination costs is reflected on the large amount of relevant scientific papers and reports that deal directly with this issue. It has been widely acknowledged [4–7] that the different methodologies, definitions and data sources used to calculate desalination costs make difficult objective comparisons between technologies and between different projects. There have been efforts in developing a global picture about this issue and streamlining the approaches followed by the desalination community. Most notably, in December 2004 MEDRC started a process aiming to develop a global standard for desalination cost calculations. The first step was a dedicated conference in Larnaca, Cyprus, where invited papers by leading experts were presented on issues like: (i) Desalination technology costs [8–14], (ii) Cost models [15–21], (iii) Boundary conditions [22–26], and (iv) Case studies [27–34]. The idea was that the conference would be followed by a “book that will be useful to decision makers, planners and the industry” and “ultimately develop a dynamic standard that is globally accepted”[4]. However, these follow-up actions were never organised and no other dedicated action or event has taken place since.

This paper aims to pick-up on this process and contribute to the development of increased understanding a common practices within the desalination community. Over 100 publications from the past 20 years (1996 – 2016) have been critically reviewed, focusing mainly on the methodologies, the assumptions and input data that they use, rather than the actual results of desalinated water cost in USD/m^3. Then the strengths and weaknesses of each approach are discussed, coming up with suggestions for desalinated water cost calculations that are reliable, defining the extent to which they can be used for different decision making processes or other purposes.

2. Literature on desalination cost reviews and correlations

2.1 Cost reviews

There are several studies that have reviewed published desalination costs. In 2008 Karagiannis et al. [35] reviewed almost 100 different cases and classified the reported costs into categories according to the type of feed water (i.e. seawater, brackish etc.), the desalination process adopted (i.e RO, MED, MSF) and the type of energy source (heat, renewable electricity or grid electricity). In 2014, Shatat et el. [36] also screened desalination costs from various sources and grouped them in tables classified by technology and energy source. The cost data come mostly from the previously mentioned work of Karagiannis and from few other published papers with original cost calculations. In 2013, Al-Karaghouli et al. [37] did a similar work, where cost data from 23 publications were used to develop a table providing cost ranges for all major desalination technologies powered by conventional sources and another 29 papers were used to compile a similar table with the costs of desalination powered by renewable energy. Also Ziolkowska in 2015 [38] presented an analysis where over 50 papers, reports and databases have been used and the costs reported have been discussed, providing also a cost breakdown to operating, maintenance and capital cost. All these papers [35–38] classify costs based on technology and energy source and sometimes plant size; however the grouping of the costs in all these papers does not take into account critical factors, such as:

(i) *The different year of construction*. For example, Al-Karaghouli et al. in his paper in 2013 [37] derived a cost range for PV-RO from 11.7 to 15.6 USD/m^3 by grouping together costs taken from papers published from 1991 [39,40] up to 2009 [41].

(ii) *The different geographical locations.* For example Karagiannis et al. [35] gave a cost range from 0.48 to 1.62 USD/m^3 for RO systems with capacities from 15,000 to 60,000 m^3/day, grouping together data from countries with very different conditions such as USA, China, Greece and UAE.

(iii) *The assumptions/methodologies used to derive these costs*. For example Ziolkowska [38] grouped together costs reported in the Global Water Intelligence (GWI) database from real desalination plant EPC contracts, cost assessments from the literature and results she derived from applying the DEEP 5 model developed by the International Atomic Energy Agency.

By grouping together information without accounting for these three factors the conclusions can be misleading. As will be shown in Section 2.2, it has been proven that the year of construction and the geographical location are two of the most important factors affecting the cost. For example, a decision maker that reads in a 2013 paper [37] that the cost of water produced by a PV-RO system ranges from

11.7 to 15.6 USD/m^3 may very well decide against considering that technology as it seems very expensive. However, within the 22 year period from 1991 (from when some of the data are derived) to 2013 (when the paper is published) the cost of PV has actually reduced by 90% [42–46].

2.2 Cost correlations

Some papers develop cost correlations (i.e. regression equations as a function of main parameters), based on desalination project cost databases. One of the important works in this category was presented in 2014 by Loutatidou et al. [47]. They performed statistical analysis of real cost data from 950 RO plants and showed that the most important parameters affecting the cost were:

- the plant capacity,
- the year of construction,
- the feed water salinity,
- the region where the plants are installed

In addition, this paper [47] derived an equation that can be used to assess the EPC costs of SWRO and BWRO plants installed in the GCC or Southern Europe, a useful tool for decision makers that need an initial estimation of the costs they should be expecting.

Also Wittholz et al. [48] published in 2008 a paper where a series of cost correlations were developed for order of magnitude cost estimations. Their initial database included over 500 plants and the focus was on large scale MSF and MED plants both for seawater and for brackish water. Finally, Lamei et al. [49] also attempted to develop a cost correlation for forecasting PV-RO prices. However, their paper was based on a database of only 21 plants of very different sizes, feed-water qualities and energy supply arrangements, making it difficult to come-up with a reliable correlation.

2.3 Factors affecting costs

The factors affecting the water cost have been discussed in some papers. One such paper was published in 2013 by Ghaffour et al. [6] and was based on an extensive review of the literature; it can be used as a check-list when analysing the economics of desalination plants. Then, in 2015 Ghaffour et al. [2] discussed the potential of renewable energy driven desalination technologies, including a discussion on their costs. It is an exhaustive paper, built on 210 references.

There are more review papers on desalination technologies, which also touch on the issue of costs. For example Reif et al. [50] and Bundschuh et al. [51] both in 2015 reviewed renewable energy combinations with thermal desalination, however the former did not go into specific costs while the latter grouped together costs from several sources ending up with very wide ranges that cannot be used for decisions or clear conclusions.

3. Methodologies for calculating desalination costs

3.1 Investment evaluation indicators

Desalination plants involve several kinds of costs and revenues over a long period of time during the planning, construction, operation and decommissioning phases, which results in complicated cash flows.

There are well established methodologies applied in any kind of industry to compare different projects involving cash flows over several years. The most commonly applied indicators used in the evaluation of investments are the Net Present Value (NPV), the Internal Rate of Return (IRR) and the (Discounted) Payback Period (PBP). There are many textbooks and papers where these indicators are defined, providing equations for their calculation (see for example Levy et al. [52]).

The calculation of the NPV can be done using the following equation:

$$NPV = \sum_{t=1}^{n} \frac{R_t - C_t}{(1+i)^t} - I_0 \qquad (1)$$

The calculation of NPV requires the knowledge of the initial capital investment (I_0), the revenues and costs in year t (R_t*, and* C_t *respectively*) for all years from the first to the last (*n*). In addition, it is needed to select an appropriate discount rate (*i*), which reflects the expected return by the investor and depends on macro-economic assessments. The selection of the discount rate can be difficult as it is affected by non-technological elements that can vary widely among industries, countries and over time. Especially for theoretical cost calculations, as is often the case in the scientific literature, its selection can be quite random. In that respect the IRR can be a more interesting indicator as it solves Eq. (1) to calculate the required discount rate (*i)* for the project to break even (*NPV*=0) by the end of its technical/accounting lifetime and therefore the calculation of the IRR does not require the selection of a discount rate; it rather calculates the return on investment that can be expected from a specific project.

In the case of desalination projects the R_t reflects the revenues from selling the produced water; as a result the calculation of NPV or IRR requires the assessment of the amount of water that will be produced and the price at which the water can be sold at the point of production from year 1 to year n. For example the R_t can be calculated easily in the case of a contractor who develops and operates a project on behalf of a client like a municipality, which as part of the agreement has offered a guarantee that it will purchase all produced water at a well-defined price over a certain period of time. However, for theoretical cost calculations the selection of a water selling price and its evolution over time can be difficult as it depends on volatile market framework conditions over a period of 20 to 30 years.

The situation is similar in energy projects, where the price at which the generated electricity can be sold has to be known. In that case the concept of Levelised Cost of Electricity (LCOE) has been introduced, which is an assessment of the price at which the electricity would have to be sold for the project to break even and is calculated by dividing the discounted costs over the lifetime of the project by the discounted energy produced over the same period. By adapting that concept for desalination and other water production technologies, Eq. (2) is obtained for the Levelised Cost of Water (LCOW), where C_t is the annual cost of operation and $M_{w,t}$ is the amount of water produced in year t:

$$LCOW = \frac{I_0 + \sum_{t=1}^{n} \frac{C_t}{(1+i)^t}}{\sum_{t=1}^{n} \frac{M_{w,t}}{(1+i)^t}} \qquad (2)$$

By calculating the LCOW it is easier to compare the relative feasibility of different technologies, plant layouts, sizes, etc.

3.2 Review of methodologies used to calculate desalination costs

In the literature, there are only few papers using the LCOW [53–57] or the NPV/IRR [58,59] methodologies described in section 3.1.

In most of the cases [60–71] a method that some authors call "amortisation factor" or "annualised life cycle cost method" was used. In that approach, the initial capital costs were annualised by using the amortisation factor (α). The result obtained from this method is called here Simplified Cost of Water (SCOW), which can be calculated using Eq. (3):

$$SCOW = \frac{(I_0 \times \alpha\ ) + C}{M_w} \tag{3}$$

, where the amortisation factor (α) is defined by Eq. (4):

$$\alpha = \frac{i\ (1+i)^n}{(1+i)^n - 1} \tag{4}$$

The SCOW approach that was adopted in most of the reviewed papers is essentially a simplified version of the LCOW as can be seen in Eq. (3), where it is assumed that every year (from year 1 to year n) the desalination plant produces exactly the same amount of water (M_w) and has exactly the same running costs (C). It is reasonable that most papers adopted that approach, since in theoretical calculations it is standard practice not to go into too much detail and to assume stable operation over the system's technical life due to lack of actual data.

It is possible to elaborate further the assumptions within the SCOW approach. First of all, it is quite common to break down the running costs to annual fixed costs (C_F) measured in USD and variable costs (C_V) measured in USD/m^3. Then, in some cases [72], the expected variation of prices over time was taken into account by assuming an annual escalation rate (r) for running costs. In that case Eq. (3) becomes more complicated by introducing a multiplier (λ) for taking into account the price escalation over time, as observed in Eq. (5):

$$SCOW = \frac{(I_0 \times \alpha\ ) + \lambda \times C_F}{M_w} + \lambda \times C_v \tag{5}$$

The multiplier (λ) is defined as by Eq. (6) and parameter k is given by Eq. (7).

$$\lambda = \frac{k(1-k^n)}{1-k} \times \alpha \tag{6}$$

$$k = \frac{1+r}{1+i} \tag{7}$$

Different multipliers can be introduced to account for different expected escalation rates of various cost or revenue elements. The LCOE methodology is still more flexible allowing for (non-linear) future variations in costs, prices and production rates. However, the elaborate versions of the SCOW and the LCOW give practically the same results in most of the cases where simple enough scenarios are considered.

On the other hand, in some papers [7,73,74] a very simplistic calculation was performed for the cost of water (*COW*) where no discounting of future cash flows was taken into account. This simplified calculation is given by Eq. (8):

$$COW = \frac{(I_0/n\ ) + C}{M_w} \tag{8}$$

There are papers where the water cost was calculated but the methodology used was not clearly defined [75–78], while in several others [79–84] the methodology used was also not explained but reference was made to software packages used, which in most cases have built-in a methodology similar to the LCOW or at least the SCOW.

4. Assumptions and estimations of input data

As discussed in section 3, the methodology used can affect the calculated cost of water, as there are differences depending on whether the following parameters are considered: the value of money over time and the variations of the system's performance, costs and revenues over its technical lifetime.

However, even if a correct and detailed equation is used to calculate the costs, the quality and detail of the input data and the accuracy of the assumptions about future performance, costs and revenues will be the main elements that define how relevant or reliable the results are. These assumptions and estimations are discussed in this section.

4.1 Boundary Conditions

As a starting point, the boundaries for the cost calculation have to be defined; depending on the purpose of the calculation and the specific conditions in every site, it might make sense to take into account the auxiliary equipment and materials under the capital cost and their running requirements under operating costs. Items that can be either included or excluded are: water storage, desalinated water distribution, laboratory for quality control, electricity grid extension, access roads opening and desalination plant decommissioning at the end-of-life.

For example Shahabi et al. in 2015 [56], when comparing alternative desalination options for the Perth water supply in terms of RO plants alternative sizes and siting options, included in the calculation the investment and running costs of the infrastructure for the water distribution to the end-users, concluding that one of the decentralised scenarios provided water that costs 18% less than in the centralised scenario. If the distribution costs were ignored, the centralised scenario would appear to cost 40% less than the selected decentralised scenario, leading to a totally different conclusion. This example reflects the importance of defining properly the boundary conditions.

4.2 Capital Costs (I_0)

4.2.1 Hardware costs

All examined papers take into account the equipment and material costs in their calculation. Most papers used a fixed figure as *specific capital cost* (usually in USD/m^3/day) for the desalination technology, including standard pre-treatment and post-treatment equipment and materials. The specific capital cost figures reported, are most of the times reproduced from one paper to the other without taking into account critical factors which can affect that cost substantially as discussed in section 3.2, like year of construction, scale and location.

For an accurate definition of the capital costs, a breakdown of all equipment and materials is necessary. In order to do that, the plant design has to be known, which depends on choices made by the customer (for example the type of energy recovery equipment used) and site specific characteristics, like topography (affecting feed-water intake), feed water quality (affecting pre-treatment), the quality standards that the desalinated water has to comply with (affecting post-treatment) and regulations (affecting brine disposal). In addition to the desalination related equipment and materials, also any integrated auxiliary equipment and energy generation hardware costs have to be taken into account.

It has to be noted that many papers [7,53,60,64,65,70–72,75,77,78,83] included only the hardware in their capital costs and did not explicitly mention or take into account any of the other capital cost factors listed in section 4.2.2 below.

4.2.2 Other capital costs

Engineering, Construction and Project Management: Many of the reviewed cost assessments ignored the engineering, construction (site preparation, civil, electromechanical) and project management costs. It is common though to account for those by adding a percentage on top of the equipment hardware costs. Some examples are provided in table 1.

Table 1: Overview of Engineering, Construction and Project Management Costs used in desalination cost analysis literature

Year of publication	**Engineering, Construction and Project Management Costs**	**Reference**
1996	site preparation and utility costs at 10% of equipment and indirect costs charged at 27% of direct capital costs	[85]
2001	Foundations and buildings 15% on top of capital costs for equipment, engineering and contingency at 10% of equipment and capital	[80]
2011	Installation cost 25% of equipment cost	[62]

2011	Installation & infrastructure 30% of system capital costs, Professional costs 5% of system capital costs	[63]
2012	Engineering 3.5% of the project costs, Project development 0.5% of project expenses	[74]
2015	Site preparation 20% of equipment cost, all other indirect costs charged at 30% of direct costs	[67]

Initial Design and Permitting: None of the desalination cost assessment papers reviewed did explicitly account for the costs of the initial design and the costs of the process required to go through for securing all necessary permits. However, it has been widely acknowledged (see Ref. [47,86]) that the potential environmental impacts of desalination are increasingly recognised and lead to higher costs, for permitting but also in other capital and operating expenditures, especially in the European Union, the United States and Australia.

Cost of land: Most cost calculations ignore the cost of land. However, Lapuente in 2012 [74] in his effort to calculate *"fully and accurately desalination costs"* did account for land costs, and where data were not available he assumed 2% of the construction costs for land acquisition. Also, Shahabi et al. in their 2015 paper [56] accounted for the cost of land, using the figure of 300 AUS$/m^2, while Kosmadakis et al. [87] considered an annual cost of 3000 EUR/ha for their small-sale solar-ORC-RO system. Finally, papers that performed an assessment of desalination costs based on real plant data might have taken some kind of land costs into account, depending on the kind of data available in the sources used, which is not always clear; for example Wittholz et al. in [48] mentioned: *"Important details such as if the land and civil works were included in the capital cost were not always reported, making it difficult to develop accurate predictions of cost."* If there is a leasing agreement for the land rather than land acquisition, the annual fee paid should be included under the operating costs rather than the capital costs.

4.3 Operating Costs (C_t)

4.3.1 Energy

One of the main contributors to the cost of desalinated water is energy, and in most cases it is considered as an operating cost. There are some cases though, where energy contributes mainly through capital costs when the desalination plant includes an integrated or co-located electricity generation system. For calculating the energy related cost for year t ($C_{E,t}$) Eq. (9) can be used:

$$C_{E,t} = E_{el,t} \times P_{el,t} + E_{th,t} \times P_{th,t} \tag{9}$$

Where $E_{el,t}$ and $E_{th,t}$ the amount of electrical and thermal energy respectively used by the plant in year t and $P_{el,t}$ and $P_{th,t}$ the cost of the unit of electrical and thermal energy respectively in year t.

The energy requirements (E_{el} *and* E_{th}) are the product of the specific energy consumption (in kWh/m^3) with the water production M_w (in m^3). The specific energy consumption is determined by the desalination technology used and the design characteristics of each specific plant. The ambient conditions do also affect the specific energy consumption; for example the feed water composition and temperature affect the plant performance [88]. Some authors performed detailed calculations to determine the specific energy consumption (see Ref. [63,64] for RO and [69] for MED) while others just took a reference figure from the literature (see Ref. [54,62] for RO and [65] for MED).

The way to account for the cost of energy (P_{el} and P_{th}) depends on whether it is generated on-site or provided externally (for example electricity from the grid). For on-site generation, if the energy and desalination plants are operated by the same entity, the initial costs related to energy generation (for equipment, engineering etc.), must be taken into account as part of the capital costs, leaving only the associated running costs (like fuel , maintenance and personnel costs) to be used in Eq. (9). An alternative approach to that is to calculate separately the Levelised Cost of Energy (LCOE) and to use that as the cost of the unit of electricity [57]. If the energy plant is on-site but operated by a separate legal entity, which financed its development and sells the energy to the desalination plant, the calculation is similar to the case where externally provided energy is used, where the cost of the unit of energy is defined in the agreement between the desalination plant operator and the energy supplier.

Electricity:

The vast majority of the papers reviewed used a fixed rate for electricity over the whole lifetime of the desalination plant: most were in the 0.05 to 0.06 USD/kWh range [49,61,73,74,85,86,89], with few being at 0.03 USD/kWh [72,80] or below [83] and some at 0.08 USD/kWh [68,71] or above (as high as 0.11 USD/kWh) [65,75]. In two cases the authors performed a sensitivity analysis on the electricity costs ranging from very low to very high prices [67,79].

In all these papers though, the selected electricity price was kept stable for the whole lifetime of the desalination system. In reality the price of electricity can vary significantly over these 20 to 30 year periods. Only Kaldelis in 2004 [54] introduced an annual increase rate of 4%; he started by assuming electricity costs of 0.04 USD/kWh for 2004 and it increased gradually reaching 0.06 USD/kWh by 2014 and 0.09 USD/kWh by 2024. Looking back to this assumption now, in 2016, it seems to be much closer to reality compared to fixing the electricity price at 0.04 USD/kWh for 20 years, which is the approach that most authors followed. Especially in the case where a large desalination plant procures directly from the wholesale electricity market, rather than from a supplier, it will face much stronger variations, not only over the years, but also seasonally, daily and even hourly [90,91].

In addition to that, the industrial electricity prices vary strongly between the countries and the regions of the world. Figure 1 illustrates the industrial electricity prices in some Southern European countries from 2011 to 2015. It clearly shows that even between countries in the same region the differences can be very large. For example, industries pay for electricity in Italy more than double than what they pay in Bulgaria. Figure 1 also clearly demonstrates that in Southern Europe industrial electricity costs are higher compared to the 0.05 – 0.06 USD/kWh figure used in most papers. Also within a period of a few years the industrial electricity prices can vary significantly and this variation can be in the form of prices increases or price reductions; for example in Cyprus, a country with high desalination needs, industrial electricity prices were reduced by 39% from 2012 to 2015.

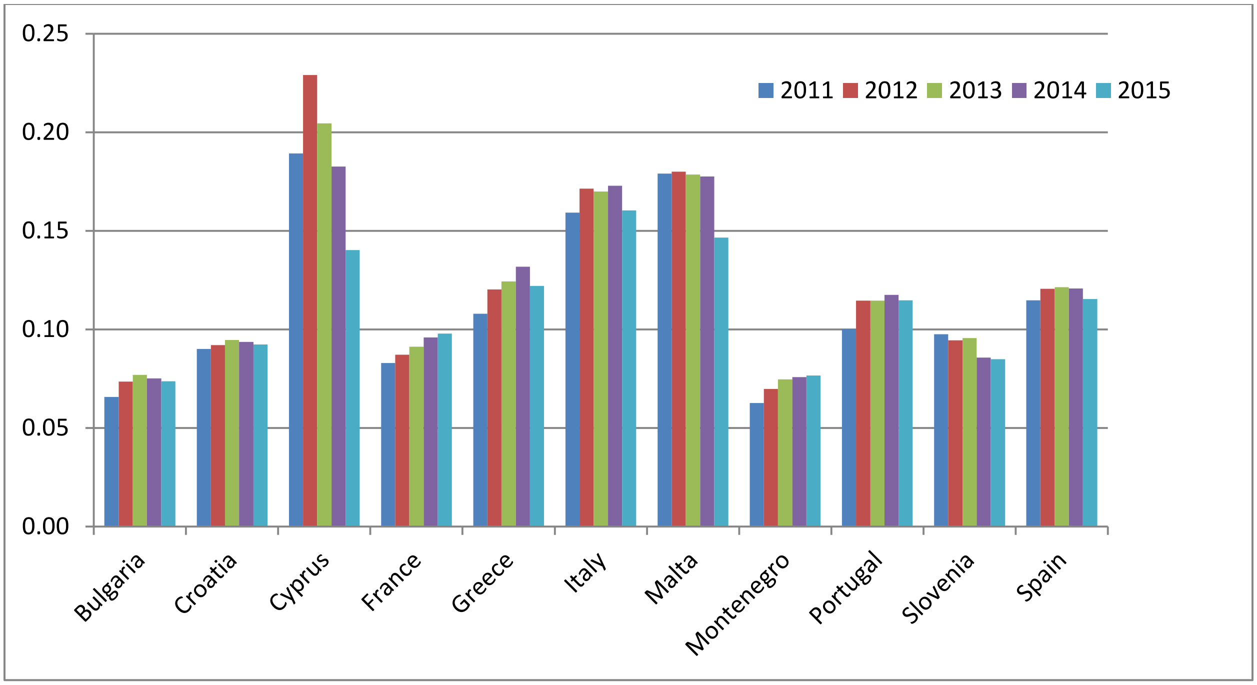

Figure 1: Industrial electricity prices in EUR/kWh in Southern Europe excluding VAT and other recoverable taxes and levies (Band IC : 500 MWh < Consumption < 2 000 MWh). Source: [92]

Thermal energy:

In most cases, thermal energy/steam is generated on-site, either directly for the desalination plant or within a co-generation installation where a power plant and a desalination plant are co-located [93–97]. Usually natural gas or oil is used to generate the heat (and electricity where applicable), but there are several other options possible like solar thermal, concentrated solar, geothermal and nuclear [98–102].

One way to take these costs into account is to include the procurement and installation of the energy generating equipment as part of the capital costs, while the fuel procurement (if any) and other running costs of the energy generation under the operating costs of the desalination system (see Ref. [60]). If electricity is also generated the revenues from selling it to the grid should also be taken into account (see Ref. [84]).

A simpler way to deal with this is to consider the desalination as a separate process and to define a price for the unit of heat/steam that is provided to drive the thermal desalination system. See for example Kesieme who put a price of 0.007 USD/kg for steam [65], using as a reference the paper of Al-Obaidani [97], who also used this value but did not explain where it came from. On the other hand, Agashichev [53] also attached a cost to the heat, but had a more sophisticated approach, starting from the capital and operating costs of an auxiliary boiler and calculating from that the levelised cost of heat.

In cases where the heat is produced on-site together with electricity, a decision has to be made for the allocation of capital and operating costs between the electricity and the heat. There are two approaches:

(a) The exergetic cost accounting method, where the costs are allocated between heat and electricity proportional to the exergy embedded to the corresponding streams entering or leaving any plant component- this is used for example by Agashichev [53].

(b) The reference cycle method as explained by Sommariva in chapter 6.1.5 of [103] where *"the energy associated to the steam extracted to the desalination plant is considered in terms of equivalent loss of electric power that would otherwise be rendered by the steam extracted in the power generation yard"* – this method is applied for example by Moser [55].

The two methods were compared in a 1999 paper by El-Nashar [104], where he concluded that the exergy method is preferable. However, both methods are still used and are widely accepted.

An interesting option is the use of "waste heat". This option is often discussed, especially as reverse osmosis has taken over the bulk of the mainstream desalination market and there is a search for niche markets where thermal desalination might have a competitive advantage. For example Rahimi [58] studied different MED plant configurations, assuming low grade sensible heat sources that are available for free. Also Ghaffour [2] and Bundschuh [51] discussed various thermal desalination options in combination with low-cost energy supply, with particular emphasis on low-cost, low enthalpy geothermal sources.

4.3.2 Other operating costs

<u>*Chemicals and other consumables:*</u>

The requirements for chemicals depend on the type of desalination plant and on the feed water quality. Many of the reviewed papers take the consumables into account using reasonable assumptions for the specific costs (USD/ m^3). A standard reference for the cost of chemicals is the 2002 paper by Ettouney et al. [61] where they included tables with a breakdown of the chemicals and their specific costs for different technologies and scales; these values ranged from 0.024 to 0.35 USD/ m^3. Similar figures, closer to the lower end of this range were used in most of the papers reviewed where the costs of chemicals were explicitly taken into account, as indicated in Table 2.

Table 2: Overview of Chemical Costs used in desalination cost analysis literature

Year of publication	**Chemicals costs**	**Reference**
2001	0.024 USD/ m^3 for MED and MSF and 0.047 USD/ m^3 for RO	[80]
2002	0.024 to 0.35 USD/ m^3	[61]
2003	0.025 to 0.035 USD/ m^3	[76]
2005	0.035 USD/ m^3	[105]

2012	0.024 €/m^3 for upwelling water uptakes and 0.042€/ m^3 for seawater intakes	[74]
2013	0.019 to 0.05 USD/m^3	[65]
2015	0.0421 USD/m^3	[58]

Labour:

The labour costs can vary widely depending on the country, the exact location, the technology and the specific design and the scale of the plant. Table 3 takes the specific costs used in some of the reviewed papers to give a taste of the values used.

Table 3: Overview of specific costs for labour used in desalination cost analysis literature

Year of publication	**Specific costs for labour**	**Reference**
2002	0.1 USD/m^3 for the thermal processes and 0.05 USD/m^3 for RO	[61]
2003	0.1 USD/m^3	[76]
2012	Ranging from 0.007€/m^3 to 0.030€/m^3 reflecting the economies of scale	[74]
2013	0.03 USD/m^3 for MD and MED and 0.02 USD/m^3 for RO	[65]
2014	0.027 €/m^3	[55]
2016	0.08 to 0.1 USD/m^3, depending on the RO size	[106]

Maintenance:

One of the major maintenance costs for RO is the membrane replacement. The membrane cost per m^2 is varying over time and depends also on other factors like region and economies of scale; finding current prices from suppliers should not be a problem. The most important for the cost calculation is a reasonable assumption for the membranes replacement rate, which depends among others on the feed water quality. Ettouney in [61] mentioned that the membrane replacement rate varies between 5 and 20%. This is confirmed in the literature where most papers used the 20% rate (see Ref. [62], [63], [65], [67], [80] and [107]) or the 10% value (see Ref. [76] and [71]). In one case [63] where PV was considered as the source of energy, 40% was used to account for the negative effect that varying pressure might have on the membranes.

Regarding other maintenance costs, like replacement of parts, pumps etc, they are often ignored, or they are accounted for by adding annually to the costs a certain percentage of the capital costs, ranging between 1.5 and 3%. Some examples are provided in the Table 4.

Table 4: Overview of other maintenance costs used in desalination cost analysis literature

Year of publication	Other maintenance costs	Reference
2002	less than 2% of capital cost per year for other maintenance and spare parts	[61]
2013	maintenance cost 2% of the normalised capital cost	[65]
2014	maintenance and repair 3 to 3.3% of capital costs for MED and 2.7% for RO	[55]
2015	maintenance, spares and insurance 1.5% of capital costs	[58]
2016	4% of the capital cost to account for all operating costs	[108]

Brine Disposal and other externalities:

As mentioned in section 5.2.2, the brine disposal is increasingly becoming an issue that attracts more attention. In addition to the permitting and infrastructure costs associated with it, also operating costs have to be allowed for. Most of the reviewed papers did not take that into account. In 2013, Kesieme quoted 0.0015 USD/m^3 for brine disposal from MD and MED [65]. However, the reference he used for that figure was [97]. This paper actually used the value of 0.015 USD/m^3 for MD, which is one order of magnitude higher. Regarding RO brine disposal, Kesieme [65] quoted 0.04 USD/m^3. The various options for dealing with the problem and their cost implications were also analysed in 2004 by Mickley [23]. On the other hand, there is a growing trend exploring the option of recovering valuable minerals [109–114] or energy [115–118] from the brine. This way the brine disposal can pay for itself or even generate additional income.

Regarding other externalities, there are some papers that introduce the price of carbon in the overall cost calculation, ranging from 19 USD/tonne [82] to 23 USD/tonne [65]. In the paper of Nisan [82], the carbon tax was termed as an environmental externality and was obviously introduced in an effort to highlight the advantage of nuclear against coal for powering desalination. However, other externalities like the nuclear waste disposal were ignored.

In the paper of Moser in 2013 [84] a different type of externality was included for the first time – the variability of PV or wind and the impact that this has on the power system was taken into account in the cost calculations. It is a topic that attracts attention lately, but the way that this should be taken into account in cost calculations is not obvious and is a matter of debate also in papers that study the electricity market issues (see Ref. [43,119]).

Others:

In most cases the tax and legal costs were not explicitly mentioned. Insurance costs fall also under that category, however some recent papers have started taking insurance explicitly into account (see Ref. [69] and [58]). In some cases this kind of costs might not be explicitly mentioned, but was included under overhead/indirect costs (see [67,85]). However, very few of the reviewed papers did include overhead costs in their calculation.

4.4 Water production ($M_{w,t}$)

The annual water production ($M_{w,t}$) is usually calculated simply as the product of the plant capacity with the plant availability. The plant availability is estimated after taking into account the planned maintenance and unplanned downtime. There are papers, which ignored availability and just used the plant capacity for the water production figure (see Ref. [62]). However, most papers did take into account a reasonable rate between 85 and 95% for availability in conventional systems, or around 25% for systems that use PV solar energy and do not have any back-up or energy storage. It has also been pointed out that availability can be affected by interruption because of failure of auxiliary equipment and therefore proper specifications are important also for such items that have small contribution to the capital costs but could affect economics by causing reduction of the availability [120]. Table 5 provides an overview of some availability rates used in the literature.

Table 5: Overview of availability rates used in desalination cost analysis literature

Availability	**Reference**
0.96	[69]
0.95	[58,74]
0.9	[48,61,63,65,67,68,72,80,121]
0.85	[85]
0.83 (operating 20 hours a day)	[64]
0.8	[59]
0.27, 0.54 and 0.82 considered	[54]
Sensitivity, starting from 0.5 and increasing up to 0.85	[56]
0.33 (PV powered)	[89]
0.25 (PV powered)	[49,77]

All papers assumed that water is produced at full capacity when the plant is technically available to do so. In most cases this is a reasonable assumption. However, as shown by Kaldellis in 2004 [54], seasonal variations in demand have to be taken also into account where relevant. For example, in the case of the touristic Greek islands that Kaldellis studied, the demand for water can be very different between the summer and the winter periods and in some cases the desalination plants might not operate at full capacity in the winter [122]. As Kaldellis et al. showed [54], this is an important consideration, as it can increase the water costs by as much as 50% when taken into account.

4.5 Financial variables and plant lifetime

Discount rate (i)

As discussed in section 4, cost assessment methods require the use of a discount rate to account for the value of money over time and the risk or uncertainty of future cash flows. However, no single paper was found which had a discussion on how the discount rate was selected. In fact, the vast majority of the desalination cost papers just picked a value, usually between 6.5 and 10%. This is a very narrow range given that the papers reviewed cover two decades and a very wide range of projects with different technologies, locations and scales. Some of the papers [79,81,82,123] included the discount rate as one of the variables for which a sensitivity analysis was performed. However, there was still no discussion on the factors that could affect the discount rate.

In reality, the discount rate can vary widely depending on various parameters. For example in the DiaCore project [124] it was shown that even during one single year (2014) for one mature technology (on-shore wind) and within the same region (Europe) the weighted average cost of capital varies significantly between the countries, from 3.5% for Germany to 12% for Greece, with the other countries being in between (7% for the UK, 8% for Italy, 9% for Poland, 10% for Spain etc).

For defining the discount rate the following three main issues have to be determined on a project-per-project basis:

- Loan to equity ratio
- Loan interest rate and duration
- Investor expectations for return on capital.

These parameters will be affected by the risk and the general economic situation, which defines inflation and alternative opportunities for the capital. The risk has several elements to it: On the one hand it has to do with the technology; in general new technologies (like emerging desalination methods) are not proven and are perceived as riskier. Then there are the general risks that have to do with the project, like risk associated with the revenues expected from selling the water, unforeseen changes in the running costs (for example big changes in the cost of energy), changes in the rules associated with product water quality or brine disposal etc. On the other hand there are the risks associated with the location and the country, like currency risk. In the calculation of desalination costs these items have to be taken into account when defining the discount rate.

Plant lifetime (t)

All methodologies seen in section 3 for evaluating the feasibility of desalination projects require the definition of the plant lifetime *(t)*, i.e the number of years for which the future cash flows will be taken into account. Normally this is defined by the decision makers, who have to fix the period of time over which they want to calculate the return on their investment, respecting the technical constraints of the plant and its components. The residual value of the plant at the end of this period has to be taken into account.

If the calculation is not done to determine a “return on investment” but the purpose is to define an average cost of water, as plant lifetime has to be used the period of time that the plant is expected to operate without the need for a major refurbishment.

In general it is common to choose a period between 15 and 25 years. In most cases 20 years are chosen, as shown in Table 6 and the residual value or decommissioning costs are never taken into account. It is not uncommon to use 30 years, especially for more recent plants. If the technology is expected to operate without problems for such a period of time, it is good to take it into account as it will give on average lower water costs, but it is important not to forget the maintenance and equipment replacement requirements that will arise at certain periods of the 30 year lifetime. In particular for thermal plants, Sommariva et al. have shown already since 2001 [125] that 30 years can be used and that this can be extended to 40 or even 50 years if an optimised material selection takes place.

Table 6: Overview of plant lifetime used in desalination cost analysis literature

Plant Lifetime (years)	
10	[83], [7], [53]
10 for mechanical and 40 for buildings/infrastructure	[73]
Ranging from 5 to 15	[54]
15	[85] [59]
20 years for all equipment but 15 years for the boiler	[70]
20	[75] [89], [62] [64], [66] [67], [72],[68], [69], [56], [71], [126]
20 in most cases but more recent ones have 30	[48]
25	[80], [76], [63], [74],[84], [78]
25 years for the PV – not clear for desalination	[49]
30	[61], [65], [58], [77]
Between 30 and 60 for power plants – not clear for desalination	[81]

Currency

The vast majority of papers reported the costs in USD, while there are few papers that used Euro [55,70,74,87], or the local currency in the land where the case study refers to, for example Indian Ruppees [62] or Egyptian pounds [77]. What is important when making a calculation is to pay attention at the input data: In which currency they are provided and in which year they were reported originally. If the input data are in a different currency than the desired one, a conversion is necessary and it has to be done taking into account the weighted averaged exchange price published by the Central Bank for the year from which the original data comes. If these data are older, they have to be updated to current prices using the Chemical Engineering Plant Cost Index. For a good example of currency conversion and update to current prices see the paper of Wittholz et al. from 2008 [48].

Subsidies

Subsidies can make a big difference in the viability of desalination projects. Still there is very little attention to them in the papers that study the desalination costs. At a minimum, it has to be made clear if any subsidies are taken into account for the calculations, or if any form of subsidies can be expected in the future. The subsidies can be in the form of low cost or free land, low cost energy supply, loans with low (or no) interest or a capital subsidy. The only paper that clearly took a potential subsidy into account during the desalination cost assessment is Kaldellis et al. in 2004 [54], who included in the calculation the 40% capital subsidy, which was available under certain conditions at the time for development of desalination plants in Greece.

5. Discussion

When trying to define best-practices regarding the methodology, assumptions and data sources used for the calculation of desalination costs, there is a need to consider the following key question: "*What is the purpose of the cost calculation?*" Depending on how that question is answered, there are different approaches that would be recommended in terms of the methodology that should be used, the assumptions that are acceptable and the adequate procedure for identifying the most suitable values/sources for the data needed to perform the calculation.

Some of the common reasons for which calculations of desalination are performed are listed below, discussing briefly for each one the aspects of the calculation where attention should be focused.

1. Comparing configurations: For any desalination technology, there are different possible configurations or possible additional equipment that can improve certain performance characteristics of the system, as for example energy recovery devices for RO. An economic analysis can be performed to assess the impact of any proposed design options on the final cost of water (Some papers, just calculate the break-even cost of additional equipment/design modifications of established plants. See for example [64]). In this category belongs the assessment of innovative design modifications of desalination technologies (see Ref. [58,66,69,72,78,127]) or the comparison between different possible energy sources for the same desalination technology (see Ref.[63,70,82,84,128]).
2. Comparing desalination technologies: There are fundamentally different types of desalination technologies and the preferences change over time, between the different regions of the world and between the end-user categories. It is common to compare the cost of water between the

various desalination technologies [129], usually focusing in a specific part of the world and for a certain project scale, i.e small, medium or large scale (see Ref. [60,65,76,83]). Under this category comes also the evaluation of emerging technologies. Already at the very early stages of technological development, the question of the cost comes up and there are studies that try to determine the cost and compare it to the state-of-the-art (see Ref. [67,71]).

3. Comparing water supply options: When it comes to a specific site and deciding the technology, the energy supply and the details of the plant design, comparing the costs of alternative options is an important factor in the decision making process. This is similar to category *"1. Comparing configurations"*. However, for decision making regarding actual plant construction the calculation will be more detailed, especially when comparing desalination technology options between them or trying to decide between desalination and alternative water supply options (For benchmark prices of water supply see for example [86]). The cost estimation might not be only for one site, but it could include the evaluation of different sites, for the water supply of one specific area. (see Ref. [54,74,86]).
4. Comparing investment options: For someone providing the financing for a desalination project, an assessment of its economic performance is necessary. This process might involve also the comparison of different options for selecting the most viable. This is a process that will be performed by an investor, the bank or the owner of the project and is a very site specific and detailed calculation (see Ref. [59]). A similar calculation is performed for fixing the base cost for public tenders, where public authorities request offers for producing and selling water at a cost which must be below the tender base cost.

In general, the classification above starts with the type of analysis (comparing configurations) which has the lowest requirements and moves through more complicated options towards the last one (comparing investment options), which is the most demanding. For example, when the purpose of the desalination cost calculation is to compare the economic performance of two different plant designs (i.e. RO with or without energy recovery), it is acceptable to simplify the calculation, by leaving out items, such as the cost of land, which might be the same or very similar between the two options. When the comparison extends between different desalination technologies, it is still common to simplify by leaving out certain elements; however it is important to ensure that these elements would have the same impact between the two technologies compared. If the two technologies have a very different footprint, ignoring the cost of land could lead to misleading conclusions. As we move to specific sites, details become more important. Also the boundary conditions are of relevance when comparing different types of water supply options. Finally, for investment evaluation, the calculation has to be as detailed as possible, with the most critical element being the forecast of future costs and revenues.

Table 7 below provides a guideline for the elements that should be taken into account for each of the four identified desalination cost assessments purposes.

Table 7: Guidelines for elements to be taken into account in the desalination cost calculation depending on the purpose of the analysis

	Comparing configurations	**Comparing desalination technologies**	**Comparing water supply options**	**Comparing investment options**
Methodology	SCOW (see Eq. 3 or 5)	SCOW (see Eq. 3 or 5)	LCOW (see Eq. 2)	NPV or IRR (see Eq. 1)
Boundary conditions	Almost anything can be acceptable, restricted down to the core desalination plant if so wished	Should include at least all peripheral systems (like pre- and post-treatment), unless they are expected to be identical between the compared options	Should be wide enough to allow a fair comparison between alternative water supply options, especially in cases where centralised and decentralised options are compared	Should be restricted to the level that will be under the direct responsibility of the plant investor/owner
Hardware costs	Literature data can be used (adapted to current prices[1]), but a more accurate estimation for the hardware costs of the innovative part must be provided	The hardware costs of the technologies to be compared, must be assessed with similar assumptions[2] (prices to refer to the same year, region, scale, currency etc)	Normally real costs expected for the specific location and plants should be used – first screening of options can be based on literature data (adapted to current prices)	Real costs, quoted for the specific project should be used
Engineering / Civil / Project Management	Can be ignored	Can be ignored, or can be added as a fixed percentage of the hardware costs (usually between 20 and 30%)	Should be taken into account – can be as a fixed percentage of the hardware costs (usually between 20 and 30%)	Detailed estimation of the cost should be taken into account
Permitting / Cost of land	Can be ignored	Can be ignored, unless the technologies compared have significantly different	Should be taken into account – an assessment or inclusion to the indirect costs could be	Real cost estimations should be used

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[1] Chemical engineering plant cost index

[2] When a technology at the very early stages of development is compared with a state-of-the-art one, it makes sense to use for the emerging technology assumed costs for when the technology is at least on a pilot scale, if not market ready – however, if such an assumption is made it has to be very clear

<table>
<tr><td></td><td></td><td>footprint</td><td>acceptable</td><td></td></tr>
<tr><td>Energy costs</td><td>Should be taken into account – especially in case the design modification affects energy consumption</td><td colspan="2">Should be taken into account with realistic assumptions about future energy costs – a sensitivity analysis could be useful to show impact of energy cost variations in the future</td><td>Data from the agreement with the energy supplier should be used where relevant – otherwise detailed forecast should be procured and sensitivity analysis performed to assess risk</td></tr>
<tr><td>Chemicals / Consumables</td><td rowspan="5">Can be ignored or included as a fixed rate of operational costs unless the design modification affects specifically one of these elements.</td><td colspan="2">Should be taken into account, based on literature data if detailed assessment is not easy</td><td rowspan="3">Detailed assessment of the expected costs in these categories should be included</td></tr>
<tr><td>Labour</td><td>Cab be ignored, unless the technologies compared are expected to have significantly different labour requirements</td><td>Should be taken into account, based on literature data if detailed assessment is not easy</td></tr>
<tr><td>Maintenance</td><td colspan="2">Should be taken into account, based on literature data if detailed assessment is not easy</td></tr>
<tr><td>Brine disposal</td><td>Can be ignored</td><td>Should be taken into account, if any</td><td>Should be taken into account, if any</td></tr>
<tr><td>Externalities</td><td>Can be ignored unless the technologies compared are expected to have significantly different results</td><td>Should be taken into account</td><td>Externalities can be ignored in the cost calculation, but public acceptance must be ensured</td></tr>
<tr><td>Tax / Legal / Insurance</td><td>Can be ignored</td><td>Can be ignored</td><td>Can be ignored or added as a small fixed percentage of the operational costs</td><td>Should be taken into account</td></tr>
</table>

Availability	A standard figure can be used (normally between 85% to 95%). A more careful assessment of the availability should be carried out if there are specific situations like large seasonal variability in demand, or intermittent power supply			The availability has to be calculated based on maintenance requirements and other local conditions
Discount rate	A standard figure can be used (usually around 0.08 – depending on the country and the general economic situation in the year the analysis is carried out)	A standard figure can be used (around 0.08). If the technologies compared are at very different stages of development, sensitivity analysis can be used to show the impact higher discount rates have on the new technologies with higher perceived risks	A standard figure can be used (usually around 0.08 – depending on the country and the general economic situation in the year the analysis is carried out).	The discount rate has to be calculated, based on the risk and the financing structures expected for the project – alternatively the IRR metric can be used
Plant lifetime	A standard figure can be used (usually 20 years)	A standard figure can be used (usually 20 years), unless differences are expected between the technologies compared	A standard figure can be used (usually 20 years)	It has to be defined, depending on the water sale agreements, loan duration and investor expectations. The residual value (if any) has to be taken into account as well.
Subsidies	Subsidies should be taken into account, if any			

6. Conclusions

In the current work, all available scientific literature that has been published over the past 20 years on assessing the costs associated with water desalination was analysed. The main conclusions are summarized below:

- In order to assess the cost of desalination, a suitable equation has to be used. In general most papers use suitable equations.
- A clear definition of the boundary conditions is necessary, defining the infrastructure that is assumed as a given (like general infrastructure, distribution of the water to the end user etc.) and what is included into the cost of the desalinated water (water intake, post-treatment and storage)
- Certain elements (like EPC, permitting, land costs, taxes, insurance etc) are very often ignored when calculating the costs of desalination. This can be acceptable, depending on the purpose of the calculation. However, it is always important to clearly acknowledge and explain the costs that are ignored, so that the final result is assessed at the correct context.
- The element that defines to the larger extent the accuracy and relevance of the cost assessment is the quality of the data/estimated values used for the key variables:
    - Regarding the hardware costs, when using assumptions based on other projects, it is crucial to account for the year of construction, the scale of the plant, the location and the appropriate currency conversion where relevant.
    - Regarding the operating costs, it is important to try and foresee the variations expected during the lifetime of the system. A sensitivity analysis can be very helpful to assess the impact on the water cost in case where operating expenses develop in a different way than expected.
    - On the financial parameters, the discount rate has to reflect the risk associated with the technology and with the wider economic and political situation at the project's location.

Overall, it was concluded that the methodology, data and assumptions that are suitable on each occasion depend on the purpose of the cost calculation. A table was developed to give guidance to this respect. Irrespective of the calculation purpose though, when using a cost calculation for making decisions and drawing general conclusions, it is important to take into account the assumptions that were made during the calculation and understand the impact it would have on the result if the real conditions were different from the assumed ones.

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Nomenclature

C: costs per year
$C_{E,t}$: Energy related cost for year t
$E_{el,t}$: the amount of electrical energy used by the plant in year t
$E_{th,t}$: the amount of thermal energy used by the plant in year t
i: discount rate
I_0: initial capital investment
M_w*: amount of water produced per year*
$P_{el,t}$: the cost of the unit of electrical energy in year t
$P_{th,t}$ the cost of the unit of thermal energy in year t
r: annual escalation rate for running costs
R: revenues per year
α: amortisation factor

Subscripts
t: value in year t

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