Life Cycle Assessment for Desalination: A Review on Methodology Feasibility and Reliability

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Abstract: As concerns of natural resource depletion and environmental degradation caused by desalination increase, research studies of the environmental sustainability of desalination are growing in importance. Life Cycle Assessment (LCA) is an ISO standardized method and is widely applied to evaluate the environmental performance of desalination. This study reviews more than 30 desalination LCA studies since 2000s and identifies two major issues in need of improvement. The first is feasibility, covering three elements that support the implementation of the LCA to desalination, including accounting methods, supporting databases, and life cycle impact assessment approaches. The second is reliability, addressing three essential aspects that drive uncertainty in results, including the incompleteness of the system boundary, the unrepresentativeness of the database, and the omission of uncertainty analysis. This work can serve as a preliminary LCA reference for desalination specialists, but will also strengthen LCA as an effective method to evaluate the environment footprint of desalination alternatives.

Keywords: environmental impacts; sustainability; life cycle impact assessment; system boundary; uncertainty analysis; brine disposal

Nomenclature

CDI	Capacitance deionization
ED	Electrodialysis
EIO-LCA	Economic-input output life cycle assessment
ELCD	European reference Life Cycle Database
FEI	Freshwater ecosystem impact
FO	Forward osmosis
FWI	Freshwater withdrawal impact
GH	Gas hydrates
HDH	Freezing, humidification-dehumidification
LCA	Life cycle assessment
LCI	Life cycle inventory
LCIA	Life cycle impact assessment
MBR	Membrane bioreactor
MED	Multiple-effect distillation
MD	Membrane distillation
MIET	Missing inventory estimation tool
MSF	Multi-stage flash
RO	Reverse osmosis
VC	Vapor compression
WEST	Water-energy sustainability tool

1. Introduction

1.1 Desalination and associated challenges

There are decades of successful implementations that show desalination technology can provide supplementary or even main water sources. It is estimated that the capital expenditures for new desalination plants will exceed US$17 billion by the year 2016 (Subramani *et al.* 2011). The desalination process can be roughly categorized into two major types: thermal and membrane separation (Van der Bruggen and Vandecasteele 2002, Subramani *et al.* 2011). The thermal process mimics the natural water cycle of evaporation and condensation, and produces output water with very low salt concentration (Van der Bruggen and Vandecasteele 2002). The membrane separation process works by prohibiting or permitting the passage of specific salts ions. Multi-stage flash (MSF), multiple-effect distillation (MED), and reverse osmosis (RO) are among the most popular technologies in thermal and membrane desalination. There are also other emerging technologies such as vapor compression (VC), electrodialysis (ED), forward osmosis (FO), membrane distillation (MD), capacitance deionization (CDI), gas hydrates (GH), freezing, humidification-dehumidification (HDH), solar stills, *etc.* (Mezher *et al.* 2010).

While desalination technologies are well developed, there are also some challenges that hinder broader implementation. Energy demand associated with removing salts and dissolved contaminants is far greater than treatment of freshwater by conventional water treatment processes. Desalination technologies are also subject to poor public perception related to the discharge of concentrated brine and chemical residuals (Miri and Chouikhi 2005, Sadhwani *et al.* 2005, Abdul-Wahab 2007) as well as the disposal of used membranes (Van der Bruggen and Vandecasteele 2002, Sadhwani *et al.* 2005).

1.2 Life Cycle Assessment (LCA) definition and principles

Concerns of natural resource depletion and environmental degradation caused by desalination are motivating, the industry to investigate solutions to minimize these adverse impacts. Thus, exploring opportunities to move beyond compliance using pollution prevention strategies and environmental management systems are warranted to improve desalination technologies.

One useful tool to evaluate environmental impacts is Life Cycle Assessment (LCA). According to the ISO 14040 (ISO 2006a), LCA is a “cradle-to-grave” approach for assessing the environmental impacts of products. Fig.1 illustrates LCA’s “cradle-to-grave” concept applied to desalination. The potential environmental burdens of desalination are attributed to the production of potable or non-potable water, which leads to the consumption of natural resources and discharge of pollutant emissions through infrastructure construction, energy generation, chemical production, membrane fabrication, and waste management.

As defined in the ISO 14040 and ISO14044 standards (ISO 2006a, b), LCA has four phases (Fig. 1). The “goal and scope definition” attempts to set the function unit and system boundary. The function unit describes the primary purpose of a system and enables different systems to be treated as functionally equivalent (Guinee *et al.* 2002). In desalination LCA studies, the functional unit is often defined as 1 m^3 of produced water. Boundary selection determines the processes and activities included in an LCA study. The determination of system boundary is often affected by factors such as the purpose of the study, geographic area affected, relevant time horizon, *etc.* (Reap *et al.* 2008a). “Life cycle inventory” (LCI) analysis is a methodology for estimating the consumption of resources, the quantities of waste flows and emissions caused by, or otherwise attributable to, a product's life cycle (Rebitzer *et al.* 2004). “Life cycle impact assessment” (LCIA) usually includes characterization, normalization, and weighting. The characterization is a compulsory step, while the latter two are considered optional. The characterization step evaluates impact in terms of several impact categories (such as climate change, toxicological stress, water use, land use, *etc.*) and, in some cases, in an aggregated way (such as years of human life lost due

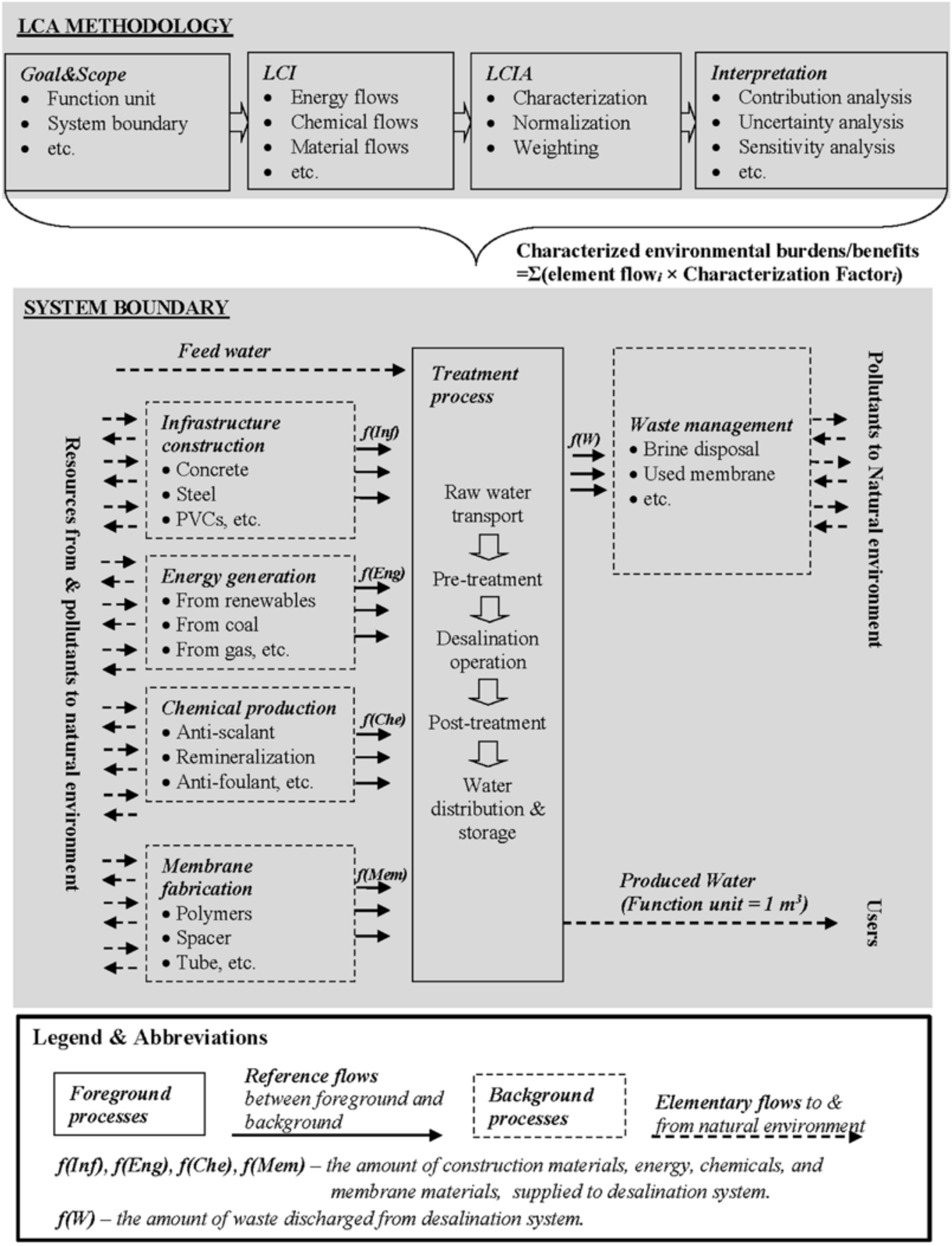

Fig. 1 – LCA methodology used to assess the potential environmental impacts of desalination

to climate change, carcinogenic effects, *etc.*) (Rebitzer *et al.* 2004). After the impact assessment, the "interpretation" guides decision-makers by providing a better understanding of uncertainties and assumptions. ISO 14044 (ISO 2006b) recommends several checks to determine the level of confidence in the final results, including contribution analysis, uncertainty analysis, sensitivity analysis, *etc.*

1.3. Overview of prior studies

The studies included in this review are listed in Table 1. These studies show that life cycle thinking facilitate comparison between desalination technologies. Morton *et al.* (1997) qualitatively examine two seawater desalination plants in Middle East, and identify that RO discharged less marine and atmospheric pollutants than MSF distillation. Since the standardization of the LCA methodology, several studies in the literature quantitatively estimate the environmental impacts from desalination plants. Raluy *et al.* (2005b, 2006) compare the environmental loads associated with MSF, MED, and RO. The results show that the overall environmental burden associated with RO is typically one-order of magnitude lower than that with thermal process without taking advantage of the residual heat. Desalination technologies are also compared with other water treatment alternatives, such as ion exchange (Ras and von Blottnitz 2012), ozonation coupled with microfiltration (Tangsubkul *et al.* 2005), *etc.* The results emphasize that desalination technologies require more energy, although they can achieve comparable or improvements in effluent quality.

As RO technology is generally considered more environmental-friendly and commercially-competitive, more research efforts exist to investigate its energy consumption. Raluy and her colleagues (2004, 2005b, 2006) confirm that energy plays a key role in RO desalination since more than 80% of the environmental impact is associated with the electricity consumption of the process.

Table 1 – Chronological review of LCA studies of desalination

Ref	Goal & scope	LCA tool	Supporting database	LCIA method/ indicator	Reference flows in desal system	Geographical coverage	Tiers of uncertainty analysis
Del Borghi *et al.* (2013)	Comparison of potable water supply systems in 2009 & 2010	NR	NR	EPD, energy use, water use	f(Eng), f(Inf), f(Che), f(Mem)	Italy	Tier 0
Godskesen *et al.* (2013)	Comparison of water supply alternatives	GaBi	PE data	EDIP 1997, water usage	f(Eng), f(Inf), f(Che), f(Mem)	Denmark	Tier 2
Amores *et al.* (2013)	Comparison of different urban water cycles	NR	Ecoinvent	CML, water usage	f(Eng), f(Inf), f(Che), f(Mem), f(Bri)	Spain	Tier 0
Zhou *et al.* (2013)	Environmental impacts of brine disposal	Manual	USEtox, Eolia dataset	Eco-toxicity impact	f(Bri)	NA	Tier 2 & 3
Norwood and Kammen (2012)	Environmental impacts of desalination + renewable energies	EIO-LCA	US EIO data	GWP, Energy usage	f(Eng), f(Inf)	Unite States	Tier 0
Lawler *et al.* (2012)	Comparison of membrane disposal alternatives	Manual	NR	CO_2	f(Mem),	Australia	Tier 0
Ras and von Blottnitz (2012)	Comparison of RO and ion exchange	Manual	NR	GWP, energy use	f(Eng), f(Che), f(Mem)	South Africa	Tier 0
Tarnacki *et al.* (2012)	Comparison of RO & Menstill	NR	Ecoinvent	CML	f(Eng), f(Inf), f(Che), f(Mem)	European countries	Tier 0
(Salcedo *et al.* (2012), Antipova *et al.* (2013))	Environmental impacts of desalination + renewable energies	Manual	Ecoinvent	CO_2	f(Eng)	Spain	Tier 0
Hancock *et al.* (2012)	Comparison of *SWRO & FO+ODN*	SimaPro	Ecoinvent	CML	f(Eng), f(Che), f(Mem)	NA	Tier 2
Jijakli *et al.* (2012)	Comparison of water supply alternatives	SimaPro	Ecoinvent	Eco-indicator99	f(Eng), f(Inf), f(Che), f(Mem)	UAE	Tier 0
Zhou *et al.* (2011b)	Comparison of LCIA approaches in BWRO applications	SimaPro	Ecoinvent	CML, TRACI	f(Eng), f(Inf), f(Che), f(Mem)	Spain	Tier 3
Zhou *et al.* (2011a)	Comparison of energy production alternatives in BWRO applications	SimaPro	Local data, Ecoinvent	CML	f(Eng), f(Inf), f(Che), f(Mem)	Singapore, United States, & Spain	Tier 2 & 3
Pasqualino *et al.* (2010) Meneses *et al.* (2010)	Comparison of different brine disposal scenarios	SiSOSTAQUA	Ecoinvent	CML, water use, energy use	f(Eng), f(Inf), f(Mem), f(Bri)	Spain	Tier 0
Beery *et al.* (2010a, 2010b, 2011)	Comparison of pre-treatment technologies for SWRO	GaBi	PE data	CO_2	f(Eng), f(Inf), f(Che), f(Mem)	NR	Tier 0
Munoz *et al.* (2010)	Comparison of water supply systems	SimaPro	Ecoinvent	GWP, HTP, POCP, AP, energy demand	f(Eng), f(Inf), f(Che), f(Mem)	Spain	Tier 2 & 3

Abbreviations: NR - not reported; NA – not applicable; f(Eng) – energy flows; f(Inf) – construction material flows; f(Che) – chemical flows; f(Mem) – membrane material flows; f(Bri) – Brine flows; the definition of different Tiers – Section 3.3; the detailed information about f(Che) and f(Mem) – Table 2 and 3

Table 1 – Chronological review of LCA studies of desalination (continued)

Ref	Goal & scope	LCA tool	Supporting database	LCIA method/ indicator	Reference flows in desal system	Geographical coverage	Tiers of uncertainty analysis
Frutos *et al.* (2009)	Environmental impacts of SWRO	Manual	NR	CO_2	f(Eng), f(Inf), f(Che)	NR	Tier 0
Biswas (2009)	Comparison of SWRO+fossil energy & SWRO+renewable energies	Manual	Local data, Ecoinvent	CO_2	f(Eng), f(Inf), f(Che), f(Mem)	Australia	Tier 0
Lyons *et al.* (2009)	Comparison of water supply systems	SimaPro	Ecoinvent	Eco-indicator99	f(Eng), f(Inf), f(Che)	United States	Tier 0
Vince *et al.* (2009)	Environmental impacts of SWRO	Eolia Potable Water	Ecoinvent	Impact 2002+	f(Eng), f(Inf), f(Che), f(Mem), f(Bri)	France	Tier 0
Vince *et al.* (2008)	Comparison of water supply systems	NR	PE data, Ecoinvent	Impact 2002+	f(Eng), f(Inf), f(Che), f(Mem)	European countries	Tier 0
Munoz and Fernandez-Alba (2008)	Comparison of BWRO & SWRO	SimaPro	Ecoinvent	Partial CML, energy demand, salinity	f(Eng), f(Inf), f(Che), f(Mem)	Spain	Tier 3
Stokes and Horvath (2006)	Comparison of water supply systems	WEST	US EIO-LCA data	GWP, SO_X, NO_X, PM, VOC, CO	f(Eng), f(Inf), f(Che), f(Mem)	United States	Tier 2
Raluy *et al.* (2005a, 2006)	Comparison of RO, MSF, & MED,	SimaPro	Ecoinvent	CML Eco-points97 Eco-indicator99	f(Eng), f(Che), f(Mem)	Spain	Tier 0
Raluy *et al.* (2005c)	Comparison of water supply alternatives	SimaPro	Ecoinvent	CML Eco-points97 Eco-indicator99	f(Eng), f(Inf), f(Che), f(Mem)	Spain	Tier 0
Raluy *et al.* (2005a)	Environmental impacts of RO, MSF, & MED integrate with renewable energies	SimaPro	Ecoinvent	CML Eco-points97 Eco-indicator99	f(Eng), f(Inf), f(Che), f(Mem)	Spain	Tier 0
Raluy *et al.* (2004)	Comparison of RO, MSF, & MED, integrate with different energy production systems	SimaPro	Ecoinvent	CML Eco-points97 Eco-indicator99	f(Eng), f(Che), f(Mem)	Spain	Tier 0
Tangsubkul *et al.* (2005)	Comparison of water recycling technologies	Hybrid tool	US EIO-LCA data, local data	Partial CML salinisation Potential for soil	f(Eng), f(Inf), f(Che), f(Mem)	Australia	Tier 2
Lundie *et al.* (2005)	Comparison of metropolitan water services	GaBi	PE data	Partial CML, energy use, water use	f(Eng), f(Inf), f(Che)	Australia	Tier 2

Abbreviations: NR – not reported; NA – not applicable; f(Eng) – energy flows; f(Inf) – construction material flows; f(Che) – chemical flows; f(Mem) – membrane material flows; f(Bri) – Brine flows, the definition of different Tiers – Section 3.3; the detailed information about f(Che) and f(Mem) – Table 2 and 3

Other studies carried out by Frutos *et al.* (2009), Vince *et al.* (2009), and Zhou *et al.* (2011a), lead to similar conclusions regarding the dominant role of electricity consumption in LCA of RO desalination.

Researchers also apply LCA to evaluate different urban water cycles. Lundie *et al.* (2004, 2005), Stokes and Horvath (2006), Raluy *et al.* (2005c), Vince *et al.* (2008), Lyons *et al.* (2009), Munoz *et al.* (2010), Jijakli *et al.* (2012), Amores *et al.* (2013), Godskesen *et al.* (2013), Del Borghi *et al.* (2013) report separate efforts to compare local desalination with alternative water supply systems, such as wastewater reclamation, fresh water transfer, *etc.* Results indicate that the long distances for surface water transport require significant amounts of energy, and the associated environmental impacts can be comparable to that of the RO desalination. Compared to wastewater reclamation, desalination is suitable to relieve the water stress in potable applications which require high water quality, but might not be appropriate for non-potable purposes due to its high energy consumption.

Other than comparing different technologies and urban water cycles, LCA efforts exist that explore the solutions to relieve the environmental burdens of desalination. Since most environmental impacts are highly associated with the energy demand of desalination, any reduction in process energy usage can be beneficial. Reducing the salinity of feed water (Munoz and Fernandez-Alba 2008), employing effective pretreatment (Beery *et al.* 2010a, 2010b, 2011), and engaging new membrane technology (Hancock *et al.* 2012, Tarnacki *et al.* 2012) are all promising opportunities that may reduce the overall environmental impacts of desalination. Another method is to reduce the heavy reliance on fossil fuel energy which can improve the environmental performance of desalination indirectly. Some desalination LCA studies demonstrate that moving towards cleaner energy sources, such as natural gas (Zhou *et al.* 2011a), and renewable energies (Raluy *et al.* 2005a, Biswas 2009, Jijakli *et al.* 2012, Norwood and

Kammen 2012, Salcedo *et al.* 2012) is advantageous. Several studies explore potential improvements of overall environmental performance of desalination by addressing brine disposal (Meneses *et al.* 2010, Zhou *et al.* 2013) and used membranes (Lawler *et al.* 2012). However, these studies are at the stage of method development or scenario construction and can be further improved.

There is great interest in the adoption of LCA for evaluating the environmental impact of desalination. However, the LCA methodology itself has several technical issues that are not yet completely resolved (Reap *et al.* 2008a, b). Previous studies generally engage LCA for desalination without further discussing the potential biases inherent to the studies' respective methodologies. This review serves as an introductory LCA reference for water treatment specialists who are interested in quantifying and addressing the environmental burdens associated with desalination. This review focuses on two pressing concerns of which desalination researchers should be aware of, namely the feasibility and reliability. The former (discussed in Section 2) covers three elements used to support the implementation of LCA, including accounting methods, supporting databases, and life cycle impact assessment approaches; the latter (discussed in Section 3) clarifies three essential aspects that drive the uncertainty of the results, including the incompleteness of the system boundary, the unrepresentativeness of the database, and the omission of uncertainty analysis. Section 4 concludes this review by providing recommendations. We hope that, by articulating the feasibility and reliability concerns, this work can help improve LCA practices in desalination and other water industries.

2. Feasibility of applying LCA to desalination

In this work, feasibility refers to the approach applied to make all acquired LCA knowledge easily available in a usable way for desalination studies. It refers to three elements, including accounting methods, supporting databases, and life cycle impact assessment approaches.

2.1 Accounting methods

As summarized in Table 1, a majority of desalination LCA studies are carried out with commercial software packages. SimaPro (by PRé Consultants) and GaBi (by PE International) are the two most popular choices. Other commercial packages include SiSOSTAQUA used by Pasqualino *et al.* (2010) and Eolia used by Vince *et al.* (2009). All software packages mentioned above design their accounting methods based primarily on the process model. The LCA practitioners need to itemize the physical quantities of energy and material inputs as well as environmental outputs for each stage of the life-cycle (Huang et al. 2009). Instead of using commercial software, Frutos *et al.* (2009) and Beery *et al.* (2011) built their own simple speadsheets. Both studies also adpoted process model to quantify the impacts but they only focused on the carbon dioxide emission and its corresponded Global Warming Potential.

Several studies take the hybrid method that combines the process model with the economic input-output LCA (EIO-LCA) model developed by Carnegie Mellon University Green Design Institute (2014). The EIO-LCA model augments a matrix of economic data with another matrix of environmental discharges to calculate economy-wide environmental impacts. Unlike the physical inputs (*e.g.* mass of material consumed) used in process model, the inputs to EIO-LCA model are expenditures in related economic sectors. Two examples include studies carried by Tangsubkul *et al.* (2005) and Stokes and Horvath (2006). In both studies, the environmental impacts associated with the construction materials are estimated using EIO-LCA via the dollar spent, while the impacts of other processes in desalination were accounted by process model.

Software packages remain popular, possibly a result of their direct integration with supporting databases and impact assessment approaches. However, users should be cautious of the underlying accounting methods. The process model implies a certain degree of cutoff error when the detailed reference flow is not readily available, while the EIO-LCA model introduces significant aggregation uncertainties related to the varying prices of products and coarse graining of processes (Huang *et al.* 2009, Lee and Ma 2013). In desalination applications, many previous studies engage the process model as the backbone of an applied accounting method. EIO-LCA only serve as a supplementary model since it is based on national sectoral data and thus is relatively more difficult to capture technique-specific/site-specific details.

2.2 Supporting databases

As indicated in Fig. 1, all the desalination processes can be categorized into either the foreground or the background. In this review, the foreground processes includes the desalination operation steps, while the background processes refers to steps more remote to the desalination operation, including infrastructure construction, energy generation, chemical production, membrane fabrication, and waste management. The connections between foreground and background processes are the reference flows, which refer to the amount of energy and material supplied to, as well as the amount of waste disposed from, desalination treatment steps. The connections between the natural environment and the desalination system are the elementary flows, which stand for the amount the natural resources extracted from, and environmental emissions discharged to, the natural environment.

Since LCA attempts to derive all foreground processes from the initial resources extraction to waste disposal (cradle to grave), it can quickly spiral into an overwhelming number of elementary flows. Even for a very simple chemical for membrane cleaning, sulfuric acid (H_2SO_4) as an example, over 600 natural resource inputs and emission outputs are connected with its production.

The databases incorporated in a software package serve as an importance data source for the background processes. As discussed in Section 2.1, SimaPro and Gabi are two of the most popular software packages, likely due in part to their wide range of included databases. The latest version of SimaPro (SimaPro 8) includes eight databases into its libraries, such as Ecoinvent v3 LCI database, European Life Cycle Data, Swiss Input Output, *etc.* GaBi software is generally bundled with a data package called PE Professional Database, which includes data from PE International, European reference Life Cycle Database (ELCD), and Plastics Europe. On top of the PE Professional Database, GaBi users can also pay for additional databases such as PE sector-specific data, Ecoinvent, and US LCI.

As summarized in Table 1, most previous studies use Ecoinvent or PE Professional databases. Both databases integrate several thousand industrial datasets in the areas of energy supply, chemicals, construction materials, polymer materials, waste treatment, *etc.* However, Gabi users have to engage several additional databases for desalination LCA studies, such as *Extensive Database – construction materials* for infrastructure construction, *Extensive Database – energy* for non-renewable and renewable energy generation, *Extensive Database – organic* and *inorganic intermediates* for chemical production, *Extensive Database – plastics* and *Extensive Database – coatings* for membrane fabrication, and *Extensive Database – end of live* for waste management. It is worthy to note that the representativeness of database is one of the critical factors on reliability of LCA results. The details are elaborated in Section 3.2.

2.3 Life cycle impact assessment approaches

Life cycle assessment practitioners generally use the predefined impact assessment approaches provided in the LCA software package. As indicated in Table 1, many desalination LCA practices use the approach proposed by the Institute of Environmental Science of Leiden University (CML). This is a result of the approach being a set of baseline characterization methods published in the Handbook on LCA (Guinee *et al.* 2002) and its implementation in the commercial software packages since the early 2000s. Practitioners might choose other predefined approaches, such as Eco Indicator 99, Eco points 97, IMPACT 2002+, and TRACI, depending on the purpose and geographical coverage of the research. Although the CML and other predefined approaches are increasing in sophistication and are widely used in various LCA efforts, they are still not able to capture certain environmental impacts related to desalination. This review identifies two important issues that, to date, are not properly integrated into previous LCA studies of desalination: 1) the impact assessment of brine disposal and 2) the impact assessment of freshwater savings and consumption.

(1) The impact assessment of brine disposal

There is a growing interest in understanding the aquatic eco-toxic impact of brine disposal. Many laboratory based studies (Latorre 2005, Sanchez-Lizaso *et al.* 2008, Dupavillon and Gillanders 2009), field-based experiments (Latorre 2005, Sanchez-Lizaso *et al.* 2008), and ecological monitoring studies (Fernandez-Torquemada *et al.* 2005, Gacia *et al.* 2007, Ruso *et al.* 2007, Sanchez-Lizaso *et al.* 2008) report similar findings that indicate brine disposal is a major cause of aquatic eco-toxic impact. It is also recognized that credible and reliable impact estimates for brine disposal are needed, but many early desalination LCA studies simplify the assessment by assuming that the desalination brine is fully diluted before discharge and poses negligible impacts to the aquatic eco-system (Table 1). This assumption likely results in an underestimation of the aquatic eco-toxicity of brine disposal. While recent studies are beginning to address this challenge, further research is warranted given the concerns associated with brine disposal and the limitation of current aquatic eco-toxic assessment approaches, including chemical specific, whole effluent, and group-by-group approaches.

The chemical specific approach calculates the total effluent impact as the sum of the individual chemical impacts based on the aquatic eco-toxic potential of each elementary chemical present in the effluent. This approach is more suitable for assessing effluents containing limited numbers of contaminants that have well-defined ecotoxicological properties. Desalination brine, unfortunately, contains tens of thousands of chemicals and by-products. Assessing ecotoxicity for each compound requires extensive time and resources, therefore, some researchers choose to focus on specific compounds in the brine. In one of the first LCA studies addressing desalination brine, Meneses *et al.* (2010) include six salt ions and two metals in his study, while noting that the limited focus may underestimate the overall impacts. Another challenge for the chemical specific approach is that it is unable to capture the impact of salinity, chlorine, and other inorganic chemicals because their ecotoxicologial properties are not readily available.

Considering the limitations of the chemical specific approach, Vince *et al.* (2009) introduced the whole effluent concept to estimate the overall aquatic eco-toxic impact of brine disposal. Compared to the chemical specific approach, the whole effluent approach eliminates the need to characterize the composition of the effluent, but by providing a measure of the combined effects of all the components in a complex effluent (Gotvajn and Zagorc-Koncan 1998). Although the whole effluent approach resolves some limitations discussed regarding the chemical specific approach, it provides only a one-time estimation of the ecotoxicologial property of the concentrate; this snapshot ecotoxicity may not be representative with increasing time-scale.

Zhou *et al.* (2013) developed the group-by-group approach to quantify the impact of complex and variable seawater desalination concentrates. This approach combines the merits of the two common approaches discussed above. It not only reduces the data requirement, but also provides a more comprehensive coverage. However, the current group-by-group approach is supported by freshwater eco-toxic characterization factors in USEtox database. Its application to ocean disposal, land disposal, and other disposal alternatives is still uncertain due to lack of the eco-toxicological data in marine and terrestrial compartment.

(2) The impact assessment of freshwater savings and consumption

Compared to alternative water supply systems, desalination has the advantage of reducing freshwater withdrawal because it is able to replenish water reserves and make use of previously inaccessible water resources (*e.g.* seawater, brackish water, wastewater, *etc.*). As most predefined LCIA approaches haven't included the impacts associated with freshwater usage into their scope, some desalination LCA studies employ additional impact assessment indicators to supplement the predefined approaches.

Lundie *et al.* (2004, 2005), Meneses *et al.* (2010) Pasqualino *et al.* (2010), and Del Borghi *et al.* (2013) use the amount of freshwater consumed to represent the benefit of water savings achieved through desalination. Although this approach is relatively simple to implement, it may not adequately represent the true impacts of freshwater savings. For instance, 1 m^3 of water produced from a desalination plant should carry more benefits for arid areas than for freshwater abundant regions.

Munoz *et al.* (2010) and Amores *et al.* (2013) address freshwater savings through a freshwater ecosystem impact (FEI) metric. This approach considers the water abstractions in both the foreground and background, as well as the lost precipitation caused by land use changes. The potential impact in a water scarce region is reflected as the change in freshwater availability for ecosystem. Although the FEI approach provides additional details about the level of stress upon the local water resources, its application is restricted by the inventory data availability. A typical example is the impact from groundwater abstraction for desalination. The challenge is that most of the groundwater reserves are seldom quantified in terms of their relative abundance compared to their potential usage.

Godskesen *et al.* (2013) employ another approach, the freshwater withdrawal impact (FWI). Similar to FEI, the FWI addresses the impact of freshwater withdrawal at a local level, but is more, readily integrated into LCIA. The FWI score can be calculated via multiplying the volume of freshwater withdrawn by the characterization factor, which is consistent with the characterization equation shown in Fig. 1.

Although not yet incorporated in desalination LCA practices, several studies attempt to improve evaluation of impacts associated with freshwater usage (Boulay *et al.* 2011, Motoshita *et al.* 2011, Zelm *et al.* 2011). Compared to the approaches discussed above, these efforts consider not only the stress on water resource availability, but also include impacts from reductions in water quality. These efforts provided an important basis for further research direction; however, parallel efforts specifically addressing inclusion in desalination LCA studies are similarly warranted.

3. Reliability of LCA results for desalination

Several studies (Pennington *et al.* 2004, Rebitzer *et al.* 2004, Reap *et al.* 2008a, b) raise the concerns about the reliability of LCA results. This section attempts to resolve doubts associated with underlying, but essential aspects of LCA, including the incompleteness of the system boundary, the unrepresentativeness of the database, and the omission of uncertainty analysis.

3.1 The incompleteness of the system boundary

In principle, an LCA should track all elementary inputs and outputs in the life cycle. However, LCA studies are usually unable to include such a comprehensive boundary due to time and resource constraints, even with the help of available databases (Section 2.2). In order to reduce data requirements, it is common for LCA users to ignore a number of reference flows between background and foreground. The ideal decision making metrics regarding inclusion or exclusion of a particular reference flow should be based on its contributions to different impact categories. In actual practice, many decisions are unable to fulfill this requirement, especially for those reference flows for which contributions are poorly documented.

All studies included in this review choose to incorporate the specific energy demand of desalination into the system boundary because of its considerable impacts, while only a limited number considers the burdens resulting from brine disposal due to the limitation of current impact assessment approaches (Section 2.3). The desalination LCA studies ignore a number of material and energy flows from infrastructure construction, chemical production, and membrane fabrication, however, justifications for these choices are not presented. The justification of the subjective boundary definition with regard to these three background processes and the potential influence on reliability is investigated herein.

(1) Infrastructure construction

The comprehensive aspects considered in the infrastructure construction include those related to the construction materials and energy required for building a desalination system. However, due to the difficulties in acquiring data detailing the complete construction process, most applications only consider the production of widely used construction materials, such as concrete, cement, steel, PVC, *etc.* Raluy *et al.* (2004, 2005b, 2006) indicate that the infrastructure construction contributes less than 10% of overall environmental impacts. Other studies carried out by Vince *et.al.* (2009), Lyons *et.al.* (2009), Munoz *et.al.* (2008), and Stokes *et.al.* (2006) lead to similar results regarding the insignificant role of infrastructure construction.

Some of the studies in this review exercise did not include the infrastructure phase (Vince *et al.* 2008, Biswas 2009, Meneses *et al.* 2010, Beery *et al.* 2010a, Hancock *et al.* 2012, Salcedo *et al.* 2012). The exclusion was made based on two justifications: their minor contribution identified by other previous studies and the small mass of construction materials resulting from the long time span of the infrastructure.

The exclusion of the infrastructure phase from the LCA is challenged by several other studies. Tangsubkul *et al.* (2005) and Frutos *et al.* (2009) assess the environmental performance of an RO process coupled with pre-treatment. The results indicate that infrastructure construction contributes from one-third to one-half of total Global Warming Potential (GWP). Jijakli *et al.* (2012) compare LCAs of local photovoltaic-powered RO, local solar still, and distant RO. Results indicate that concrete, stainless steel, and PVC are important contributors to CO_2 emissions. The impacts from the infrastructure construction stand out mainly due to two reasons: 1) the system boundary is extended to include auxiliary facilities, such as infrastructure of pre-treatment (Tangsubkul *et al.* 2005, Frutos *et al.* 2009) and supplementary renewable energy systems (Jijakli *et al.* 2012) and 2) the impacts associated with other phases is reduced due to renewable energy (Jijakli *et al.* 2012) and low salinity in raw water (Tangsubkul *et al.* 2005).

(2) Chemical production

The comprehensive system boundary of the chemical phase should include the production and transportation of all chemicals required for operating the desalination system. Similar to the discussion in infrastructure construction, previous studies generally consider only widely used chemicals, such as coagulant, anti-scalant, and anti-foulant used in pre-treatment, alkaline compounds, acidic chemicals and polymers used to clean desalination modules, remineralisation chemicals, pH adjustment agents, and disinfectant used in post-treatment , *etc.* (Table 2).

Many studies reason that the overall contribution from chemical production is insignificant. However, concluding that chemical production can be safely ignored may be premature. Chemical usage and energy consumption vary according to the specific operation and maintenance conditions. These differences can translate to varying levels of environmental impacts. As part of the optimization component, the overall life cycle impact from the chemical usage is an indispensable aspect in a trade-off study. The LCA practitioners should take extra caution when excluding chemicals, especially those with large dosage. The scale inhibitor, the membrane cleaning chemicals, and the remineralisation chemicals are three such examples with large dosage. The first has substantial contributions to acidification, eutrophication, and photochemical oxidation impacts as indicated by Zhou *et.al.* (2011a) and Hancock *et.al.* (2012), while the last two are important contributors to global warming (Vince *et al.* 2008) and ozone depletion (Tarnacki *et al.* 2012), respectively.

(3) Membrane fabrication

Membrane fabrication represents the activities carried out (*e.g.* extracting the membrane foil) and resources consumed (*e.g.* polymers) in manufacturing membrane modules. Some studies simplify the membrane phase as the production of membrane material, while others also included the production of spacer, housing, collection tube, adhesive, *etc.* (Table 3).

Regardless how the LCA practitioners itemize the membrane phase, all studies report the membrane fabrication has a minor contribution to overall impact. However, removal of membrane fabrication from the system boundary may be premature as previous studies do not incorporate impacts from solvents and coating compounds used in complicated membrane preparation

Table 2 – System coverage of chemical flows

Reference	Del Borghi *et al.* (2013)	Godskesen *et al.* (2013)	Ras and von Blottnitz (2012)	Tarnacki *et al.* (2012)	Hancock *et al.* (2012)	Jijakli *et al.* (2012)	Zhou *et al.* (2011a, b) Meneses *et al.* (2010)	Amores *et al.* (2013)
Pretreatment								
PH adjustment	H_2SO_4	H_2SO_4	--	H_2SO_4	--	--	--	H_2SO_4
Coag-floc	Polyelectrolyte $FeCl_3$	$Al_2(SO_4)_3$	--	$FeCl_3$	$FeCl_3$	--	--	Coagulant
Anti-foulant	HOCl	HCl	Cl_2	--	--	H_2SO_4	Cl_2	NaOCl
Anti-scalant	Acrylic acid	--	HCl	--	STP	PC	STP	STP
Declorination	Na_2SO_3	--	$NaHSO_3$	$NaHSO_3$	--	--	--	SMB
Membrane cleaning								
	NaOH NaOCl	HOCl NaOCl	NaOH CA	NaOH NaOCl	HCl NaOH SDBS	--	--	--
Post-treatment								
pH adjustment	Na_2CO_3	--	--	--	--	--	--	$Ca(OH)_2$
remineralisation	$Ca(OH)_2$ CO_2	$Ca(OH)_2$ CO_2	--	--	--	--	--	--
disinfection	--	--	--	Cl_2	--	--	--	--

Abbreviations: CA - citric acid; FSA - fluorosilicic acid; PAS - polymer aluminum sulphate; PC – polycarboxylates; SMB - sodium metabisulphite; STP - sodium tripolyphosphate; SDBS - alkylbenzene sulfonate

Zhou *et al.* (2013), Norwood and Kammen (2012), Lawler *et al.* (2012), Salcedo *et al.* (2012), Pasqualino *et al.* (2010), Vince *et al.* (2008), Stokes and Horvath (2006), Tangsubkul *et al.* (2005) haven't reported the chemical consumption in their studies.

Table 2 – System coverage of chemical flows (Continued)

Reference	Beery *et al.* (2010a, 2010b, 2011)	Munoz *et al.* (2010)	Frutos *et al.* (2009)	Biswas (2009)	Vince *et al.* (2009)	Lyons *et al.* (2009)	Raluy *et al.* (2004, 2005a, b, c, 2006)	Lundie *et al.* (2004, 2005)
Pretreatment								
PH adjustment	--	--	--	H_2SO_4	--	--	--	--
Coagulation-flocculation	$FeCl_3$	--	--	Polymers	PAS	--	--	--
Anti-foulant	Cl_2	Cl_2	--	NaOCl, DBNPA	Cl_2	Cl_2	Cl_2	Cl_2
Anti-scalant	--	STP	--	Nalco PC1020	PC	--	--	--
Declorination	$NaHSO_3$	--	SMB	SMB	--	--	--	--
Membrane cleaning	--	--	--	CA Detergent	EDTA NaOH	H_2SO_4	--	--
Post-treatment								
pH adjustment	--	--	--	--	--	--	--	--
remineralisation	--	--	$Ca(OH)_2$ CO_2	$Ca(OH)_2$ CO_2, FSA	$CaCl_2$ $Ca(OH)_2$	$Ca(OH)_2$	--	$Ca(OH)_2$ CO_2
disinfection	--	--	NaOCl	Cl_2	NaOCl	--	--	--
boron removal	--	--	--	--	--	--	--	--

Abbreviations: CA - citric acid; FSA - fluorosilicic acid; PAS - polymer aluminum sulphate; PC – polycarboxylates; SMB - sodium metabisulphite; STP - sodium tripolyphosphate; SDBS - alkylbenzene sulfonate

Zhou *et al.* (2013), Norwood and Kammen (2012), Lawler *et al.* (2012), Salcedo *et al.* (2012), Pasqualino *et al.* (2010), Vince *et al.* (2008), Stokes and Horvath (2006), Tangsubkul *et al.* (2005) haven't reported the chemical consumption in their studies.

Table 3 – System coverage of membrane material flows

Reference	Godskesen *et al.* (2013)	Lawler *et al.* (2012)	Ras and von Blottnitz (2012)	Tarnacki *et al.* (2012) [a]	Hancock *et al.* (2012)	Jijakli *et al.* (2012)	Zhou *et al.* (2011a, 2011b)
Membrane	PA	PA, PSU PET	PA	PA PTFE	PA	CA	PA
Spacer	PE	PP PE	--	PP PE	PE	cotton fabric, PP	--
Membrane Housing	glass fibre	glass fibre	--	coated steel PP, steel	glass fibre	--	--
Collection tube	PET	ABS EPDM	--	PET	PVC	--	--
Adhesive	--	epoxy	--	--	epoxy	ethylene rubber	--
Energy	--	--	--	--	--	--	extrusion

Abbreviation

ABS - acrylonitrile butadiene styrene; CA - cellulose acetate; EPDM - ethylene propylene diene monomer; PA - polyamide; PE - polyethylene; PET - Polyethylene terephthalate; PP - polypropylene; PSU - polysulfone
PTFE - Polytetrafluoroethylene; PVC - polyvinylchloride

Del Borghi *et al.* (2013), Zhou *et al.* (2013), Norwood and Kammen (2012), Salcedo *et al.* (2012), Beery *et al.* (2010a, 2010b, 2011), Pasqualino *et al.* (2010), Frutos *et al.* (2009), Lyons *et al.* (2009), Stokes and Horvath (2006), Tangsubkul *et al.* (2005), and Lundie *et al.* (2004, 2005) haven't reported the membrane material flows in their studies.

Table 3 – System coverage of membrane material flows (Continued)

Reference	Meneses *et al.* (2010) Amores *et al.* (2013)	Munoz *et al.* (2010)	Biswas (2009)	Vince *et al.* (2008, 2009)	Munoz and Fernandez-Alba (2008)	Raluy *et al.* (2004, 2005a, b, 2005c, 2006)
Membrane	PA	PA	PA	PA	PA	PA
Spacer	--	--	--	--	--	--
Membrane Housing	--	--	--	--	--	--
Collection tube	--	--	--	PVC	--	--
Adhesive	--	--	--	epoxy	--	--
Energy	--	extrusion	--	--	extrusion	--

Abbreviation

ABS - acrylonitrile butadiene styrene; CA - cellulose acetate; EPDM - ethylene propylene diene monomer; PA - polyamide; PE - polyethylene; PET - Polyethylene terephthalate; PP - polypropylene; PSU - polysulfone

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Del Borghi *et al.* (2013), Zhou *et al.* (2013), Norwood and Kammen (2012), Salcedo *et al.* (2012), Beery *et al.* (2010a, 2010b, 2011), Pasqualino *et al.* (2010), Frutos *et al.* (2009), Lyons *et al.* (2009), Stokes and Horvath (2006), Tangsubkul *et al.* (2005), and Lundie *et al.* (2004, 2005) haven't reported the membrane material flows in their studies.

processes. Further investigation of membrane fabrication procedures are warranted to determine the validity of exclusion of membrane fabrication if the contribution of solvents and coatings are considered.

3.2 The unrepresentativeness of databases

As discussed in Section 2.2, engaging available databases is a common practice in LCA studies. Therefore, the reliability of LCA results relies heavily on the database chosen, which sometimes are more of a concern than the choice of system boundary (Section 3.1).

As indicated in Table 1, most previous studies are carried out for European contexts due to the longer history of LCA in that region. Two commonly used databases, Ecoinvent and the PE database, are comprised of data generally collected from European industries. Several previous studies outside of Europe (Biswas 2009, Zhou *et al.* 2011a, Norwood and Kammen 2012) employ the local database (*e.g.* US LCI, AusLCI, SG LCI, *etc.*) when possible. It is important to highlight that the environmental burdens of a desalination system are sensitive to the geographical representativeness of the energy production data. The different national energy production databases can lead to order of magnitude differences in overall impact (Raluy *et al.* 2004, Zhou *et al.* 2011a). The LCA users should be circumspect in choosing the databases for their practices.

Another important concern is the time coverage of the available databases. Although the Ecoinvent Center and PE International update their data regularly, some data collected from the industrial sector is back-dated to the 1990s. Since most previous studies date from the 2000s, the materials and technologies utilized in desalination LCA studies may differ from those represented in the database. The burdens associated with 1 m^3 of produced water from a desalination plant, for instance, are significantly reduced with the development of high-flux membranes and increases in the efficiency of energy supply system.

3.3 The omission of uncertainty analysis

An LCA depends on a large number of input elements, and these elements are often based on the information of varying quality, which in turn affect the robustness of LCA outcomes. Several researchers have put forward approaches to address the uncertainty issue (Pennington *et al.* 2004, Rebitzer *et al.* 2004, Reap *et al.* 2008a, b). While a fully satisfactory methodology may be difficult to agree upon, the evaluation approaches can be categorized into four "tiers" proposed in the International Program on Chemical Safety (IPCS 2006).

- *Tier 0: default assumption; single value of result;*
- *Tier 1: qualitative but systematic identification and characterization of uncertainties*
- *Tier 2: quantitative evaluation of uncertainty making use of bounding values, interval analysis and sensitivity analysis*
- *Tier 3: probability assessment with single or multiple outcome distributions reflecting uncertainty and variability*

In desalination LCA studies, uncertainty analysis is not yet a common practice. Previous studies generally do not address this issue, thus the impacts of input variety are either ignored (Tier 0) or roughly analyzed qualitatively (Tier 1).

Munoz and Fernandez-Alba (2008), Munoz *et al.* (2010), and Zhou *et al.* (2011a, b, 2013) employed Monte Carlo simulation, one of the most popular probability assessment methods, to mathematically represent uncertainties in input data (Tier 3). Although its application is facilitated by the mathematical algorithm incorporated in SimaPro software and probability distribution documented in Ecoinvent database, the main challenges in actual desalination LCA practices may reside in the reference flows, such as the energy demand, chemical and membrane material consumptions, *etc.* The reference flows are recommended from on-site experimental data.

However, it is generally impractical for LCA practitioners to collect enough on-site data to derive the probability distribution. In such cases, one could employ the Pedigree matrix to estimate the variability of reference flows based on five major aspects, including the reliability of source, completeness, temporal correction, geographical correlation, and further technical correlation of available datasets (Weidema and Wesnæs 1996).

The Tier 2 qualitative evaluation can serve as another alternative when uncertainty cannot be readily represented by probability distributions due to the sparsity or non-probabilistic nature of available information. A typical example is choice uncertainties. In order to check the robustness of LCA results, the sensitivity analysis may include a number of choices in energy efficiency and sustainable energy generation (Raluy *et al.* 2004, 2005a, 2006, Hancock *et al.* 2012), in demand management (Lundie *et al.* 2005, Munoz *et al.* 2010, Godskesen *et al.* 2013), in service life (Godskesen *et al.* 2013), to name a few.

4. Conclusions

This paper discussed the feasibility and reliability issues confronted in desalination LCA studies.

From the feasibility aspect, the accounting approaches, supporting databases, and impact assessment approaches attract a growing number of applications in desalination. Some important notes are listed for considering.

- The process model is a better suited accounting method for desalination, while the EIO-LCA model can serve as supplementary method depending on the availability of EIO database and the scope of the practitioners' research.
- Similar to other LCA efforts, desalination LCA studies are generally data intensive. The LCA practitioners can take advantage of available databases to support the background processes, including infrastructure construction, energy generation, chemical production,

membrane fabrication, and waste management. However, consideration of the representativeness of the selected database is warranted.

- Life cycle impact assessment can be further improved with the development of new knowledge. The brine disposal and freshwater savings are two important characteristics of desalination system. The current assessment models used to translate those characteristics into corresponding impacts are, unfortunately, still far from establishment, and potentially leading to significant under-estimation of environmental impacts. This highlights an area requiring more research efforts to represent the true impacts of desalination.

Reliability is another important consideration of desalination LCA. The concerns in this aspect are mainly on the incompleteness of the system boundary, the unrepresentativeness of database, and the omission of uncertainty analysis.

- It is sometimes necessary to narrow the system boundary by ignoring a number of reference flows from background to foreground. This approach is attractive, from the practitioners' point of view, because it can reduce the burdens of primary data collection. However, the exclusion of certain chemicals, construction and membrane materials should be made cautiously, because they are highly dependent on the goal of study and the impact categories of interest.
- Similar to other LCA efforts, the temporal and spatial representativeness of a database engaged in desalination LCA is important. Most current databases rely on European data back-dated to the late 1990s or early 2000s. Quantify environmental impacts of newly constructed desalination plants in different geographic locations may require engaging regional and updated data to capture the technological development and local context.

- Uncertainty estimation may be improved by providing and tracking metrics of data quality, with respect to how the data are acquired, to what extent the data are validated, and how well the data capture technological, spatial, temporal variations. Further efforts are needed to provide guidance and “best practices” in uncertainty analysis.

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