The Carbon Footprint of Desalination:
An input-output analysis of seawater reverse osmosis desalination in Australia for 2005–2015

ISA, The University of Sydney
EVUR, Technical University of Berlin

Please cite this study as:
Heihsel, M., Lenzen M., Malik A., Geschke A. (2019): The carbon footprint of desalination: An input-output analysis of seawater reverse osmosis desalination in Australia for 2005–2015, Desalination, 454, 71-81, https://doi.org/10.1016/j.desal.2018.12.008.

The carbon footprint of desalination

An input-output analysis of seawater desalination in Australia for 2005 - 2015

Michael Heihsel[1*], Manfred Lenzen[2], Arunima Malik[2,3], Arne Geschke[2]

[*] michael.heihsel@campus.tu-berlin.de

[1] Department of Energy Engineering, Technical University of Berlin, Straße des 17. Juni 153, 10623 Berlin Germany
[2] ISA, School of Physics, The University of Sydney, Sydney, New South Wales 2006, Australia
[3] Discipline of Accounting, The University of Sydney Business School, Sydney, New South Wales 2006 Australia

Abstract

This study examines greenhouse gas emissions for 2005-2015 from seawater desalination in Australia, using conventional energies. We developed a tailor-made multi-regional input-output-model. We complemented macroeconomic top-down data with plant-specific desalination data of the largest 20 desalination plants in Australia. The analysed capacity cumulates to 95% of Australia's overall seawater desalination capacity. We considered the construction and the operation of desalination plants. We measure not only direct effects, but also indirect effects throughout the entire value chain. Our results show the following: We identify the state of Victoria with the highest emissions due to capital and operational expenditures (capex and opex). The contribution of the upstream value chain to total greenhouse gas emissions increases for capex and decreases for opex. For capex, the construction of intake and outfall is the driving factor for carbon emissions. For opex, electricity consumption is the decisive input factor. Both in construction and operation, we identify the critical role of the electricity sector for carbon emissions throughout the supply chain effects. The sector contributes 69% during the zenith of the construction phase and 96% during the operating phase to the entire emissions. We estimate the total emissions for 2015 at 1,193 kt CO_2e.

Keywords: Input-output analysis, life cycle analysis, multi-regional, greenhouse gases, sustainability

Accepted manuscript of: Heihsel, M., Lenzen, M., Malik, A., & Geschke, A. (2019). The carbon footprint of desalination. Desalination, 454, 71–81. https://doi.org/10.1016/j.desal.2018.12.008.

1 Introduction

Increasing lack of fresh water is one of the most severe global problems of the future decades. About two-thirds of the world's population has no access to fresh drinking water at least once a year [1]. More than 783 million people have no access to clean drinking water [2], and half a billion people suffer from water shortages throughout the year [1]. The most affected regions include the west of North America, the east of Spain, the Middle East and North Africa (MENA) region, as well as Australia and northern China. Archipelagos like the Canary Islands face these problems, too [3].

Meanwhile, California experienced a prolonged and unusually severe drought from 2011 to 2017, resulting in daily life restrictions, high water costs, and economic slowdown. Climate change, prosperity, and exponential population growth will further aggravate these problems. Water is increasingly becoming a scarce and therefore valuable commodity. It is becoming more difficult for the regions mentioned to meet the demand for fresh water which inevitably leads to conflicts of use.

Many of these arid regions are close to the seashore and thus close to substantial water resources. Some areas are already using desalination technology, which is the most expensive option to meet water demand. However, it is already indispensable for many regions. For example, Saudi Arabia covers 50% of its water needs from desalination, using 25% of its oil and gas for water and electricity production in combined power-desalination plants [4]. Mitigating water scarcity becomes a self-accelerating problem. Drought is increasing as a result of climate change. In order to solve this problem, the use of desalination is proliferating, which in turn catalyses climate change due to high energy demand. Water production needs energy, but electricity generation also needs water in large quantities, that is why academia speaks of the water-energy-nexus [5].

Numerous studies address technical, economic or ecological issues of conventional and renewable operated desalination. However, the current literature shows some knowledge gaps. Gude (2016) states in his study:

> “Although some of the facts and recent developments discussed here show that desalination can be affordable and potentially sustainable, contributions that meaningfully address socio-economic and ecological and environmental issues of desalination processes are urgently required in this critical era.” [6]

Haddad (2013) also draws attention to the need for holistic studies in the field of desalination research. Only by incorporating effects throughout the entire supply chain (indirect effects), a comprehensive assessment is possible [7]. Whether or not desalination can sustainably solve the problems of water availability in arid and semi-arid regions depends on its holistic socio-economic and ecological sustainability.

Lattemann and Höpner (2008) provide an overview of the leading environmental impacts of desalination and possibilities to minimise impact and risks [3]. The World Bank estimates that 99 per cent of carbon dioxide equivalent (CO_2e) involved in a business-as-usual scenario could be avoided by desalination with renewable energies [8]. This estimation illustrates the enormous carbon reduction potential of combining renewable energies and desalination. Einav et al. (2003) show the factors that significantly influence the ecological footprint of desalination [9]. These factors are land use, the groundwater, the marine environment, noise pollution and the use of energy. According to Muñoz and Fernández-Alba (2008), the type and quality of feedwater can reduce the environmental impact (such as energy demand, acidification potential or human toxicity potential) of the Reverse Osmosis (RO) process up to 50 per cent [10]. Liu et al. (2015), Setiawan et al. (2009), Vince et al. (2008) and Sadhwani et al. (2005) offer analyses of the ecological effects [11][12][13][14]. A good overview of current trends and ecological challenges can be found in Goosen et al. (2014) [15].

We have found several studies in the field of input-output analysis and life cycle assessment of desalination. Raluy et al. (2006) use a process-based LCA to investigate different desalination technologies [16]. Zou and Liu (2016) use input-output analysis on desalination in China to measure the economic impact of investments [17]. Storkes and Horvath (2006) use a hybrid LCA to study water supply systems in California [18]. Shahabi et al. (2014) use a hybrid approach to investigate a desalination plant in Western Australia [19].

There is no doubt that desalination plays an essential part in the water supply strategy of regions which are affected by severe drought and have access to seawater. However, desalination must prove its economic, environmental and social sustainability. Our study contributes to quantifying environmental sustainability by measuring the carbon footprint of desalination in Australia. For the study, we assume that operation and construction processes use electricity from conventional energy in line with the Australian energy mix. It is the first study of desalination, where a comprehensive multi-regional model has been created and used for measuring the supply chain impacts. With the aid of our multi-regional model, we can also present regional impacts for the first time. Our approach rates the country's largest 20 plants, which represents 95% of the total capacity – that to over more than ten years.

2 Methods and data

A carbon footprint captures the carbon emissions of a product, a technology or a technical process. This approach does not only analyse carbon emissions directly generated by the desalination process itself. It also accounts for indirect effects, defined as all carbon emissions generated by suppliers within the entire supply chain. Our approach captures carbon emissions throughout the entire supply chain (upstream). We consider desalination as final demand and analyse carbon emissions from sectors from which desalination purchases inputs. Our approach does not assume that additional water from desalination induces further carbon emission downstream the supply chain.

Leontief (1966) [20] invented Input-Output Analysis (IOA) and applied it in several studies. For this seminal work, Leontief earned the Nobel Prize in 1973. Researchers have used IOA to analyse economic effects of monetary demand on economic key figures, mainly effects on industrial output. Model extensions use IOA to analyse further economic, social or environmental effects [21] [22]. We apply IO-methodology to estimate the carbon footprint of desalination in Australia.

Footprint studies apply input-output-tables (IOTs) that show monetary trade flows of economic sectors. In order to produce goods, companies purchase intermediate goods from other companies. These intermediate streams are the core of IOTs. The columns of these tables show which input factors a particular sector purchases to produce their goods. The rows of the table show the production of a sector, which this sector produces for other sectors as intermediate inputs. The intermediate input matrix gives a comprehensive picture of the intermediary inputs and creates a production recipe for the produced goods of each sector. These recipes provide the opportunity to carry out value-added analysis and combine it with satellite accounts (such as the sectors' greenhouse gas emissions). The combination allows for comprehensive carbon footprint studies by considering the entire value chain, without truncation errors such as those found in classic process-based LCAs [23].

The benefit of a hybrid LCA approach is to combine bottom-up process data with top-down macroeconomic input-output data and hence include the technical process into the macroeconomic system of a whole economy.

To the best of our knowledge, our study is the first comprehensive multi-regional carbon footprint study for a country's desalination application.

2.1 Construction of a multi-regional input-output database

IOA applies data from national accounts. IOTs arrange and structure the data. The tables describe the structure of an economy with detailed information about output, intermediate and final demand. IOTs can describe an economy by industry or commodity classification. Furthermore, IO-models can classify an economy in a single-regional or a multi-regional framework.

Compiling tailor-made IOTs is a work-intensive task. Finding data for different regions and sectors is challenging because the data are often incomplete or inconsistent. Lenzen et al. (2014) developed a cloud-based virtual laboratory, the Industrial Ecology Laboratory (IELab), to compile tailor-made IOTs for Australia [24]. A collaborative group of researchers feeds the database in an ongoing process. An algorithm converts the data into a specific structure, the so-called root classification. The root has 1284 sectors in Input-Output Product Classification (IOPC) [25] and 2214 regions in Statistical Area Level 2 (SA2) classification [26]. Due to the vast amount of data, IELab offers high-performance-computing for IOT compiling and calculations [27]. We apply a supply-use-framework [28].

For this study, we constructed a multi-region input-output (MRIO)-framework with 123 sectors and eight regions that represent the Australian states and territories. The desalination input data determine the structure of the sector classification. In contrast to available input-output tables, this allows for a detailed and accurate analysis that avoids aggregation errors. For our carbon footprint study, we compiled a satellite account of CO_2e emissions of industrial sectors.

We compiled several concordances for this study [24]. The generation of tailor-made IOTs requires concordances from root to study-specific sector classification and from root to study-specific region classification. To compute demand vectors, we compiled concordances from desalination input data structure to study-specific sector classification. Since supply-use-frameworks are twice the size of usual IO-frameworks, the framework includes 2 x 123 sectors (industry and commodity) in 8 regions. The structure results in a transaction matrix in the size of 1,968 x 1,968. We compiled tables for the years 2005 to 2015, whereas the years refer to Australian financial years.

Compiling IOTs requires the application of mathematic optimisation algorithms. The critical challenge is that the number of variables to be determined significantly exceeds the number of constraints. The IELab implemented advanced optimisation approaches like quadratic programming and Konfliktfreies RAS (KRAS) to solve the optimisation problem [29].

The creation of large MRIO tables represents an underdetermined optimisation problem. Raw data for large economic transactions are much more available than raw data of small transactions. Hence, the number of constraints used for the optimisation is much smaller than the number of elements that we determine in the table. Therefore, large transactions are supported by many raw data points, while small transactions are supported only by a few raw data points. Within the optimisation process, this results in MRIOs representing large transactions with high reliability. However, small transactions are often subject to significant adjustments. Monte Carlo techniques can be used to show that the results of impact analyses remain stable [30].

We show this phenomenon in the calculation of the sectors' outputs from the MRIO. We can calculate outputs in input-output tables in two ways. One way is to calculate outputs by row sums, which represents the production of the intermediate demand for other sectors and the production for the final demand. Also, we can determine the output of a sector by the column sum of this sector. The column sum corresponds to the sum of all goods necessary for the production of one sector's goods, and the value added created by this sector.

Both ways should ideally come to the same result. Since the creation of an MRIO is an underdetermined optimisation problem, adjustments are necessary, which results in deviations. Figure 1 shows, however, that our MRIO represents large transactions with high reliability and small transactions are subject to greater uncertainty. The impact analysis thus provides reliable results.

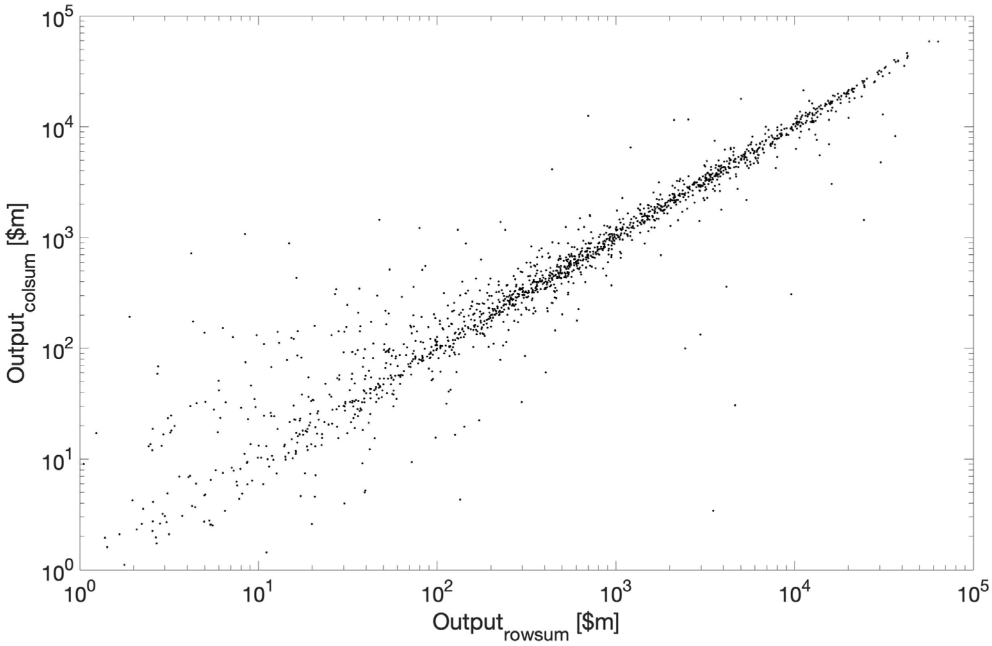

Figure 1 Rocket plot of outputs calculated via row sum and column sum in 2015.

2.2 Preparation of desalination data

Data on desalination is scarce [31][32]. Wittholz et al. (2008) attempted to estimate the cost structures of desalination plants [33]. The Desalination Economic Evaluation Program (DEEP) model of the International Atomic Energy Agency is also a common model to estimate the cost structure of desalination plants [34]. For our analysis, we deployed data from Desaldata, a database with additional functions [35]. Desaldata offers the most detailed database we found. The cost estimator tool for estimating capital expenditure (capex) and operational expenditure (opex) structures as functions of several variables is also a part of the platform.

Desaldata contains data for 349 seawater desalination, brackish water and wastewater plants in Australia with capacities from 30 to 444,000 m^3/d. For our study, we used data for of the largest 20 seawater reverse osmosis desalination plants (SWRO) that cumulate to 95% capacity of all Australian seawater desalination plants with particular plant capacities from 4,000 to 444,000 m^3/d (see appendix 1). RO is the common desalination technology in Australia, and there is only a small number of other technologies like MED or MSF.

Even though Desaldata is the most detailed database we found, it is fragmentary and partially unreliable. Desaldata offers complete data for location, capacity, feedwater type, award date, and online date. Data of Engineering-Procurement-Construction (EPC) price, feedwater conditions, and power consumption were sketchy. We validated years of construction, capacity, capex, opex, and specific energy consumption by additional literature and adjusted the data if necessary (see appendix 1). Thus, we were able to validate data for the largest eight plants with a cumulated capacity of 95.9% of all 20 analysed plants. For the residual plants with 4.1% of cumulated capacity, we used the raw results of Desaldata's cost estimator and adjusted capex sums by the database's value if available.

Desaldata's cost estimator tool provides a breakdown for opex and capex depending on different attributes such as location, salinity, temperature or energy consumption. If data for EPC prices were available, we used the capex cost estimator only for ratios of the cost structure. If EPC prices were not available, we used the capex cost estimation for the capex sum as well. We estimated seawater temperatures by yearly average temperatures of the nearest city [36]. We estimated electricity prices by the annual volume-weighted spot prices of states and territories in 2009 [37]. We used Western Australia's Short Term Energy Market (STEM) data for both Western Australia and the Northern Territory since data for the Northern Territory is not available [38]. The cost estimator is only capable of calculating costs for plant capacities larger than 8,000 m^3/d. Hence, we used values of this plant to extrapolate cost structures of all smaller plants. The smaller plants account for only about 3.5% of the total investigated capacity. An over- or underestimation will therefore not significantly affect the overall outcome of the study. The cost estimator calculates in US$ currency, so we converted AU$ into US$ using exchange rates from International Monetary Fund [39]. We used 2009 as the base year for the initial cost estimation. We assumed a utilisation rate of 95% for all modelled plants. Even if some plants are currently unused because municipalities are currently not in water shortage (like Sydney or Melbourne), we also modelled these plants with a utilisation rate of 95%. Our research objective is not to focus on the reproduction of the most accurate costs of real operations, but rather quantify the carbon footprint of the plants when they produce their capability.

Finally, we estimated data for 20 plants, each of the plant covers twelve data points for capex and four data points for opex demand. The left diagram in figure 2 shows the input data for our analysis.

We calculated the final demand vectors as follows:

1. Construction of preliminary demand vectors $\mathbf{y_1}$ for opex and capex.

2. $\mathbf{y_2} = \mathbf{y_1} r^a$ converts the demand vector $\mathbf{y_1}$ from US\$ into AU\$ with the exchange rate r^a for year a. We applied the exchange rate of the online year for all capex vectors. We converted the opex vectors by the exchange rate of 2015.

3. We distribute capex and opex over the construction period. We prorated capex according to $\mathbf{y_3^a} = \frac{1}{n}\mathbf{y_2}$ for each year a with n as the number of construction years. We assumed only half of the capex investments in the first and the last year of construction works, so we apply $\mathbf{y_3^a} = 0.5\frac{1}{n}\mathbf{y_2}$ for the online and award year respectively. If we assumed a plant that was awarded in 2009 and went online in 2012, then n is 3 as award and online year respectively only gets a half year value. The vector $\mathbf{y_2}$ is distributed among $n + 1$ vectors $\mathbf{y_3^a}$. For opex distribution, we applied $\mathbf{y_3^a} = \mathbf{y_2}$ for each year after the online year. We assumed $\mathbf{y_3^o} = \frac{1}{2}\mathbf{y_2}$ for the online year o.

4. We inflated the demand vectors by $\mathbf{y_4} = \mathbf{y_3}\frac{p_s^a}{p_s^b}$, where p_s^a is the producer price index for sector s of year a [40]. p_s^b is the producer price index of the base year. The base year of capex vectors is the online year. For opex, we assumed 2015 as the base year.

5. We applied $\mathbf{y_5^a} = \mathbf{C}\mathbf{y_4^a}$ to expand the demand vectors of each year from a 1x15 to a 1x123 demand vector. $\mathbf{C}$ is a 123x15 concordance matrix.

6. Since we use an Australian MRIO, we separated the domestic vectors from (rest of the world) import vectors. We aggregated the compiled MRIO tables to the national level to compute the import quota vectors $\mathbf{q^a}$ for each year a. The vector consists of q_i^a for each sector i, defined by $q_i^a = \frac{\sum_{j=1}^{N} I_{i,j}^a}{\sum_{j=1}^{N} U_{i,j}^a}$. $I_{i,j}$ is the import intermediate demand matrix and $U_{i,j}$ the total intermediate demand matrix, composed as $\mathbf{U}_{i,j} = \mathbf{T}_{i,j} + \mathbf{I}_{i,j}$. $\mathbf{T}_{i,j}$ is the domestic intermediate demand aggregated to the national level. We calculated the domestic desalination demand vectors by $\mathbf{y_6^a} = \mathbf{y_5^a} \# \mathbf{q^a}$, where # denotes element-wise multiplication. The import quota in our model was about twenty per cent in average respective the different years and sectors.

7. As the last point, we expanded the demand vectors $\mathbf{y}_6^{\mathbf{a}}$ to the size of the MRIO-framework. For the regional allocation, we converted the geographical coordinates of the location of the desalination plants into SA2 classification. We placed the vector $\mathbf{y}_6^{\mathbf{a}}$ into the rows of the respective region and the columns of the respective year. The constructed opex and capex demand matrices $\mathbf{O}_\mathbf{p}$ and $\mathbf{C}_\mathbf{p}$ of each plant p have 1,968 rows (MRIO size) and 11 columns (one column for each year). We aggregated all matrices to one final demand matrix $\mathbf{Y} = \sum_{p=1}^{66} \mathbf{O}_\mathbf{p} + \sum_{p=1}^{66} \mathbf{C}_\mathbf{p}$.

2.3 Calculation of the carbon footprint

Researchers widely use environmentally extended IOA for carbon footprints of individual products, processes, economic agents like companies or final consumers [41]. Pomponi and Lenzen (2018) demonstrate the superiority of using IOTs in a hybrid LCA approach over of using only bottom-up process-based data for LCA [23].

IOTs catch the industrial intermediate dependencies by linear functions. The linear approach causes basic assumptions: Industries have fixed input structures (linear production function), constant economies of scale and commodity prices are constant. Hence, we can interpret the cost structure as average variable costs rather than marginal costs. Furthermore, IOA is an ex-post analysis. Miller and Blair provide a well-detailed overview on IOA [42].

In IOA, we use Leontief's inverse to calculate the total impact of a demand on the output of an economy. We derive the inverse from the basic relationship between supply and demand. Suppose $\mathbf{x}$ as the M x 1 total output vector, $\mathbf{T}$ as the M x M intermediate demand matrix and $\mathbf{Y}$ as the M x N final demand matrix, then

$$\mathbf{x} = \sum_{j=1}^{M} \mathbf{T}_{i,j} + \sum_{j=1}^{N} \mathbf{Y}_{i,j} \,. \qquad [\,1\,]$$

As the production recipe of the sectors, we can express the technical coefficient matrix $\mathbf{A}$ as

$$\mathbf{A} = \mathbf{T}\hat{\mathbf{x}}^{-1} \qquad [\,2\,]$$

It follows from the preceding that

$$\mathbf{T} = \mathbf{A}\hat{\mathbf{x}}. \qquad [\,3\,]$$

We can insert the preceding equation in equation 1 and rearrange to

$$\mathbf{x} = (\mathbf{I} - \mathbf{A})^{-1}\mathbf{Y} \qquad [\,4\,]$$

as the basic formulation of Leontief, while

$$\mathbf{L} = (\mathbf{I} - \mathbf{A})^{-1} \qquad [\,5\,]$$

is the Leontief inverse that captures all direct and indirect effects of demand **Y** on the output **x**. The matrix **I** is the identity matrix. We extend the economic Leontief model by a satellite account of industrial carbon dioxide equivalent emissions **e** and calculate the direct emission intensities

$$\mathbf{q} = \mathbf{e}\hat{\mathbf{x}}^{-1}. \quad [6]$$

Furthermore, we obtain the direct and indirect effects captured in a matrix representing the multipliers for each sector-to-sector relationship from

$$\mathbf{m} = \hat{\mathbf{q}}\mathbf{L}. \quad [7]$$

The total carbon emissions of desalination throughout the entire value chain are finally captured by

$$\mathbf{E} = \hat{\mathbf{q}}\mathbf{L}\hat{\mathbf{y}}. \quad [8]$$

Row sums **r** of the matrix **E** result in carbon emissions referring to sectors and regions where they physically occur. Hence, row sums reflect the emitting sectors or regions, depending if we aggregate to sectors or regions. Column sums **c** will refer to desalination inputs and regions where emissions are accounted regarding consumption responsibility of the analysed desalination plant. We calculate row sums or the column sums by multiplying the Matrix E by sum vector i, which is a column vector with the number of rows according to matrix **E** with every element equal to 1.

$$\mathbf{r} = \mathbf{E}\,\mathbf{i}, \quad [9]$$

or

$$\mathbf{c} = \mathbf{i}'\,\mathbf{E}. \quad [10]$$

We aggregate the vectors by multiplying them with aggregators, so-called concordances **C**.[1] The concordances are tailored to each aggregation and sum up the 1,968 sectors to sectors or regions of research interest (e.g. classification of Australian states or desalination input commodities). For example, if the desalination plants emit 100 kt CO_2e, row sums of matrix **E** assign emissions to the region where the desalination plant is located respectively the input products, which the desalination plant directly demanded. Column sums assign the same 100 kt CO_2e emissions to the regions where the emissions effectively occur respectively to the sectors which physically emitted the greenhouse gases.

We get the final vectors as

$$\mathbf{v} = \mathbf{C}\,\mathbf{r}, \quad [11]$$

respectively

$$\mathbf{v} = \mathbf{c}\,\mathbf{C}. \quad [12]$$

---

[1] For more information on using concordances, see supporting information in [24].

For the production layer decomposition, we formulate the Leontief inverse as

$$\mathbf{L} = \mathbf{I} + \mathbf{A} + \mathbf{A}^2 + \mathbf{A}^3 + \dots + \mathbf{A}^{\mathrm{n}}. \quad [10]$$

We disaggregate the total carbon emission into several layers. $\mathbf{E_1} = \hat{\mathbf{q}}\mathbf{A}\hat{\mathbf{y}}$ results in emission for the first layer, defined as direct effects. $\mathbf{E_2} = \hat{\mathbf{q}}\mathbf{A}^3\hat{\mathbf{y}}$ gives emission for the second layer and so on. Each layer represents one supplier-stage of production. The first layer consists of carbon emissions from direct suppliers. The second layer shows carbon emissions of the supplier-suppliers.

3 Results and discussion

Desalination is an energy- and thus carbon-intensive technology for gaining fresh water. IOA methodology enables to uncover not only direct carbon emissions of desalination but also indirect effects along the entire value chain. The following section will present detailed insights into the carbon footprint of desalination in Australia over the years 2005 to 2015.

3.1 Cost and CO_2e emissions overview

Within the last 15 years, Australia has faced an extreme drought, mainly from 2003 to 2012. One consequence of this drought has been a political discussion about Australian's freshwater strategy. Desalination was used already before in a much smaller scale. However, facing this severe drought, several Australian cities, states, and firms have started huge investments in desalination plants.

The left axis curve of the left diagram in figure 2 shows domestic capex and opex expenditures from 2005-2015 in current year prices. The total expenditures reach their maximum in 2010 by AU$2.3 bn. Capex was the predominantly driver of the expenditures.

Average opex per produced water (right axis) increased within the 11 years from about AU$0.2 per cubic meter to AU$0.5 per cubic meter. Increasing energy costs mainly determine the growth of opex. The construction of different sized desalination plants within the analysed period also affect the growth of opex.

The bar graph (left axis) in the right figure shows the total carbon emissions (direct and indirect effects) due to operational and capital expenditures. We can see that CO_2e due to capex is predominant until 2011. After the main investment period, opex becomes predominant. In 2013, desalination emitted 1,269 kt CO_2e mainly driven by opex. The right axis figure shows the total carbon emission per cubic meter of produced water, only determined by opex. We observed increasing opex per cubic meter up to 2000 g/m^3 at the end of the investigated period.

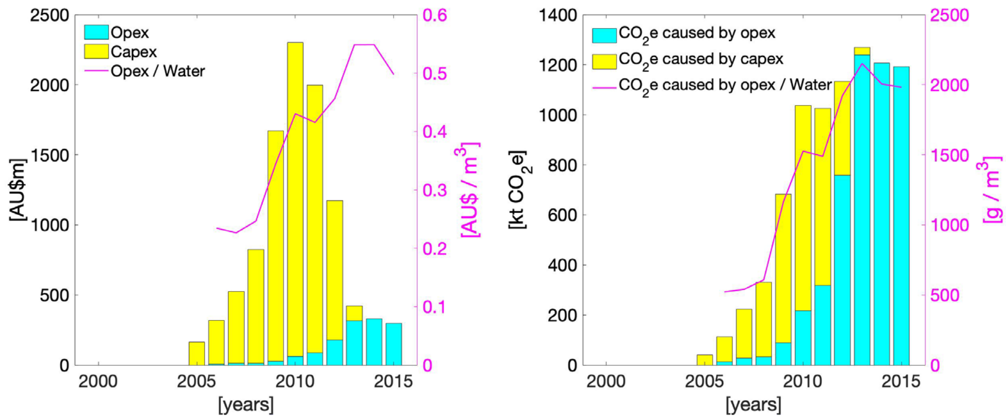

Figure 2 Overview of costs and CO_2e emissions.

Table 1 shows the direct, indirect and total carbon emissions for the years 2005 to 2015 due to opex and capex. Construction activities determine capex while the operation of existing plants results in opex. In 2005, only capex was responsible for CO_2e emissions. As of 2012, opex was the driving force. During the construction phase, CO_2e emissions due to capex played a significant role with a peak of 820kt CO_2e. These high carbon emissions focus on just a few years. The annual CO_2e emissions due to opex exceed the emissions of capex already in 2012 with 759kt CO_2e. Due to the runtime of the plants over several decades, opex makes a significant contribution to the carbon footprint over its lifecycle. The last column shows the carbon multiplier c, that is defined by $c = \frac{Q^a_{tot}}{Q^a_{dir}}$, with the total carbon emission Q^a_{tot} and the direct carbon emission Q^a_{dir} for the year a. Due to the larger multiplier of capex, we see that its supply chain has a more significant impact on CO_2e emissions than the supply chain of opex. Over the years, the multiplier of capex increases (except in 2013), while the multiplier of opex decreases. The higher the multiplier, the higher is the contribution of the upstream value chain to the overall effects. In conclusion, the value chain of the construction of desalination plants becomes more unsustainable over time, while the value chain of operations becomes more sustainable.

Table 1 Carbon emissions due to opex and capex of desalination in Australia.

	CO_2e effects caused by capex				*CO_2e effects caused by opex*			
year	direct effect *[kt CO_2e]*	indirect effect *[kt CO_2e]*	total effect *[kt CO_2e]*	multiplier *[kt CO_2e / kt CO_2e]*	direct effect *[kt CO_2e]*	indirect effect *[kt CO_2e]*	total effect *[kt CO_2e]*	multiplier *[kt CO_2e / kt CO_2e]*
2005	21	20	41	2.0	0	0	0	-
2006	50	48	99	2.0	8	5	13	1.7
2007	100	95	195	1.9	17	12	28	1.7
2008	158	141	299	1.9	19	13	32	1.7
2009	286	309	595	2.1	58	30	89	1.5
2010	375	445	820	2.2	155	62	217	1.4
2011	311	397	708	2.3	229	88	317	1.4
2012	159	216	375	2.4	544	215	759	1.4
2013	16	15	31	1.9	882	356	1239	1.4
2014	0	0	0	-	854	353	1207	1.4
2015	0	0	0	-	845	349	1193	1.4

IOA with MRIOs is well suitable to uncover the spatial distribution of observed effects. In our study, we show the spatial distribution of carbon emissions. We can assign carbon emissions either to desalination inputs and locations of the plants or to emitting industries and emitting locations. Figure 3 shows carbon emissions in 2012 due to capex and opex assigned to locations of the desalination plants. We created tables with eight regions representing the eight states and territories in Australia. In 2012, we can still observe a high level of construction activities, but also high expenses for operations. Australian Capital Territory and Tasmania do not operate desalination plants, so there is no carbon emission assigned. Northern Territory's desalination activity induces negligible emissions due to opex in 2012. In Queensland and New South Wales, we only find emissions due to opex. Western Australia and South Australia have emissions due to opex and capex on a medium scale. Victoria built the Victorian Desalination Plant from 2009 to 2012. Hence, the state is the leader in emission due to opex and capex in 2012.

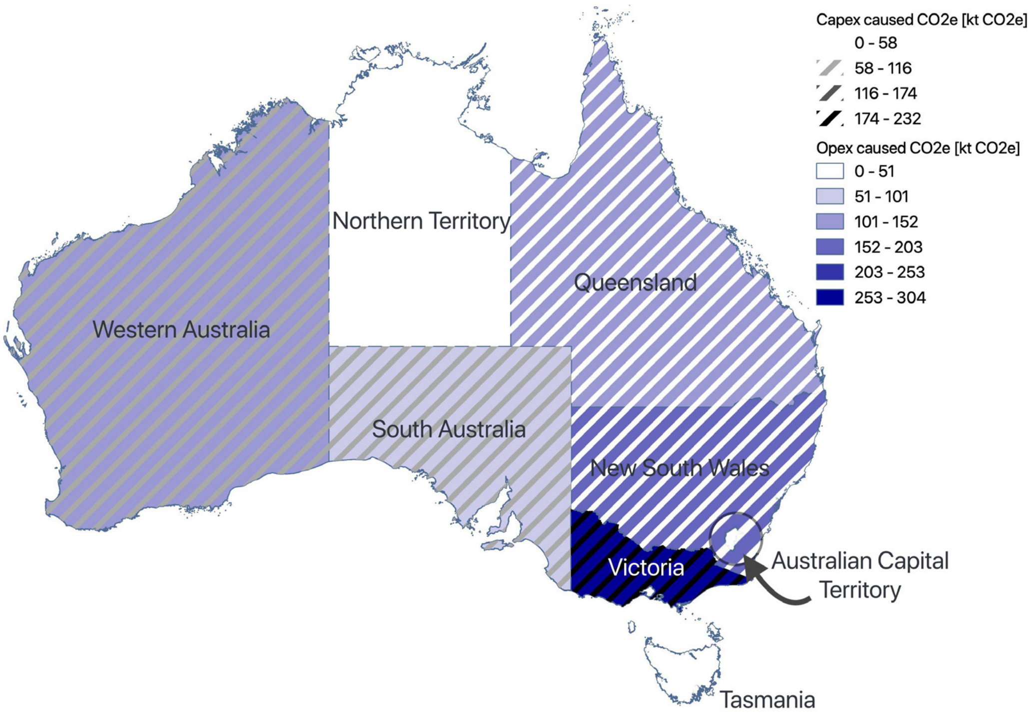

Figure 3 CO_2e emissions by states and territories caused by capex and opex in 2012.

Figure 4 shows the total carbon emissions for 2005-2015. The four individual diagrams break down the emissions according to different systematics. We see that the emissions increase over time, dominated by capex in 2010. As of 2012, opex contributes significantly to carbon emissions.

In the left-hand diagrams, we assigned carbon emissions to emission-causing desalination inputs and locations of the plants. The diagrams on the right side show emitting industries and emitting locations. We compiled individual demand vectors for capex and opex so that we can illustrate the effects of opex and capex separately.

The diagram on the top left shows the carbon emissions assigned according to desalination inputs, each for capex and opex. The peak of capex caused emissions marks the boom in construction activities around 2010. Construction of inlets and outlets cause the main emissions. The second most considerable emission-causing input is the construction process of pipes. Both mainly require steel, which explains the high-level emissions. Opex-caused emissions mainly occur due to the demand for electricity as a direct input. At the end of the period, electricity causes almost all carbon dioxide. We aggregated all other inputs such as parts, chemicals and membranes for the sake of convenience. Since desalination plants usually operate for several decades up to 20 to 40 years, opex especially the energy source is the crucial point regarding environmental sustainability of desalination in the long run.

In the upper right chart, we can see which industry sectors emitted CO_2e due to the production of inputs, also divided into emissions caused by capex and opex. It is noticeable that even for capex demand the electricity sector emits a significant amount of CO_2e. The manufacturing sector is another key sector for carbon emissions during the construction phase, followed by the construction sector as the third largest emitter. As we have already discovered that the primary input of opex is electricity, it is not surprising that the electricity sector has the highest emissions. It indicates that the value chain of conventional energy plays a minor role in carbon emissions.

The graph at the bottom left shows the carbon emissions assigned to the desalination plant's locations, separated by capex and opex. Around the year 2010 Victoria caused the most substantial emissions due to capex, followed by South Australia. In the years around 2008, construction activities in New South Wales were a significant driver. In the following years after 2011, when the construction activities decline, opex becomes dominant for carbon emissions. Victoria has by far the most significant emissions of CO_2e, followed by Western Australia and New South Wales.

The diagram to the right shows in which states and territories CO_2e was emitted. At high trading volume, the graphs differ because consumption and production happen on different locations. Here we see that the diagrams are almost identical. Already in the diagrams above, we found for capex and opex that the electricity, gas, water and waste service sector dominates the carbon emissions. Even if Australia has a national electricity market, electricity trade between different states is at a low level. Western Australia and the Northern Territory are not even connected to the National Electricity Market [43].

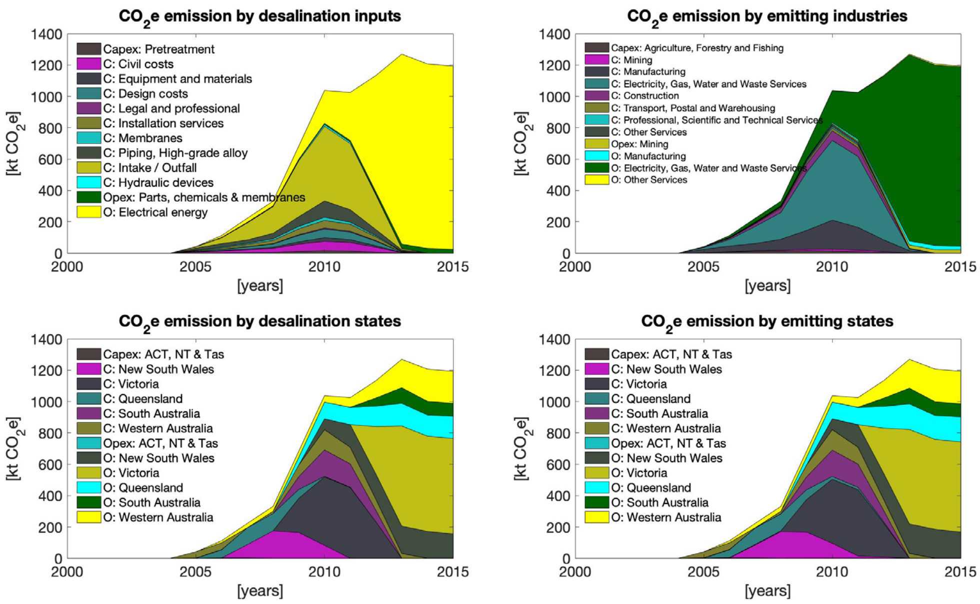

Figure 4 CO_2e emission by desalination inputs and emitting industries.

Finally, we compiled a production layer decomposition (PLD) analysis for 2012. This approach determines the emissions for each production layer individually. Production layers are the several tiers within a value chain. We define the first layer as the direct effect. The direct effect accounts for carbon dioxide emitted by the direct supplier. Thus, the direct effect is the emission directly assigned to the desalination industry itself. The second layer is the supplier of the first supplier and so on. The Leontief inverse captures the whole supply chain with an infinite number of suppliers. Figure 5 illustrates the results of the PLD Analysis for 2012 for desalination inputs and (left diagrams) and emitting industries (right diagrams). We see that a higher proportion of capex's emissions (compared to opex) occur in upstream stages of the value chain (lower diagrams). For opex, this means that the direct supplier already contributes a higher share to the total CO_2e emissions. The value chain is less critical for total emissions at opex than at capex. Generally, carbon emission mainly occurs within the first three to five layers. The following layers contribute with decreasing significance.

On the upper left diagram, we see that about two-thirds of capex carbon emission occurs due to the construction of intake and outfall. For intake and outfall, we note that the supply chain makes a higher contribution to total emissions than we can note e.g. for piping and high-grade alloy. On the upper right chart, we see how the supply chains of emitting sectors contribute to total emissions. The electricity sector mainly contributes in later layers, because the manufacturing industry sectors mainly use electricity as an input.

The situation is different at opex in the lower diagrams. In the left diagram, we can see the inputs of operating desalination plants. Electricity is the input factor, that is responsible for a significant share of total emissions. As a result, the electricity sector contributes a high proportion of its total emissions already in earlier stages, as we see on the right chart. The share that the sector emits as a supplier is higher than at capex.

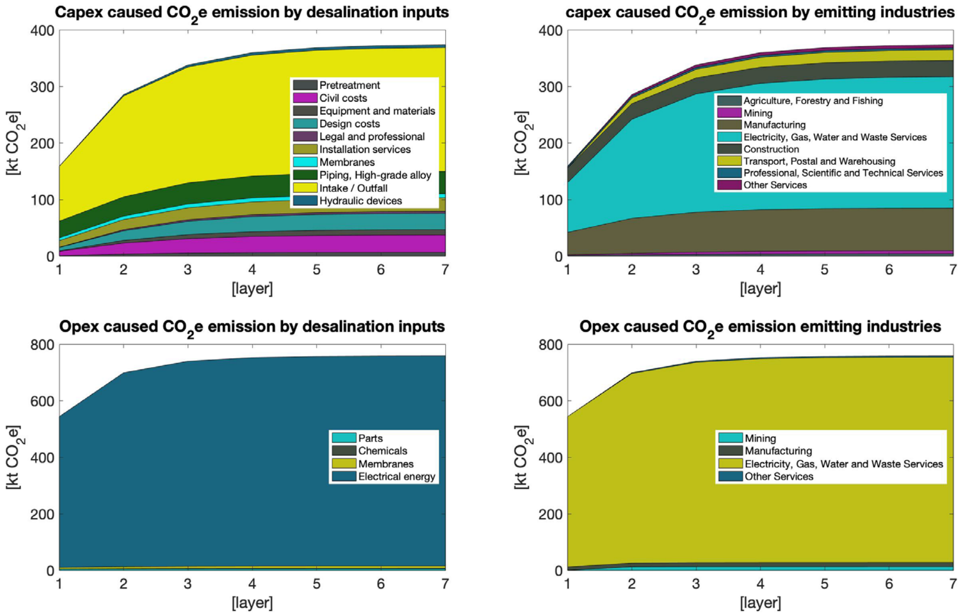

Figure 5 Production layer decomposition for desalination inputs and emitting industries in 2012.

4 Conclusion

Desalination is an energy-intensive technology. When powered by fossil fuel, high carbon emissions ensue. For our study, we have assumed that all seawater desalination plants are operated by conventional energy, even if Australia operates some plants with renewable energy. Economic requirements and population growth are the drivers of desalination and carbon emission in the first place. Carbon emissions from desalination occur first notably at the economic hot spots, especially in Victoria as the location of Australia's largest desalination plant. We want to point out that the results relate to CO_2e emissions in Australia. Our model does not cover the value chains of imports. According to the estimated domestic quotas of about 80% on average[2], we estimate that capex has covered about 80% of the emissions. Supplying countries emit additional greenhouse gases.

We show that policy must consider the entire supply chains to make desalination environmentally sustainable. Construction of intake and outfall is highly carbon-intensive within the construction period. In the construction phase, the electricity industry is the economic sector with the highest carbon emissions. The electricity sector becomes even more crucial for carbon emissions within the operation phase. The sector is not only the crucial point for carbon emissions due to direct demand,

[2] In the published version of this study, an import quota of 80% was accidentally mentioned. We have corrected this here.

but the sector is also a key factor regarding intermediate demands throughout the entire value chain. This is made clear once again, as Australia's energy sector accounts for 35% of greenhouse gas emissions in 2012-2013 [44].

The electricity sector significantly outperforms its contribution to carbon emissions within the life cycle of desalination, compared to its national contribution of 35%. During the construction phase in 2010 (with simultaneous operation), the electricity sector accounts for 69% of all greenhouse gas emissions attributable to seawater desalination. In the pure operating phase in 2015, the share of carbon emissions of the electricity sector even accounts for 96% of the total emissions.

Substitution of fossil energies by renewable energies can thus be the game changer for the sustainability of desalination. Especially dry regions are affected by climate change. These regions are strongly dependent on seawater desalination. The use of desalination is only sustainable if it does not substantially emit more greenhouse gases. Policy must act and focus on the energy sector. The key is the transformation of the electricity sector and the change in the current energy mix with a drastic increase in the share of renewable energies.

In our following studies, we will analyse carbon effects if we substitute electrical energies by renewable sources. We will further study the social and economic effects of desalination.

5 Acknowledgements

This research was supported by Integrated Sustainability Analysis in the School of Physics at the University of Sydney. The Authors acknowledge financial support by the Department of Energy Engineering at Technical University of Berlin, the National eResearch Collaboration Tools and Resources project (NeCTAR) through its Industrial Ecology Virtual Laboratory. NeCTAR is an Australian Government project conducted as part of the Super Science initiative and financed by the Education Investment Fund. We finally acknowledge the Friedrich Naumann Foundation for Freedom. The authors appreciate the anonymous reviewers for their helpful comments and suggestions on the paper.

6 Bibliography

[1] M.M. Mekonnen, A.Y. Hoekstra, Four billion people facing severe water scarcity, Sci. Adv. 2 (2016) 1–6. doi:10.1126/sciadv.1500323.

[2] WHO, UNICEF, Progress on drinking water and sanitation: 2012 update, 2012. http://www.wssinfo.org/fileadmin/user_upload/resources/JMP-report-2012-en.pdf.

[3] S. Lattemann, T. Höpner, Environmental impact and impact assessment of seawater desalination, Desalination. 220 (2008) 1–15. doi:10.1016/j.desal.2007.03.009.

[4] United Nations Development Programme, Water governance in the arab region: Managing scarcity and securing the future, New York, 2013.

[5] C.A. Scott, S.A. Pierce, M.J. Pasqualetti, A.L. Jones, B.E. Montz, J.H. Hoover, Policy and institutional dimensions of the water-energy nexus, Energy Policy. 39 (2011) 6622–6630. doi:10.1016/j.enpol.2011.08.013.

[6] V.G. Gude, Desalination and sustainability - An appraisal and current perspective, Water Res. 89 (2016) 87–106. doi:10.1016/j.watres.2015.11.012.

[7] B.M. Haddad, A case for an ecological-economic research program for desalination, Desalination. 324 (2013) 72–78. doi:10.1016/j.desal.2013.06.003.

[8] The World Bank, Renewable energy desalination. An emerging solution to close the water gap in the middle east and north africa, 2012. doi:10.1596/978-0-8213-8838-9.

[9] R. Einav, K. Harussi, D. Perry, The footprint of the desalination processes on the environment, Desalination. 152 (2003) 141–154. doi:10.1016/S0011-9164(02)01057-3.

[10] I. Muñoz, A.R. Fernández-Alba, Reducing the environmental impacts of reverse omosis desalination by using brackish groundwater resources., Water Res. 42 (2008) 801–11. doi:10.1016/j.watres.2007.08.021.

[11] J. Liu, S. Chen, H. Wang, X. Chen, Calculation of carbon footprints for water diversion and desalination projects, Energy Procedia. 75 (2015) 2483–2494. doi:10.1016/j.egypro.2015.07.239.

[12] A.A. Setiawan, Y. Zhao, C. V. Nayar, Design, economic analysis and environmental considerations of mini-grid hybrid power system with reverse osmosis desalination plant for remote areas, Renew. Energy. 34 (2009) 374–383. doi:10.1016/j.renene.2008.05.014.

[13] F. Vince, F. Marechal, E. Aoustin, P. Bréant, Multi-objective optimization of RO desalination plants, Desalination. 222 (2008) 96–118. doi:10.1016/j.desal.2007.02.064.

[14] J.J. Sadhwani, J.M. Veza, C. Santana, Case studies on environmental impact of seawater desalination, Desalination. 185 (2005) 1–8. doi:10.1016/j.desal.2005.02.072.

[15] M.F.A. Goosen, H. Mahmoudi, N. Ghaffour, Today's and future challenges in applications of renewable energy technologies for desalination, Crit. Rev. Environ. Sci. Technol. 44 (2014) 929–999. doi:10.1080/10643389.2012.741313.

[16] G. Raluy, L. Serra, J. Uche, Life cycle assessment of MSF, MED and RO desalination technologies, Energy. 31 (2006) 2361–2372. doi:10.1016/j.energy.2006.02.005.

[17] Q. Zou, X. Liu, Economic Effects Analysis of Seawater Desalination in China with Input–Output Technology, Desalination. 380 (2016) 18–28. doi:10.1016/j.desal.2015.11.010.

[18] J. Stokes, A. Horvath, Life cycle energy assessment of alternative water supply systems, Int. J. Life Cycle Assess. 11 (2006) 335–343. doi:10.1065/lca2005.06.214.

[19] M.P. Shahabi, A. McHugh, M. Anda, G. Ho, Environmental life cycle assessment of seawater reverse osmosis desalination plant powered by renewable energy, Renew. Energy. 67 (2014) 53–58. doi:10.1016/j.renene.2013.11.050.

[20] W.W. Leontief, Input-output economics, 1st ed., Oxford University Press, New York, 1966.

[21] S. Nagashima, Y. Uchiyama, K. Okajima, Hybrid input–output table method for socioeconomic and environmental assessment of a wind power generation system, Appl. Energy. 185 (2017) 1067–1075. doi:10.1016/j.apenergy.2016.01.018.

[22] B. Corona, C. de la Rúa, G. San Miguel, Socio-economic and environmental effects of concentrated solar power in Spain: A multiregional input output analysis, Sol. Energy Mater. Sol. Cells. 156 (2016) 112–121. doi:10.1016/j.solmat.2016.03.014.

[23] F. Pomponi, M. Lenzen, Hybrid life cycle assessment (LCA) will likely yield more accurate results than process-based LCA, J. Clean. Prod. 176 (2018) 210–215. doi:10.1016/j.jclepro.2017.12.119.

[24] M. Lenzen, A. Geschke, T. Wiedmann, J. Lane, N. Anderson, T. Baynes, J. Boland, P. Daniels, C. Dey, J. Fry, M. Hadjikakou, S. Kenway, A. Malik, D. Moran, J. Murray, S. Nettleton, L. Poruschi, C. Reynolds, H. Rowley, J. Ugon, D. Webb, J. West, Compiling and using input–output frameworks through collaborative virtual laboratories, Sci. Total Environ. 485–486 (2014) 241–251. doi:10.1016/J.SCITOTENV.2014.03.062.

[25] [dataset] Australian Bureau of Statistics, Input output product classification, ABS Catalogue No. 5215.0.55.001, Canberra, 2012.

[26] Australian Bureau of Statistics, [dataset] Australian statistical geography standard: Design of the statistical areas level 2, ABS Catalogue No. 1216.0.55.003, Canberra, 2010.

[27] M. Lenzen, A. Geschke, A. Malik, J. Fry, J. Lane, T. Wiedmann, S. Kenway, K. Hoang, A. Cadogan-Cowper, New multi-regional input–output databases for Australia – enabling timely and flexible regional analysis, Econ. Syst. Res. 29 (2017) 275–295.

doi:10.1080/09535314.2017.1315331.

[28] M. Lenzen, J.M. Rueda-Cantuche, A note on the use of supply-use tables in impact analyses, Stat. Oper. Res. Trans. 36 (2012) 139–152.

[29] M. Lenzen, B. Gallego, R. Wood, Matrix balancing under conflicting information, Econ. Syst. Res. 21 (2009) 23–44. doi:10.1080/09535310802688661.

[30] M. Lenzen, K. Kanemoto, D. Moran, A. Geschke, Mapping the structure of the world economy, Environ. Sci. Technol. 46 (2012) 8374–8381. doi:10.1021/es300171x.

[31] P. Glueckstern, History of desalination cost estimations, in: Proc. Int. Conf. Desalin. Costing, 2004.

[32] J.R. Ziolkowska, R. Reyes, Impact of socio-economic growth on desalination in the US, J. Environ. Manage. 167 (2016) 15–22. doi:10.1016/j.jenvman.2015.11.013.

[33] M.K. Wittholz, B.K. O'Neill, C.B. Colby, D. Lewis, Estimating the cost of desalination plants using a cost database, Desalination. 229 (2008) 10–20. doi:10.1016/j.desal.2007.07.023.

[34] K.C. Kavvadias, I. Khamis, The IAEA DEEP desalination economic model: A critical review, Desalination. 257 (2010) 150–157. doi:10.1016/j.desal.2010.02.032.

[35] [dataset] Global Water Intelligence, Desaldata, Database. (2016). http://www.desaldata.com (accessed February 1, 2018).

[36] [dataset] World Sea Temperature, World sea temperature, Database. (2018). https://www.seatemperature.org (accessed January 20, 2018).

[37] [dataset] Australian Energy Regulator, Annual volume weighted average spot prices, (2009). https://www.aer.gov.au/wholesale-markets/wholesale-statistics/annual-volume-weighted-average-spot-prices (accessed January 29, 2018).

[38] [dataset] Australian Energy Market Operator, Short term energy market data, (2009). http://data.wa.aemo.com.au/#stem-summary (accessed February 1, 2018).

[39] [dataset] International Monetary Fund, Australian dollar exchange rates, (2018). https://www.imf.org/external/np/fin/ert/GUI/Pages/CountryDataBase.aspx (accessed February 2, 2018).

[40] [dataset] Australian Bureau of Statistics, Producer price indexes, ABS Catalogue No. 6427.0, Canberra, 2017.

[41] T. Wiedmann, Editorial: Carbon footprint and input-output analysis - an introduction, Econ. Syst. Res. 21 (2009) 175–186. doi:10.1080/09535310903541256.

[42] R.E. Miller, P.D. Blair, Input-output analysis: Foundations and extensions, 2nd ed., Cambridge University Press, New York, 2009.

[43] Australian Energy Regulator, State of the energy market, Melbourne, 2017. https://www.aer.gov.au/publications/state-of-the-energy-market-reports/state-of-the-energy-market-may-2017.

[44] P. Wolfram, T. Wiedmann, M. Diesendorf, Carbon footprint scenarios for renewable electricity in Australia, J. Clean. Prod. 124 (2016) 236–245. doi:10.1016/j.jclepro.2016.02.080.

7 Abbreviations

Capital expenditure - capex

Carbon dioxide equivalents - CO_2e

Desalination Economic Evaluation Program - DEEP

Engineering-Procurement-Construction - EPC

Industrial Ecology Lab - IELab

Input-output - IO

Input-output analysis - IOA

Input-output product classification -IOPC

Input-output table - IOT

International Atomic Energy Agency - IAEA

Life cycle assessment - LCA

Konfliktfreies RAS - KRAS

Multiple-effect distillation - MED

Multi region input-output - MRIO

Operational expenditure - opex

Production Layer Decomposition - PLD

Reverse Osmosis - RO

Statistical Area Level 2 - SA2

Short term energy market - STEM

World Input Output Database - WIOD

8 Appendix

Appendix 1: Adjustment of the costs of seawater desalination plants

Desalination Plant	**Capacity [m^3/d]**	**Location**	**Award Year**	**Online Year**
Victorian Desalination Plant	444000	Victoria	2009	2012
Port Stanvac	274000	South Australia	2009	2012
Sydney Desalination Plant (Kurnell)	250000	New South Wales	2007	2010
Kwinana	143700	Western Australia	2005	2006
Southern Seawater desalination plant	140000	Western Australia	2009	2011
Sino Iron Ore Project, Cape Preston	140000	Western Australia	2008	2012
Southern Seawater Desalination Plant (expansion)	140000	Western Australia	2011	2013
Tugun (Gold Coast)	133000	Queensland	2006	2009
Browse downstream engineering processes	10560	Western Australia	2011	2012

Agnes Water Integrated Water Project	7500	Queensland	2008	2011
Bechtel Wheatstone construction	7500	Western Australia	2012	2012
Onslow	7500	Western Australia	2013	2013
Gorgon	7000	Western Australia	2010	2012
Curtis LNG Project	5000	Queensland	2010	2011
Jabiru	5000	Northern Territory	2006	2007
Bechtel Wheatstone compaction 2	4500	Western Australia	2011	2012
Onslow2	4500	Western Australia	2013	2013
Onesteel Whyalla Plant	4100	South Australia	2010	2011
Penrice	4050	South Australia	2005	2006
Fortescue Metals Group Port Headland	4000	Western Australia	2011	2012

Appendix 2: Adjustment of the costs of seawater desalination plants

#	**Plant**	**Adjustment**	**Used Sources**
1	Victoria Desalination Plant (Melbourne)	Capacity and construction years not adjusted • not adjusted Capex: • $1.8 bn (desaldata) • A$3.5 bn (2009) • adjusted to US$3.908 bn (2012) Opex: • net present value $2.602 bn, 27 years, intern	Capacity: https://www.aquasure.com.au/uploads/files/DesalinationProcessFactSheet-1482449673.pdf Capex: https://www.copyschool.com/wp-content/uploads/2014/09/Olex-Cables-Case-Studies.pdf https://www.dtf.vic.gov.au/sites/default/files/2018-01/Project-Summary-for-Victorian-Desalination-Project.pdf https://en.wikipedia.org/wiki/Victorian_Desalination_Plant#Cost

		7.3%, assumption progression factor 3%, result: A$167 m (2009), US$162 m (2015), subtracted labour cost according to share of cost estimator, final result: US$128 m (2015) Electricity: • 4.8 kWh/m^3	https://www.water.vic.gov.au/__data/assets/pdf_file/0013/54202/Fact-sheet-project-costs-March-2015.pdf https://www.water.vic.gov.au/__data/assets/pdf_file/0013/54202/Fact-sheet-project-costs-March-2015.pdf Opex: https://en.wikipedia.org/wiki/Victorian_Desalination_Plant https://www.dtf.vic.gov.au/sites/default/files/2018-01/Project-Summary-for-Victorian-Desalination-Project.pdf Electricity: email from operator watersure
2	Port Stanvac (Adelaide)	Capacity and construction years not adjusted Capex: • US$ 1.374 bn (desaldata) • Source AU$1.824 bn • adjusted to AU$1.883 bn (2012) Opex: • Source AU$130 m (2010) • adjusted to US$123 m (2015) Electricity: • 3.6 kWh/m^3	Capex: https://www.water-technology.net/projects/adelaide-plant/ http://www.acciona.com.au/projects/water/desalination-plants/adelaide-desalination-plant/ https://www.mcconnelldowell.com/markets/water-waste-water/42-adelaide-desalination-plant-project https://www.environment.sa.gov.au/topics/water/resources/desalination https://en.wikipedia.org/wiki/Adelaide_Desalination_Plant Opex: http://www.abc.net.au/news/2017-10-28/adelaide-desal-plant-too-big-and-too-expensive/9096046 http://www.abc.net.au/news/2010-12-01/130m-annual-cost-to-run-desal-plant/2358158 Electricity: http://www.awa.asn.au/AWA_MBRR/Publications/Water_e-Journal/SEAWATER_DESALINATION__A_SUSTAINABLE_SOLUTION_TO_WORLD_WATER_SHORTAGE_.aspx
3	Sydney Desalination Plant	Capacity and construction years not adjusted Capex:	Official reports: https://www.ipart.nsw.gov.au/Home/Publications Capex:

		• US$865 m (desaldata) • source AU$1.803 m (2010) • US$1.591 m (2010) Opex: • own calculations of average from 2012-2017 cost at full production: AU$85.5 m (2012) • US$76 m (2015) Electricity: • own calculations 3.6 kWh/m^3	https://ac.els-cdn.com/S0011916409004822/1-s2.0-S0011916409004822-main.pdf?_tid=772d2a54-cf01-4a98-a874-d046d29407f1&acdnat=1537779245_70eb5b6abda146143e7804e2640c58cb http://www.awa.asn.au/AWA_MBRR/Publications/Fact_Sheets/Desalination_Fact_Sheet.aspx https://link.springer.com/content/pdf/10.1007%2Fs11269-014-0901-y.pdf http://www.onlineopinion.com.au/view.asp?article=19874 Opex: https://www.ipart.nsw.gov.au/files/sharedassets/website/shared-files/pricing-reviews-water-services-metro-water-legislative-requirements-investigation-into-pricing-for-sydney-desalination-plant-pty-ltd-from-1-july-2017/final-report-sydney-desalination-plant-pty-ltd-review-of-prices-from-1-july-2017-to-30-june-2022.pdf https://www.ipart.nsw.gov.au/files/sharedassets/website/trimholdingbay/consultant_report_-_review_of_operating_and_capital_expenditure_by_sydney_desalination_plant_pty_ltd_-_halcrow_-_october_2011-_website_document.pdf Electricity: https://www.ipart.nsw.gov.au/files/sharedassets/website/shared-files/pricing-reviews-water-services-metro-water-legislative-requirements-investigation-into-pricing-for-sydney-desalination-plant-pty-ltd-from-1-july-2017/consultant-report-by-atkins-sydney-desalination-plant-expenditure-review-february-2017.pdf
4	Perth Seawater Desalination Plant	Capacity and construction years not adjusted Capex: • AU$347 m (desaldata) • source AU$387 m (2007) • US$304 m (2006) Opex • source AU$22.5(2006) • adjusted to US$ 24 m (2015)	Capex: https://www.water-technology.net/projects/perth/ https://ac.els-cdn.com/S0011916409004822/1-s2.0-S0011916409004822-main.pdf?_tid=7f58ad1e-7572-4dbb-8969-98a20db72204&acdnat=1537799019_c48bd7caca98a56c8fb033b96743b013 https://www.watercorporation.com.au/about-us/news/media-statements/media-release/desalination-plant-per-kilolitre-cost-based-on-comprehensive-analysis Opex:

		Electricity: • 4.2 kWh/m^3	https://www.water-technology.net/projects/perth/ https://www.watercorporation.com.au/about-us/news/media-statements/media-release/desalination-plant-per-kilolitre-cost-based-on-comprehensive-analysis http://pacinst.org/wp-content/uploads/2013/02/financing_final_report3.pdf http://www.ecosmagazine.com/?act=view_file&file_id=EC124p23.pdf Electricity: https://www.water-technology.net/projects/perth/ http://www.degremont.com.au/media/general/Perth_Seawater_Desalination_Plant_1.pdf https://ac.els-cdn.com/S0011916409004822/1-s2.0-S0011916409004822-main.pdf?_tid=7f58ad1e-7572-4dbb-8969-98a20db72204&acdnat=1537799019_c48bd7caca98a56c8fb033b96743b013 https://www.researchgate.net/publication/228491362_Low_energy_consumption_in_the_Perth_seawater_desalination_plant Construction: http://www.degremont.com.au/projects/perth-seawater-desalination-plant/ Electricity: https://en.wikipedia.org/wiki/Perth_Seawater_Desalination_Plant
5 & 7	Southern Seawater Desalination Plant (Perth)	Capacity not adjusted Online year of expansion adjusted to 2014 Capex: • desaldata: US$592m first stage and US$471 m expansion • AU$955 m (first stage in 2011) • US$ 944 m (2011)	Capex: https://www.water-technology.net/projects/southern-seawater-desalination-plant/ http://www.abc.net.au/news/2009-06-24/final-approval-for-sw-desalination-plant/1330958?site=news https://www.bunburymail.com.au/story/1253516/first-seawater-flows-into-binningup-desalination-plant/ https://www.water-technology.net/projects/southern-seawater-desalination-plant/

		• AU$450 m (expansion in 2013) • US$463 m (2013) Opex: • no data, we used cost estimator sum Electricity: • 4.0 kWh/m^3	http://www.ancr.com.au/southern_seawater_desalination.pdf Construction: https://www.bunburymail.com.au/story/1253516/first-seawater-flows-into-binningup-desalination-plant/ https://www.water-technology.net/projects/southern-seawater-desalination-plant/ https://www.watercorporation.com.au/about-us/news/media-statements/media-release/southern-seawater-desalination-plant---expansion-project-update Electricity: http://www.epa.wa.gov.au/sites/default/files/EPA_Report/2797_Rep1302Desal_61008.pdf http://www.epa.wa.gov.au/sites/default/files/EPA_Report/2797_Rep1302Desal_61008.pdf
6	Sino Iron Project	Capacity and construction years not adjusted no further data found, we used data from desaldata without adjustments	Capacity: https://www.ide-tech.com/en/our-projects/cape-preston-desalination-plant/?data=item_1 Construction: https://www.ide-tech.com/en/our-projects/cape-preston-desalination-plant/?data=item_1
7	Gold Coast Desalination Plant	Capacity and construction years not adjusted Capex: • Desaldata: US$838 m (2009) • AU$1.12 bn (2009) • Desaldata is correct, no adjustment needed • Opex: • Desaldata: • AU$1,021 per megalitre (2012) at full capacity • own calculations: AU$47 m (2012), US$42 m (2015) Electricity: • 3.6 kWh/m^3	Capex: https://www.advisian.com/en-gb/global-perspectives/the-cost-of-desalination https://en.wikipedia.org/wiki/Gold_Coast_Desalination_Plant https://www.water-technology.net/projects/gold-coast-plant/ Opex: https://www.advisian.com/en-gb/global-perspectives/the-cost-of-desalination http://www.qca.org.au/getattachment/8da7c759-06cf-462c-96df-de7bcbe29514/Seqwater-submission-Appendix-C.aspx http://www.parliament.qld.gov.au/Documents/TableOffice/TabledPapers/2015/5515T1824.pdf Electricity: https://www.water-technology.net/projects/gold-coast-plant/ https://www.water-technology.net/projects/gold-coast-plant/
