Towards new opportunities for reuse, recycling and disposal of used reverse osmosis membranes

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ABSTRACT

In an effort to reduce its environmental impact, the desalination industry constantly seeks more sustainable operational and maintenance practices. Based on the increasing number of large desalination plants using membrane technology, the resulting number of old reverse osmosis (RO) modules to be discarded is expected to become a critical challenge. Although the fate of old RO membranes has rarely been considered in the past, a wide range of opportunities can be considered for the potential reuse and recycling of the old modules. Reuse options include direct application of the old membranes within lower throughput systems (i.e. brackish water treatment) and chemical conversion into porous, ultrafiltration-like filters. Other options include, direct recycling of the various module components, and energy recovery through incineration. In addition to the remaining technical issues related to the feasibility of these proposed options, strategic and policy challenges will need to be addressed. However, the concept of product stewardship, already implemented in many parts of the world for electronic wastes and packaging, can provide guidelines for future policies for RO disposal. Finally, the framework for a life cycle assessment of the various disposal options is discussed which may provide guidance for the future implementation of these strategies.

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1. Introduction

Over the last two decades, the number of reverse osmosis (RO) desalination plants has increased by 70%, with a total of 9000 installations currently online around the world [1]. The size of these RO plants has also increased significantly, now exceeding 500,000 m³/d in many parts of the world. Notwithstanding this growing constant need to secure water production, the industry still faces the challenge of improving its environmental sustainability [2,3]. Although the large amount of energy needed to pressurise the feed water for desalination is the primary environmental concern, the disposal of old RO modules is emerging as a critical issue to be addressed. So far, used RO modules are considered as common waste and are generally incinerated or discarded to municipal landfills, with few disposal alternatives proposed to RO users.

Given the range of pre-treatment water qualities and their associated operating conditions, it is estimated that an average of 100 of the 8″ modules is generally needed to produce each mega litre per day (MLD) of water. Based on an average of 13.5 kg per 8″ module [4],

the use of a basic single pass system, and a mean membrane life of 6 years, the inventory of the current plants worldwide allows the estimation of the total mass of modules to be disposed annually (Fig. 1). The steady increase in the mass of old membranes, reaching 12,000 tonnes (per year) by 2015, clearly indicates the magnitude of the potential disposal problem.

Concepts inherent in the waste management hierarchy are shown in Fig. 2. This figure can help to prioritise and assess the most sustainable strategies for the management of old RO modules [5]. While avoiding and reducing the use of the RO modules is not considered within the scope of this publication (refer to Ref. [6] for a recent review on improved capacity and lifespan of RO membranes), direct reuse of the product is generally recommended over recycling, with waste disposal being the least desired option. In the case of RO modules, energy recovery is expected to present significant opportunities, and is generally regarded as more preferable to disposal [4].

In accordance with general waste management principles, detailed characterisation of the material remains the initial and critical step for determining the potential waste management strategies. Advanced analysis of two RO membranes (i.e. DOW FILMTEC BW30 and LE-440i, 2.5″ and 8″ respectively) has already facilitated the observations of the internal makeup of commercial membranes [4]. The first
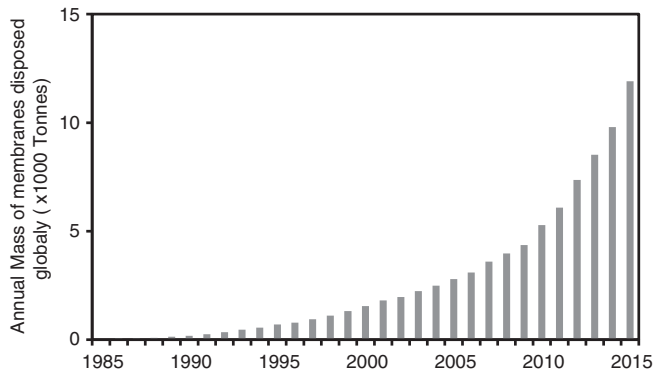
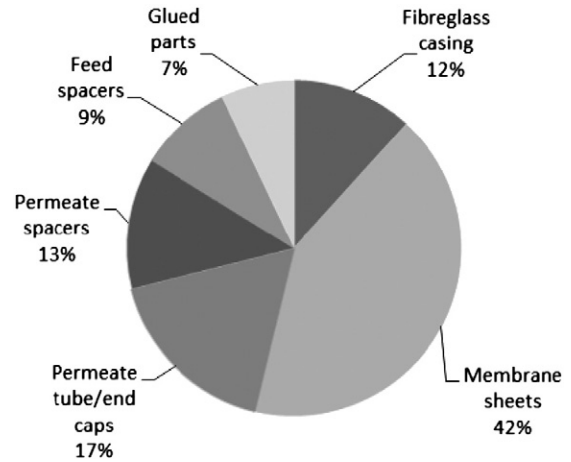Fig. 1. Estimation of the annual mass of RO modules to be discarded.

Fig. 3. Composition of a typical 8″ RO membrane [4].

important observation is the composition of the various elements of the RO modules which are essentially polymeric. A breakdown of the typical composition of components of a new 8″ RO membrane can be seen in Fig. 3.

The composite RO membrane sheet is typically made of thin aromatic polyamide dense layer, supported by microporous polysulfone (PSf) inner layer and non-woven polyester webbing. In addition, the following plastics are used in the fabrication of the two autopsied RO membranes: polypropylene (PP) for feed spacer, polyester for permeate spacer, acrylonitrile butadiene styrene (ABS) for the permeate tube and end-caps, and fibreglass for the outer casing. Finally, glued parts (i.e. containing proprietary epoxy-like components) accounted for 7 to 9% of the weight of the two analysed modules. Through this detailed analysis of the RO modules, this study can help to anticipate the challenges and opportunities related to the management of this type of composite waste product.

Additionally, it is important to understand the mechanisms of membrane ageing and to assess its consequences, which ultimately results in the decline of RO performance, such that it no longer meets its initial specifications. Several factors contribute to RO damage, which can be functionally determined by an increase in permeate throughput and/or a decline in salt rejection. Another common indicator for the decline in system performance is an increase in pressure drop along the pressure vessel. The loss of RO performance can result from irreversible organic and/or inorganic fouling [7,8] and chemical degradation of the active membrane layer [9]. Microbiological fouling, generally defined as the consequence of irreversible attachment and growth of bacterial cells on the membrane, is also a common reason for discarding old membranes [10]. A variety of oxidative solutions, cleaning and antifouling agents is widely used in desalination plants, and their repetitive and incidental exposure can adversely affect the membranes, generally through the decrease of their rejection efficiencies [11,12].
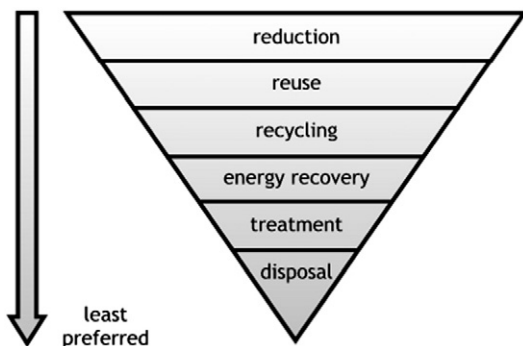

Fig. 2. Waste management hierarchy from most to least preferred options.

Consequently, the current disposal of old RO modules can result in significant environmental impacts. The aim of this initial study is therefore to present potential strategies for the reuse, recycling and alternative disposal of old RO modules used in the desalination industry, and provide an initial assessment of their viability. The main outcomes of this project will help to minimise the environmental impacts by increasing the lifecycle of the membrane elements via a secondary use or material reuse, and thereby lowering the carbon footprint and further improving sustainability of RO technology.

2. Reuse options

2.1. Direct membrane reuse

Published only recently, a very limited number of reports have mentioned the potential of direct RO reuse. The two identified studies were based on the detailed characterisation of old RO filters after seawater filtration [4,13]. One study from France [13] used autopsy techniques including hydraulic permeability, salt rejection, morphological and topographical parameters with field emission scanning electron and atomic force microscopies. Not surprisingly, the old RO element showed performances similar to those usually obtained by nanofiltration (NF) membranes including an increase in permeability from 1.0 to 2.1 L m^{-2} h^{-1} bar^{-1} and a decrease in NaCl rejection from >90% to 35–50% [13]. Given their average molecular weight cut off (MWCO) ranging between 100 and 1000 Da, and their capacity to remove small organics and divalent ions, NF membranes are generally used in the food processing, water and wastewater industries (industrial and domestic). Similar findings were obtained when the performances of used membrane elements were compared to those reported for new membranes during another study in Australia [4]. It was concluded that although the sampled membranes were no longer in accordance with the manufacturer's performance criteria of 99.5% salt rejection, all tested membranes showed more than 96% rejection. The authors proposed that the high level of salt-rejection would allow repurposing of the membranes for applications including brackish-water treatment [4]. Other direct reuse applications such as seawater pretreatment and selective demineralisation of brackish water can be considered as suitable reuse strategies for old RO membranes [14–17].

Although direct reuse of old membranes without any additional treatment is obviously preferred, appropriate assessment of their current performances, further validation and potential chemical cleaning will most likely be required. Information on the used membrane performance from the plant of origin, as well as a number of additional monitoring and characterisation methods, can enable a tailored

cleaning system to be developed [18]. Based on the type of feed water used and location of the RO membranes within the filtration train, standard chemical cleaning protocols could be established in order to efficiently remove most of the fouling/scaling that may have occurred during the filtration. A combination of cleaning agents can be used to remove a variety of foulants, including acids for iron and metal oxides [19]; commercial anti-scalants [20,21]; and alkalines, biocides, detergents and enzymes for bio-fouling [10,22,23]. In addition to fouling, membrane compaction can adversely affect the performance; however, due to advances in membrane material technology, these effects are reduced [24,25]. The slow creep of the polymer due to long term application of pressure results in a loss of water permeability, which requires an increase in operating pressure to maintain productivity. A critical step in this reuse process is the validation of the cleaned membranes, as integrity, permeability and rejection must be demonstrated before the membranes can be successfully reused. This could be simply obtained through detailed report of the RO performance at the end of their initial life time.

To date, one US-based company, WaterSurplus, has recognised the potential of direct reuse of membranes. The company indeed offers a wide range of new surplus as well as used, cleaned and repackaged, RO, UF and NF membranes and associated equipment. Based on the condition of the used RO products, unit cost ranges from USD150 to 400, with batches of up to 400 elements available to purchase [26].

2.2. Multi-membrane vessel design

The concept of using RO elements with different performances within the same pressure vessel in order to optimise the overall process efficiency has been recently introduced [27]. This novel hybrid system generally proposes the use of high rejection, low productivity membranes in the upstream section of the filtration train, followed by high productivity, low energy membranes downstream. This design benefits from either a reduction in power consumption as a result of lower pressure requirements, or an increase in productivity. With fewer modules and pressure vessels required for a given application, this concept could also result in significant decrease in capital costs [28].

It is proposed to adapt this original concept, by internally reusing older RO membranes within the same pressure vessel. The sequential, strategic movement of membranes to higher productivity positions can coincide with a change in performance, resulting from membrane ageing and degradation. When a fresh high rejection membrane is inserted into the lead position of the module, the removal of the oldest module at the end of the vessel will be conducted simultaneously, allowing a gradual movement to older membranes downstream. This movement is demonstrated in Fig. 4. A more rigorous cleaning protocol could be applied just prior to this changeover, thus sparing the fresh module from the potentially damaging process. In order to assess the viability of this concept, the membrane performance will first need to be validated and monitored, as well as an economic impact of the extra labour required.

2.3. Membrane conversion

Given the nature of the composite membrane usually used in RO production [29], and especially the structure of the supporting layer, relatively simple conversion of the dense RO into a porous material is possible through the degradation of the polyamide layer. Indeed, the combination of the polysulfone and polyester support layers within RO membranes is markedly similar to ultrafiltration (UF)

materials [30]. The relative vulnerability of the polyamide dense layer towards conventional oxidative agents could be used as a conversion method [31]. The resulting converted RO membrane could then be expected to feature hydraulic and removal performances that are comparable to commercially available UF products.

Initial attempts to convert used RO into porous membranes have been conducted a decade ago in Spain [32]. In this early work, sodium hypochlorite (NaOCl) and other strongly oxidative chemicals, including hydrogen peroxide (H_2O_2), sodium dodecyl sulphate and potassium permanganate ($KMnO_4$), were tested under different operating conditions (active recirculation versus passive immersion) to remove the active layer from the membrane. From these initial tests, $KMnO_4$ was found to be the most effective agent to convert old RO membranes, with an optimal dose of approximately 1000 mg/L for 1 to 2 hours [32]. In addition, it was concluded that an active recirculation contact method was more successful than a passive immersion method. The use of the newly converted membranes within the tertiary treatment step of municipal wastewater was then assessed in a following study [33]. The converted membranes demonstrated a potential to remove up to 96% of the suspended solids before further RO treatment. Although a high level of fouling was recorded during the filtration, the deposition was easily reversible by hourly flushing and alkaline chemical cleaning every 3 to 4 days. A nearly complete recovery of the converted membrane permeability was possible for the few weeks of the test [33].

Although presenting an interesting avenue for subsequent re-use of old RO membranes, this original concept had not been further explored. Thus, following on this idea, a study has been recently initiated in Australia [34]. One of the outcomes of the current, ongoing work is to further characterise the optimal operating conditions for the conversion. By using the concept of the product of concentration and ageing time in ppm-h, this study has revealed the higher degradation impact of NaOCl over $KMnO_4$ when the resulting converted membranes were assessed in terms of permeability performances and salt rejection.

Following the recommended ageing process (i.e. exposure to a solution of 6.25 g/L NaOCl for 48 hours, equivalent to 300,00 ppm-h), the permeability of a DOW FILMTEC BW30FR membrane increased from 4 to > 170 L m^{-2} h^{-1} bar^{-1}, while the NaCl rejection declined to below 5%. These results clearly demonstrated the capacity of the chemical treatment to successfully degrade most of the polyamide layer, converting the original membrane into a UF-like filter. Preliminary protein rejection characterisation was conducted on both converted RO membranes and commercially available UF membranes (10 kDa MWCO). Given that the two tested membranes featured similar rejection performance, it was concluded that the MWCO of the converted RO samples ranged between 10 and 100 kDa, which classifies them as UF. Fig. 5 presents the scanning electron microscopy (SEM) pictures of the surface of the BW30FR membrane before (A) and after (B) the chlorine conversion treatment (300,000 ppm-h), compared to the SEM of the surface of a Pall Omega 10 kDa PES UF membrane.

As the study employed membranes from different suppliers and from a variety of uses, a resulting wide range of both used and virgin brackish and sea water membranes will need to be tested to fully validate this conversion process. While all samples treated so far resulted in very low rejection performances [34], a range of hydraulic capacities was observed that were within UF-like specifications. This can potentially be attributed to the individual composition of the support layer among the different manufacturers, and will require further consideration.
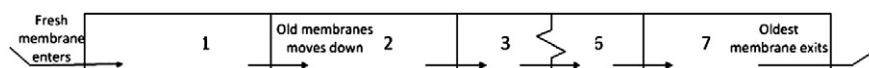

Fig. 4. Old membrane movement along the pressure vessel in hybrid system.
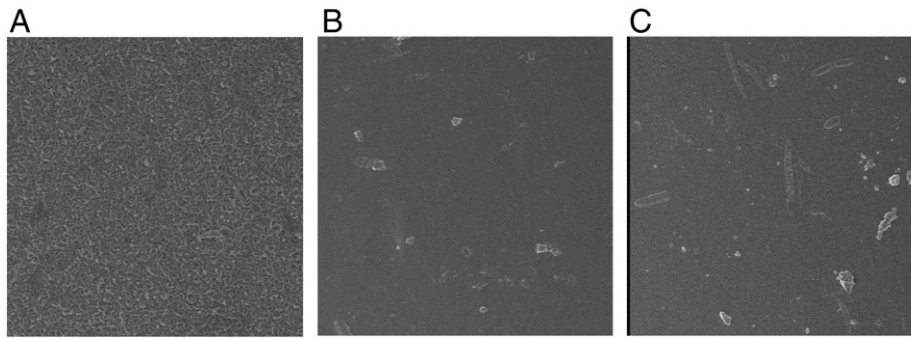
Fig. 5. Scanning electron microscopy images at 3000× magnification: RO membrane before (A) and after (B) chlorine exposure and standard UF membrane (C).

Potential applications for the converted RO membranes include use in pre-treatment filtration in desalination plants or within advanced treatment of wastewater. In both cases, it is expected that converted RO modules could remove all suspended solids, large organics species, and a significant fraction of pathogens from feed streams. Converted membranes can also be considered for low cost water disinfection for rural communities and in developing countries, with such applications being studied in ongoing investigation conducted by the authors. The concept of using membranes in gravity driven configurations has been thoroughly investigated in the literature and a number of products are currently available [35]. By assessing the membrane systems that are currently available and the previous work conducted on decentralised operations, particularly low cost gravity driven systems, a criteria for membranes that could be used in developing rural areas can be established [36]. One such system is the SkyJuice SkyHydrant [37], which could potentially be adapted to use converted RO membranes, thus reducing the cost of the unit. Large scale water treatment facilities and distribution systems can be cost prohibitive for remote communities and decentralised systems need to be simple to run and maintain, compact and low cost. It has been concluded that UF membrane of around 100 kDa MWCO is sufficient to present adequate removal of most viruses, bacteria and organic matter commonly found in feed waters, criteria which the converted RO membranes can satisfy [38–41].

3. Material recycling options

Plastic solid waste treatment and recycling can be separated into four major categories, primary (re-extrusion), secondary (mechanical), tertiary (chemical) and quaternary (energy recovery). Primary recycling is generally conducted within the manufacturing plant by reintroduction of clean scrap back into the extrusion cycle. Generally this process cannot be applied to dirty waste products, such as used or even cleaned RO modules, as the recycling materials are not expected to meet the required quality [42]. While only a relatively small number of the discussed processes are directly applicable to the recycling of RO membranes, assessing their validity is an important step in the process of investigating all recycling opportunities.

During the process of mechanical recycling, plastics are physically ground into suitable size, separated from contaminants, washed, then used as feed stock for the production of new products [43]. This process remains difficult to apply to mixed polymers or contaminated materials, as immiscible or incompatible polymers can cause mechanical property deterioration during the process. Thus, in order to make mechanical recycling economically viable, it is important to have a large volume waste stream of single-polymer plastic that is clean and homogenous [44–46].

With regards to membrane modules, each component must be considered individually to determine their potential suitability for mechanical recycling, assuming they can be successfully and economically separated. For example, the polypropylene feed spacer [4] has the ability to be directly recycled using this method [47]. Indeed, PP is commonly recycled into containers and packaging due to the strength, thermal and chemical resistances it can maintain, even after being recycled [48,49]. Depending on the type of polyester used in components such as the permeate spacer, these also have the capacity to be mechanically recycled. Because of their copolymer nature, ABS materials such as the end caps and permeate tubes can suffer a deterioration of physical properties when recycled through this method so these are generally reprocessed by other techniques [50]. Finally, the membrane sheets, which make up a large proportion of the module, are constructed from a number of different polymers and additives and would therefore be inherently difficult to accurately and efficiently separate. In addition, the membranes sheets can be contaminated by a wide variety of substances after extensive use. Due to the nature of the process and the aforementioned reasons, direct mechanical recycling the module as a whole may prove to be labour and cost prohibitive.

Chemical (or feedstock) recycling, is a process which breaks down the plastic material into smaller molecules, to be used as raw materials for petrochemicals processes, by using the reverse of the method used to create the polymer chains, such as depolymerisation and degradation [42,51]. Polyester materials (such as in the permeate spacer and components of the membrane sheet) are suitable for chemical recycling processes, and hydrolysis is used to reverse the polycondensation reaction used to make the polymer, with the addition of water to cause decomposition [52]. Chemical recycling cannot typically be used with contaminated materials [44], and while more expensive and complex than mechanical and primary recycling, its main advantage is that heterogeneous polymers with limited use of pre-treatment can be processed [42]. Chemical recycling processes are tailored for individual materials and further classification will be required to determine if this avenue is suitable for the recycling of RO membrane modules.

The final category for plastic recycling is energy recovery and thermal processing, which can be defined as the conversion of solid wastes to a secondary product with a release of heat energy [44]. These processes will be discussed at length in Section 4, as they can also be considered as viable disposal options. The major categories of thermal processing commonly used in industry include incineration, pyrolysis or thermal processing in the absence of oxygen, gasification which is the partial combustion with limited air to produce gas, and catalytic conversion to fuel oil [53]. Environmentally, gasification and pyrolysis offer advantages over simple incineration, as they produce fewer emissions, reduce waste residues, and increase energy recovery. Most importantly, these processes can be applied to mixed plastic wastes, such as the combination of materials used in the manufacturing of RO modules [42,44,46].

4. Alternative disposal options

Regarding alternative options for the disposal of end-of-life modules, current efforts have mainly focused on combustion and energy recovery from the polymeric materials. Although a number of other strategies can be considered in the future, these are not discussed at length in this paper. For example, sheets and spacers have been previously recycled as geotextiles in home gardens under a layer of gravel in order to maintain the position of decorative rocks and eliminate weed growth [13]. Additionally, potential agricultural applications for the spacers, including bird netting, wind-breakers or nets for lawn protection have also been proposed [4]. Mechanical grinding of waste RO elements could provide a filler material or aggregate that could be used in concrete. Finally, low-temperature gasification of the polymeric wastes to produce syngas has demonstrated promising results for mixed municipal plastic waste, and can be considered for membrane modules [54,55].

4.1. Combustion and carbonisation

Using the concepts of the waste management hierarchy (Fig. 2), treatment options for RO membranes include combustion and carbonisation for energy recovery. Combustion of plastic solid waste can reduce the volume by 90–99%, greatly reducing the strain on landfill. In addition, heat energy can be recovered and used for electricity generation or other heat related processes [56]. The thermal decomposition of the polymeric components of RO membranes has been reported recently [4]. With the exception of the fibreglass outer casing, the membrane components are comprised of synthetic polymers that contain C, N, H, O, S as their main constituents. As shown in Table 1, the carbon content of the polymers is between 62.2 and 88.3% by mass for the major membrane components. With a total mass of 13.5 kg, a typical 8″ RO membrane element is therefore expected to contain approximately 9.1 kg of carbon.

Fig. 6 shows the results of the thermogravimetric analyses of the membrane components performed under nitrogen atmosphere [4]. Most of the materials are comprised of multi-component systems including the fibreglass casing which showed considerable residual content (i.e. inorganic). The components comprised of ABS or PP are the least thermally stable, showing almost complete degradation at 400 °C. The other parts are comprised of components that are more thermally stable, with the membrane sheet completely degraded at 600 °C, followed by the permeate spacer and glued parts at 900 °C. It is therefore possible to thermally degrade the polymer components to carbon using thermal treatments [57].

Waste incinerators can generally operate from 760 °C to 1100 °C [58] and would therefore be capable of removing all combustible material, with the exception of the residual inorganic filler in the fibreglass casing. For a sample of the 8″ RO membrane, only 7% of the original mass remained after combustion at 900 °C. Pyrolysis of
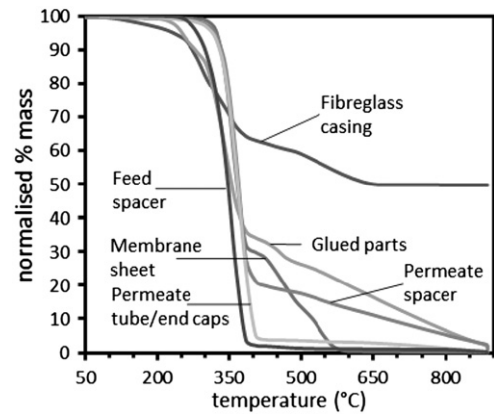
Fig. 6. Thermogravimetric analysis of membrane components calcined under nitrogen atmosphere at 20 °C min^{-1} [4].

the same membrane under nitrogen at a temperature less than 450 °C results in a higher residual of 26%. In either case, the overall volume of waste sent to landfill is significantly reduced.

The process of waste incineration, if not properly controlled, can emit greenhouse gases [59] as well as other harmful products [42]. As a result, additional emission capture technologies are expected to be considered and implemented, in accordance to the current legislation. The recovery of energy from the process can also offset the greenhouse gas emissions from traditional energy generation, further increasing the sustainability of the incineration process [60].

4.2. Energy recovery in electric arc furnace

The use of polymeric wastes as a coke substitute in the electric arc furnace (EAF) employed in steel making is a relatively new concept, although the process has already been implemented on large scale. Currently, old rubber tyres and other waste plastics are burned as a partial coke substitute in EAFs in many plants [61,62]. This section briefly describes the primary concepts underlying the potential use of old RO modules as a carbon and energy source in EAFs.

Although the most common method used to produce steel products remains the blast furnace, the use of EAFs, which accounts for 35% of global production [63], usually results in better quality steel and offers the opportunity to use plastic waste as a partial energy source. The EAF productivity can be further improved by the formation of foaming slag [64]. In this process, carbon, commonly found in the form of metallurgical coke, is injected into the reactor, where it combines with oxygen in the molten steel and generates CO and CO_2. These gases bubble through the molten metal, producing the foaming slag which improves the electrical energy transfer from the electrodes to the molten bath, while also protecting the electrodes and furnace walls. The reaction between the carbon and oxygen is exothermic and produces thermal energy, which lowers the operation costs [65]. The use of waste plastics in EAFs presents the potential to provide an extra energy source and to promote slag foaming [66]. The thermal decomposition of the polymeric substances into CO and H_2 makes them ideal for metallurgical processes, as these gases help the reduction of oxide ores [67]. Using waste polymers in EAFs provides extensive environmental advantages, such as a reduction of the amount of both the specialty cokes commonly required and the solid plastic wastes. Increased furnace efficiency, decreased power usage and decreased carbon consumption are also environmental and economic advantages. As various carbon sources are already used in EAF steelmaking, no significant modifications to the plant design are required to implement these new processes.

Table 1
Composition of typical membrane element.

Membrane element component	Composition	Approximate carbon content (%)
Outer casing	Fibreglass	30–50
Feed spacer	PP	85.7
Permeate spacer	Polyester	62.5
Membrane sheet (thin film composite)	Aromatic polyamide (0.2 μm)	71.6
	Microporous polysulfone (40 μm)	73.7
	Polyester support (120 μm)	62.5
Permeate tube/end caps	ABS	88.3
Glues	Epoxy resin	62.2
Rubber o-rings	EPDM	83.6

A standard test has been designed to assess the feasibility of given polymeric compounds to be used as coke substitute in EAFs [68]: after undergoing pyrolysis, the remaining char of the tested samples are collected and placed in a horizontal drop tube furnace at 1473 K, which replicates the EAF operating conditions. Previous tests have been successfully conducted on blends of metallurgic cokes and different proportions of PP and high-density polyethylene [66]. These studies showed that up to 30% plastic/coke blend can be used without adversely affecting the combustion efficiency of coals. Indeed, similar or slightly higher combustion efficiencies, faster gas generation and improvements in slag foaming volume and behaviour were obtained when compared to operation with standard coke [67]. This increased performance was attributed to the amount of hydrogen available in the polymer materials [69]. Given that the RO feed spacers are generally made of PP, this fraction of the old modules could potentially be used in EAF. While the chemical composition and structure of the waste plastics are known to influence the coke reactivity and subsequent combustion performance, the same tests would need to be applied to the other plastics comprising the modules in order to fully assess the feasibility of using some or all of the parts of the RO membrane in an EAF.

5. Strategic and policy challenges

The disposal of used RO membranes must be considered in the context of its relative environmental impact compared with other types of waste. In Australia alone, over 21 million tonnes of waste is disposed into landfill each year, including more than 80,000 tonnes of polyethylene terephthalate water bottles and in excess of 300,000 tonnes of electronic waste (e-waste) [70]. These large numbers have caused governments around the world to consider novel strategies to deal with domestic and industrial wastes including high-end products that have reached the end of their lifetime. This section briefly describes the practices under recent implementation for e-waste, which can be easily adopted by the desalination industry, with the intention of reducing the impact of the solid waste produced such as end-of-life RO membrane elements. The current implementation of these e-waste policies in Australia is described as an illustration of typical strategies to consider for management of old RO membranes.

5.1. Early policy attempts for e-waste

Because of their large environmental impact (both quantitative and qualitative), recent efforts have focused on the fate of e-waste, such as television and computer equipment, and a number of recycling programs have been implemented around Australia. For example, the Australian Capital Territory government has already banned landfill disposal of e-waste, while the State of Victoria has setup a computer collection and recycling scheme [71]. In addition, a number of industrial suppliers (e.g. Dell and Apple) propose various recycling schemes for their own products [71]. However, these industry programs have not significantly expanded in practice since product recycling is rarely financially viable without government support. As a result, the reported recycling rate was as low as 10% by weight during 2007/2008 [72]. While suppliers and importers usually demonstrate great interest in participating in e-waste recycling schemes, they could suffer from potential financial disadvantage if some of their competitors do not join the program. As a result, the setup of a compulsory recycling scheme appears critical in this highly competitive market [73].

5.2. Product stewardship schemes

5.2.1. National television and computer product stewardship scheme
In Australia, the "National Television and Computer Product Stewardship Scheme" is the first instalment of the Product Stewardship Scheme, developed under the new "National Waste Policy." The Product Stewardship Bill was passed by the Australian parliament in June 2011, and provides legislation for nationwide practice for evaluating entire product life-cycle, particularly end-of-life options, minimising their environmental impact and sharing of responsibility among manufacturers, importers, governments and consumers [74].

Specifically, this document provides a framework to impose obligations on key stakeholders regarding the avoidance, reduction and management of waste from products. Under the scheme, liable parties will meet their obligations by becoming a member of an approved product stewardship arrangement [74], available in three configurations:

1. Voluntary product stewardship arrangements are intended to encourage product responsibility without regulation, and to provide community assurance through an accreditation system. Once accredited, the party may use the accreditation logos to promote the environmental and social responsibility of the party [75]. However, the legislation does not require all businesses within an industry to participate in this type of arrangement.
2. Co-regulatory product stewardship features more formalised arrangements, for which the government is expected to set minimum outcomes and requirements, providing the industry with the flexibility to control how these outcomes will be met.
3. Mandatory product stewardship arrangements will be controlled by government, responsible to initiate regulations, and will be backed up by criminal and/or civil penalties if the requirements are not met.

In Australia, this scheme has recently been used to target television and computer equipment under a co-regulatory framework (i.e. "e-waste management scheme" [74]), and is expected to quickly expand to tyres, mercury containing lights and packaging [76]. Under the e-waste regulations, the key commitments for television and computer producers will include covering the cost of implementing the scheme. This will include collection infrastructure, recycling, awareness and education programs, governance activities, and development and provision of information used to identify relevant products to be covered by the scheme. A threshold will be set to exclude corporations that import or manufacture less than 5000 television and computer products annually.

One of the significant challenges facing the electronics industry is the number of product sources, with every household being a potential source of end-of-life products. The collection of such used products is a major obstacle to the effective implementation of this scheme. Plans are currently being developed to provide collection points, including council pick-up and designated drop-off locations.

5.2.2. The Australian Packaging Covenant
Another example of an existing framework for reducing the environmental impacts of consumer and industrial wastes is the Australian Packaging Covenant (APC), formerly known as the National Packaging Covenant (NPC) [77]. Established in 1999, the NPC was developed to manage the environmental impacts of consumer packaging and paper wastes. The key areas targeted by the Covenant include the following: designing packaging that is more resource efficient and more recyclable; increasing the recovery and recycling of used packaging from households and other sources; and taking action to reduce the incidence and impacts of packaging litter.

The early stages of the NPC development involved seeking cooperation between stakeholders who include all sectors of the packaging chain and included both industry, local, state and commonwealth governments. Stakeholders could sign the voluntary Covenant with the provision that they submit action plans and annual reports based on their activities specific to their industry. The original form of the NPC proposed a term of 5 years which was extended for the same period in 2005. From July 1st, 2010, the APC emerged in an

open-ended revised form that included committing signatories to national targets and key performance indicators (KPIs). Concurrently, the APC released the "Sustainable Packaging Guidelines" which signatories can use to assist them to analyse and document their packaging sustainability strategy [78]. At present (March 2012), a total of 713 Australian and international stakeholders are signatories of the APC indicating a strong commitment to the principals of the Covenant.

5.3. Towards implementation of product stewardship to RO membranes

As discussed earlier, many challenges still limit the prompt implementation of a systemic approach to the management of RO modules from cradle to grave. However, important lessons could be learned from the current implementation of the Australian e-waste management scheme and the APC to the stewardship of RO modules. For example, it is important to note that extensive consultation of all stakeholders was undertaken during the drafting of the Stewardship Bill and the NPC/ACP, and it is expected that the desalination industry at large will be keen to work towards the implementation of a similar scheme for RO membranes. It also remains crucial to clearly define the main difference between post-consumer wastes and old RO modules, and the resulting challenges and opportunities for implementing a similar scheme to RO products. When considering the significantly smaller volume of solid waste disposed of by the desalination industry, government intervention is not expected to be a national priority yet, although state and/or federal involvement could be necessary in order to implement this type of recycling scheme. At this early stage, the Product Stewardship Act already allows the desalination industry to seek voluntary accreditation for RO modules. However, no membrane suppliers or users are known to have joined this scheme in Australia to date.

As reported in Table 2, the potential RO membrane regeneration scheme (or MemRegen) offers advantages over the e-waste program, such as a significantly lower number of collection points, and therefore a much higher volume of product to collect in each location. This characteristic is expected to greatly affect the transportation costs associated with this initiative. Indeed, used RO membranes are located in a relative small number of desalination plants in known locations. Although the complex network of collection points used for the e-waste scheme will not be required, membranes will still need to be transported from the original plant to the facility responsible for reuse/recycling treatment and then to another plant for reuse in the potential second life application.

6. Assessment of environmentally appropriate strategies

Increasing awareness of the environmental impacts of products and processes has led to the development of environmental management tools to better understand and manage these impacts [79]. Life cycle assessment (LCA) is a systematic tool for assessing the potential environmental impacts and has been increasingly applied to the water [80,81], wastewater [80,82] and membrane industries [83,84]. Based on an iterative process, LCA consists of four steps: goal and scope definition, inventory analysis, impact assessment, and interpretation. Definition of the scope includes the development of a system boundary defining which materials and/or processes will be included and excluded from the analysis [85].

A proposed initial system boundary for membrane end-of-life options is shown in Fig. 7. Future modifications to the boundary may be necessary, however, based on preliminary LCA results. The system boundary includes first and second order processes for the four proposed end-of-life options: conventional disposal (landfill or incineration), reuse, recycling of components, and calorific recovery. Higher order processes, such as incinerator construction, have been excluded from the proposed boundary but should be included if construction of a new facility was required. Similarly, if the reuse option requires construction of a specific plant, the resulting environmental impacts should be considered. Although transport features in all the presented options, its impact may differ significantly depending on the locations of reuse and recycling facilities. Landfill and incineration are the current disposal routes which could be partially avoided or delayed by implementing one of the three other alternatives. These strategies also avoid production of materials or energy (highlighted in grey) which can be credited to the system using system expansion [86]. Directly reusing old RO membranes in place of lower specification membranes such as NF elements would avoid membrane production, but may require a conversion step using chemicals and generate some chemical waste requiring treatment or disposal. Recycling of the components would avoid plastics manufacture, but may require an additional cleaning step depending on the membrane source. Additionally, the disposal of the non-recyclable parts must also be considered. Finally, calorific recovery from old modules presents the potential for electricity production, but may generate emissions from the incinerator. In this case, the final waste product (ash) must still be disposed of, probably to landfill.

To complete a life cycle assessment of membrane end-of-life options in Australia, the use of Australian inventory data is preferable though may not be possible for all items. An initial assessment of the availability of required inventory data in the Australasian [87] and Ecoinvent (primarily European data—[88]) databases is shown in Table 3.

Where materials were not available in the Australasian databases, the European Ecoinvent database was consulted. Some potential gaps in the inventory data were identified such as polysulfone production, emissions from incineration and disposal of chemical waste generated in the reuse option. Life cycle assessment could be a useful tool for comparing these end-of-life alternatives; however, based on a preliminary system boundary there are still some important process inventory gaps which need to be addressed.

Given that the membranes may be manufactured and reused in different parts of the world, it is also important to consider regional differences. Local production methods and the sensitivity of the receiving environment to emissions could vary substantially between regions, resulting in significant differences in the environmental impacts of a given process. As recommended recently [89], LCA models are expected to take those factors into account when selecting inventory data. Finally, the impact model is also expected to address specific regional issues, while still capturing any inventory flows that may be of importance.

7. Conclusions

Following this initial work, a number of options have been proposed and will now need to be independently investigated for technical feasibility, environmental impact and economic viability. With

Table 2
Comparison of proposed RO membrane and e-waste management schemes (data given for Australian market).

|	E-waste	RO membrane
Scheme type	Co-regulatory	Voluntary (so far)
	Industry-run	Industry-run
	Government controlled	No mandatory participation
		Accredited promotion
Waste generation	Households	Membrane plants
Amount of waste (tonnes)	300,000 +	600 +
Waste Locations	5 million +	180 +
End-of-Life options	Direct material recycling after disassembly, limited reuse	Direct and indirect reuse, material recycling after disassembly, waste reduction.
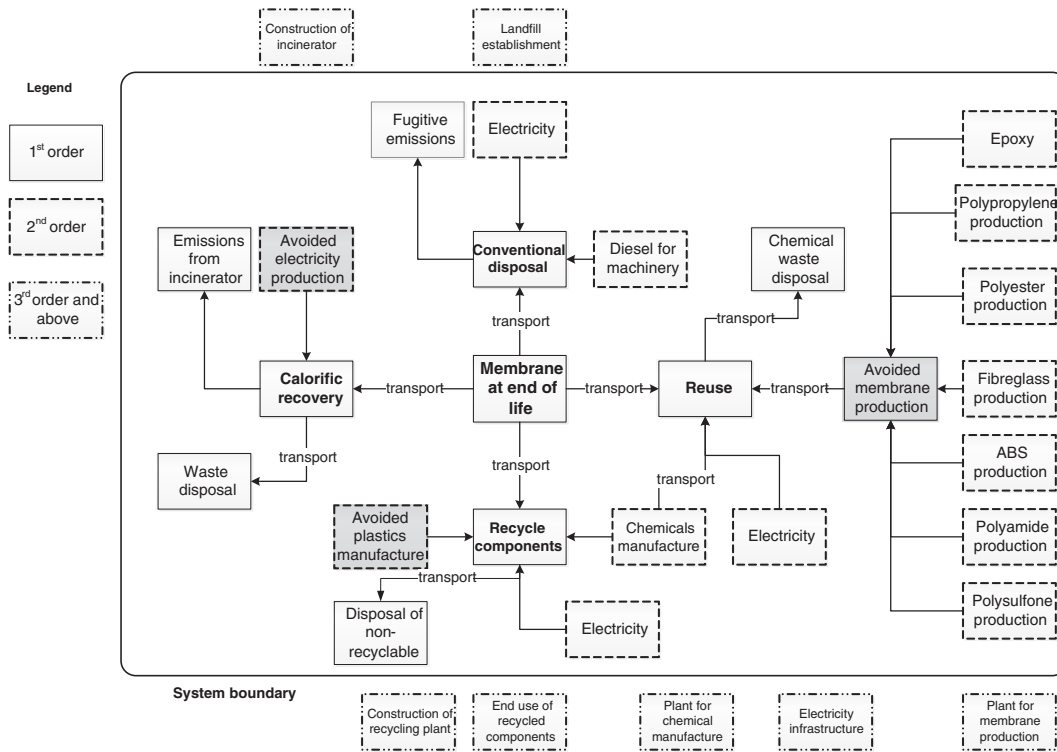
Fig. 7. System boundary for life cycle inventory of membrane end of life options.

these key factors assessed and benchmarked against the current disposal practices, a detailed and accurate comparison of the various strategies will allow final recommendations to be fully justified.

The use of more sustainable disposal alternatives is expected to benefit the desalination industry, which is still perceived by the community to be energy-demanding. Moreover, the supply of inexpensive, second-hand UF and/or NF membranes is another clear benefit for the water treatment industry at large. Reused membranes have the potential to be used in low cost humanitarian water treatment projects, for lower cost RO pretreatment, or for temporary or remote water treatment operations. Energy recovery from the old RO modules in one of the proposed alternative disposal methods presents the opportunity to turn an expensive waste liability into a potential asset. Implications for membrane suppliers also include an increased

sustainability for their product by lowering carbon footprint and embodied energy and extending the cradle-to-grave lifecycle for RO membrane elements.

Future developments and additional work in this area aim to develop knowledge on the current desalination markets and environmental impacts associated with production and disposal of desalination membranes. Additional outcomes for membrane users include the development of a systematic approach for the management of RO modules at the end of their initial application, and the assistance in finding potential users for expired membranes. In this regard, it is expected that an online database of reuse membranes based on their first use and identifying uses suitable for their second application will be produced.

Acknowledgments

Table 3
Inventory data availability for membrane components and alternative disposal options.

	Material	Data source
Membrane components		
Feed spacer	PP	[87,88]
Permeate spacer	Polyester	[88]
Fibreglass housing	Fibreglass and polyester fibres	[87,88]
Permeate tube	ABS	[87,88]
Membrane sheet	Polyamide	Literature
	Polysulfone	Not available
	Polyester	Not available
Glue	Epoxy like substances	[88]
Membrane reuse		
Chemicals	Sodium hypochlorite	[88]
	Potassium permanganate	[88]
	Sodium hydroxide	[88]
Chemical disposal	Process dependent	Process data
Recycle components		
	ABS, PP	[88]
Calorific recovery		
	Emissions from incinerator	Process data
Landfill		
	Landfill of plastics	[87,88]

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