Desalination 369 (2015) 188–200

Contents lists available at ScienceDirect

Desalination

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

# Life cycle and economic assessments of engineered osmosis and osmotic dilution for desalination of Haynesville shale pit water

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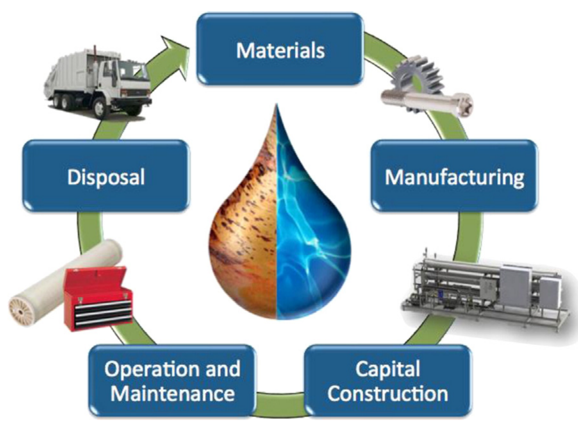
## HIGHLIGHTS

- Life cycle assessment of engineered osmosis and osmotic dilution are performed
- Environmental impacts of forward osmosis can be competitive with deep well disposal
- The cost of FO can be significantly lower (up to 60%) than deep well disposal
- FO energy demand with no upstream pretreatment is a hurdle for further development

## GRAPHICAL ABSTRACT




## ARTICLE INFO

*Article history:*
Received 6 March 2015
Received in revised form 23 April 2015
Accepted 24 April 2015
Available online xxxx

*Keywords:*
Life cycle assessment
Forward osmosis
Engineered osmosis
Wastewater treatment
Water reuse
Hydraulic fracturing

## ABSTRACT

The treatment of oil and gas (O&G) exploration wastewaters by forward osmosis (FO) could make water management in the O&G industry more sustainable. Specifically, recovery of pit water from well drilling operations and hydraulic fracturing could reduce the impacts associated with wastewater transportation, deep well disposal, and fresh water procurement for subsequent hydraulic fracturing operations. This study evaluates the environmental and economic impacts of FO for treatment of O&G pit water through comparative life cycle impact and costing assessments; the FO technology is evaluated when operated as an engineered osmosis system and as a stand-alone osmotic dilution process. Cradle-to-grave life cycle inventories are developed for each FO process and evaluated using ten environmental impact categories. The relative environmental impacts of FO are found to be comparable to the transportation and pumping energy alone required for deep well injection. At the current state of the technology, the energy demand of the FO systems when operated with no upstream pretreatment is the single greatest contributor to the negative environmental impacts. At 75% water recovery, FO can potentially reduce pit water management costs by nearly 60% compared to deep well disposal, and pit water transportation requirements can be reduced as much as 63%.



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http://dx.doi.org/10.1016/j.desal.2015.04.028
0011-9164/

## 1. Introduction

The surging exploration and production of unconventional oil and gas (O&G) has been accompanied by increased federal, state, and local governmental regulations to protect human health and the environment [1–6]. In addition to increasing regulatory requirements are public concerns regarding the volumes of water consumed for well drilling and hydraulic fracturing and the subsequent quality and volumes of wastewater generated that require careful oversight and management. Exceptional consideration has been given to the transportation and disposal of these wastewaters, especially trucking and injection into Class II disposal wells [7,8]. There are also growing concerns regarding the availability of sufficient injection well capacity, which might inhibit wastewater disposal options in active O&G shale plays [9]. The development of disposal wells has also proven to be complex and can require significant capital investment and involve numerous regulatory hurdles to overcome. Furthermore, the geology in several regions is not conducive for deep well injection, and induced seismicity could result from the development of additional disposal facilities [10,11]. Therefore, novel and innovative research is being conducted to identify technologies that can treat complex O&G wastewaters economically and in an environmentally sound manner [12–16]. Particularly, forward osmosis (FO) has gained attention as a prominent technology for treatment of such waste streams [17–21].

### 1.1. FO desalination of O&G wastewater for industrial reuse

Several studies have investigated the application of FO for the treatment of O&G wastewaters. Bear Creek Services (Shreveport, LA), in collaboration with Hydration Technology Innovations (HTI, Albany, OR), explored FO for treatment of upstream O&G exploration wastewaters using the first generation Green Machine [22]. The study was conducted at the demonstration scale in the Haynesville basin (Louisiana, USA) and used spiral wound cellulose triacetate (CTA) membrane elements to treat raw drilling wastewater and low salinity flowback water (termed pit water in this study) in a stand-alone osmotic dilution configuration. Hickenbottom et al. [23] published the first bench-scale study focusing on FO treatment of similar drilling wastewaters. The objective of the study was to further evaluate and optimize the osmotic dilution [21,24,25] process, while focusing specifically on water flux, solute transport, and organic and inorganic compound rejection by CTA membranes. McGinnis et al. [26] published a demonstration-scale study on the performance of a membrane brine concentrator (MBC, Oasys Water). The system employed spiral wound polyamide thin-film composite (TFC) membranes for desalination of pretreated hydraulic fracturing flowback water from the Marcellus shale formation. That study was the first to demonstrate a hybrid engineered osmosis [17,21,27–30] process for treatment of O&G wastewaters, where a downstream distillation process reconcentrated an $NH_3/CO_2$ draw solution. Recently, Li et al. [31] investigated the reclamation of water from shale gas operations using a novel FO process coupled with downstream vacuum membrane distillation. Yun et al. [32] simultaneously investigated a relatively new method of FO treatment of shale gas wastewater, called pressure assisted forward osmosis.

### 1.2. O&G pit water treatment with forward osmosis

While the first generation Green Machine was successful at treating pit water through osmotic dilution, the need for higher quality, low salinity product water and sustained osmotic driving force led to a second pilot-scale study conducted by HTI in collaboration with the Colorado School of Mines and Bear Creek Services. The primary objective of the study was to investigate the continuous performance of an engineered osmosis system consisting of FO coupled with downstream reverse osmosis (RO) for brine reconcentration and nanofiltration (NF) for brine polishing (Fig. 1a). The investigation was conducted in the Haynesville basin, where the engineered osmosis system treated pit water similar to that of previous investigations [22]. Unlike the first generation Green Machine, where the diluted brine from the osmotic dilution process (Fig. 1b) could be reused primarily in subsequent hydraulic fracturing operations, the second generation Green Machine provides a high quality RO permeate suitable for multiple industrial reuse applications. The new system treated 35,000 gal of raw drilling wastewater (~6.8 mS/cm initial feed conductivity) and achieved 85% water recovery using 6% w/w NaCl draw solution over 120 h of continuous operation (~32.5 mS/cm final feed conductivity) [17]. This recovery is similar to those achieved by the first generation Green Machine (>70% water recovery) when operated in osmotic dilution using a 26% w/w NaCl draw solution [23]. Additional pilot-scale results and water quality information are provided elsewhere [17,22,23].

### 1.3. Life cycle environmental and economic assessments of FO

While the performance and technical merit of FO for treatment of complex waste streams has been demonstrated, evidence regarding the long-term environmental impacts or economic benefits of employing FO for wastewater treatment is insufficient. This is especially true in the upstream O&G industry, where FO will be compared to current wastewater disposal methods, such as deep well injection, or alternative treatment technologies. Life cycle assessment (LCA) and life cycle costing (LCC) are standardized methodologies that can be used to evaluate the environmental and economic impacts associated with the

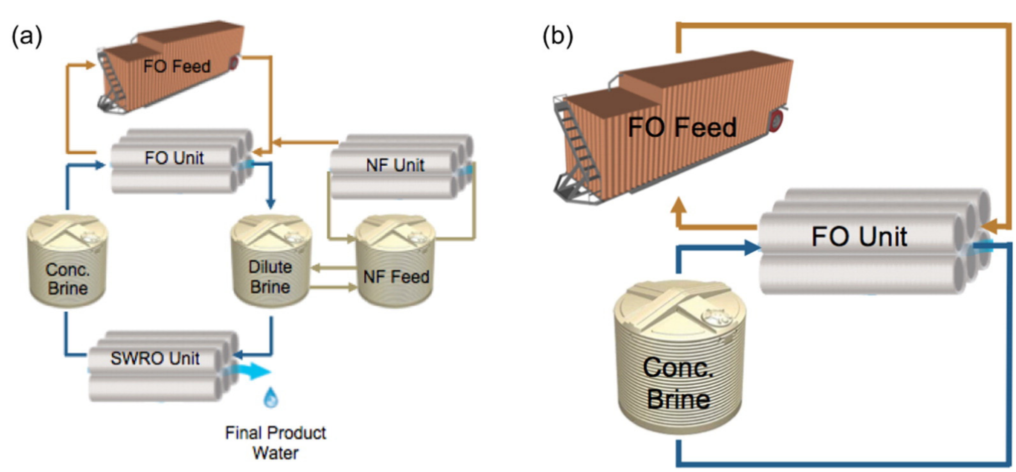


**Fig. 1.** Simultaneous desalination of O&G pit water and waste stream concentration using (a) a hybrid engineered osmosis system and (b) simple osmotic dilution. The hybrid engineered osmosis process employs seawater RO to reconcentrate the osmotic draw solution and a nanofiltration process to remove divalent ions from the concentrated brine after FO.

development and operation of products for human use. In recent years numerous studies have used LCA and LCC to estimate and compare the environmental impacts of different water treatment technologies [33–36]; however, only one publication to date has evaluated the environmental impacts of FO [37]. The study evaluated the intrinsic benefits that FO, when operated as a hybrid osmotic dilution system, provides over traditional RO processes and select hybrid technologies. The scope of the study focused primarily on water reclamation from domestic wastewater and provided no LCC analysis of the FO process. Furthermore, the life cycle inventory (LCI) was based on values suggested in the literature and did not include a comprehensive bill-of-materials for the construction and decommissioning of the modeled systems. A recent study by Thiel et al. [38] compared the energy consumption of an engineered osmosis process to other technologies used for desalination of produced water from shale O&G exploration (no LCA or LCC conducted); however, they modeled a system analogous to that of the MBC and their energy values are estimated for treatment of high salinity produced waters similar to those of the Permian and Marcellus basins.

Therefore, the main objective of this study is to evaluate the environmental and economic impacts of a decentralized FO system when used for dewatering O&G pit water. Specifically, the FO process is evaluated when operated as an engineered osmosis system and as a standalone process for osmotic dilution. A complete LCI was developed in collaboration with HTI, which included real-time data from the manufacturing, operation, and maintenance of the HTI FO membrane systems while piloted in the Haynesville basin for treatment of pit water. LCA and LCC were also conducted concurrently on the transportation and management of pit water during deep well disposal, thus providing a preliminary comparison between FO processes for recycling of pit water and traditional pit water disposal in Class II injection wells. A secondary objective of this study is to further elucidate what LCI components of the FO processes are the greatest contributors to negative environmental impacts and financial expenses, thus identifying areas of improvement for future, full-scale treatment systems. An additional engineered osmosis process commercialized by Oasys Water is known to treat O&G wastewater, but was not investigated in this study due to the extensive data already included herein.

## 2. Materials and methods

The application of LCA and LCC provides a standardized method for investigating the comparative environmental and economic impacts of FO processes in the pit water management industry. The hybrid LCA framework for this study has been thoroughly described in a previous publication [37] and formally outlined by the International Standards Organization (ISO) [39,40]; in lieu of a review by an independent LCA practitioner, two LCA experts contributed to this study. At its core, LCA is divided into four phases to evaluate overall environmental impacts: definition of the goals and scope, LCI, life cycle impact analysis (LCIA), and interpretation. The goals and scope and LCI are discussed in this section, while the LCIA and interpretation are described in the Results and Discussion section. LCC assumptions are also described in this section, while economic impacts are discussed concurrently with the LCIAs. All infrastructure requirements (capital expenditures for system construction (CAPEX)), energy use and system performance metrics (operational expenditures for system maintenance and operation (OPEX)), and information regarding FO membrane elements were provided by HTI and were based on recent demo-scale test data from the Haynesville basin. Information on NF membrane elements was provided by DOW Chemical Company (Midland, MI). The chemical composition of membrane cleaning agents was provided by King Lee Technologies (San Diego, CA). All CAPEX and OPEX data provided from industry was used concurrently in the LCA and LCC of this study. The transportation and pumping energy for deep well disposal in the Haynesville basin was estimated based on information published in the literature [41,42]. It is important to note that while a high resolution LCIA and economic evaluation of the FO processes was achieved due to support from the membrane industry, little reliable data is published in the literature about deep well injection in the Haynesville basin. Therefore, the potential environmental impacts reported in this study for deep well injection would likely increase if a more comprehensive bill-of-materials was available for inclusion in the LCI.

### 2.1. Goals and scope

The goals of this study are: (a) to compare the environmental and economic impacts of deep well disposal, engineered osmosis, and osmotic dilution based on material surveys and data collected during pilot-testing, (b) to elucidate potential improvements to the environmental and economic impacts with respect to treatment system operation, and (c) to set a benchmark scenario and dataset for future comparative analyses (e.g., comparison to conventional or emerging wastewater treatment technologies). A comparative LCA of three water management options for pit water in the Haynesville basin was used to reach these goals (Fig. 2). The first scenario (A) (Fig. 2a) is a gate-to-gate LCI of transportation and pumping energy for disposal of pit water in a Class II injection well; additional LCI components such as land procurement and capital construction, chemicals to inhibit scale formation in the wellbore, periodic equipment replacement, and facility decommissioning were not included in this study due to the lack of published data on injection wells in the Haynesville and other shale gas basins.

The second scenario (B) (Fig. 2b) is a cradle-to-grave LCI that employs the HTI engineered osmosis system consisting of FO, seawater RO for brine reconcentration, and NF for brine polishing. The FO subsystem in the engineered osmosis system consists of 3 parallel trains of 2 pressure vessels, each containing 4 horizontally oriented, 8040-CS spiral wound CTA membranes operated under forced feed flow conditions. Pit water is recirculated on the feed side of the membranes using a high capacity, low-pressure pump. Diluted NaCl draw solution is reconcentrated with the RO subsystem, where 4 pressure vessels are fed in series and house a total of 12 horizontally oriented, 8040 spiral wound TFC membranes (SWC4+, Hydranautics). The NF subsystem consists of 3 horizontally oriented 4040 spiral wound TFC membranes (NF270, DOW Filmtec). The engineered osmosis process results in a high quality permeate stream (290 mg/L total dissolved solids (TDS)) available for a wide variety of industrial reuses, including hydraulic fracturing. The third scenario (C) (Fig. 2c) is also a cradle-to-grave LCI that uses osmotic dilution to achieve high quality brine of suitable concentration and chemical composition (~65,000 mg/L TDS) for use in hydraulic fracturing [22]. The same LCI for the FO subsystem described above is employed for scenario C. The environmental impacts related to each system configuration are normalized to the management of 1 barrel (bbl) (42 US gallons) of O&G pit water, which is defined as the functional unit.

It is important to note that although any comparison between a gate-to-gate LCI and a cradle-to-grave LCI might present an incomplete evaluation of the potential environmental impacts, the purpose of this study is to establish a benchmark for future comparative analyses as more information becomes available. In conducting such a comparison, it is possible to infer the potential gap (or lack thereof) that might currently exist between deep well disposal and FO pit water treatment scenarios, thereby guiding the future development of these systems. The gate-to-gate LCI is based on materials and energy consumed during pit water transportation and disposal. The cradle-to-grave LCIs are based on the materials consumed during system fabrication, materials consumed during membrane cleaning and periodic membrane replacement, and energy required for system operation. The LCI boundaries for each scenario are shown in Fig. 2. The construction phase of each cradle-to-grave LCI occurred at HTI and therefore a comprehensive inventory based on a bill-of-materials was provided for this study (see Table S1 in the supplementary data). In instances where a complete bill-of-materials was not available (i.e., pumps, motors, variable frequency drives (VFDs), programmable logic controllers (PLCs)), the U.S. dollar value was used in place of material type and weight and all U.S. dollar values were normalized to the same year (see Table S2 in the supplementary data). The year 2002 was chosen to match data for the USA Input-Output 2002 database in the SimaPro LCA software, which is the most recent update to these input output databases that relate dollar values to environmental impacts. This hybrid LCA approach, utilizing both process-based and economic input-output data, has been employed by others [43,44]. The operating phase for each LCI is limited to treatment of pit water in the Haynesville basin; however, the environmental impacts associated with material and chemical transport from various equipment vendors to the field are not considered. Waste streams generated during the operating phase (i.e., landfill disposal of membrane elements at the end of their service life and disposal of membrane cleaning chemicals at the municipal wastewater treatment plant) are included in each LCI. Landfill disposal of all materials consumed during system fabrication is also considered at the end of service life for each cradle-to-grave LCI.

### 2.2. Life cycle impact assessment

SimaPro LCA software was used to evaluate the environmental impacts associated with the material and energy flows tracked in the LCI, and the U.S. Environmental Protection Agency's (U.S. EPA) Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI) 2.1 impact assessment method was used to convert the information into values associated with ten environmental impact categories [45]. TRACI 2.1 is a midpoint oriented LCIA methodology and was chosen because it was developed for input parameters consistent with U.S. locations. The ten impact categories evaluated during the LCIA included ozone depletion (OD), global warming (GW), smog formation (SM), acidification potential (AP), eutrophication potential (EP), carcinogenic potential (CP), non-carcinogenic potential (NCP), respiratory

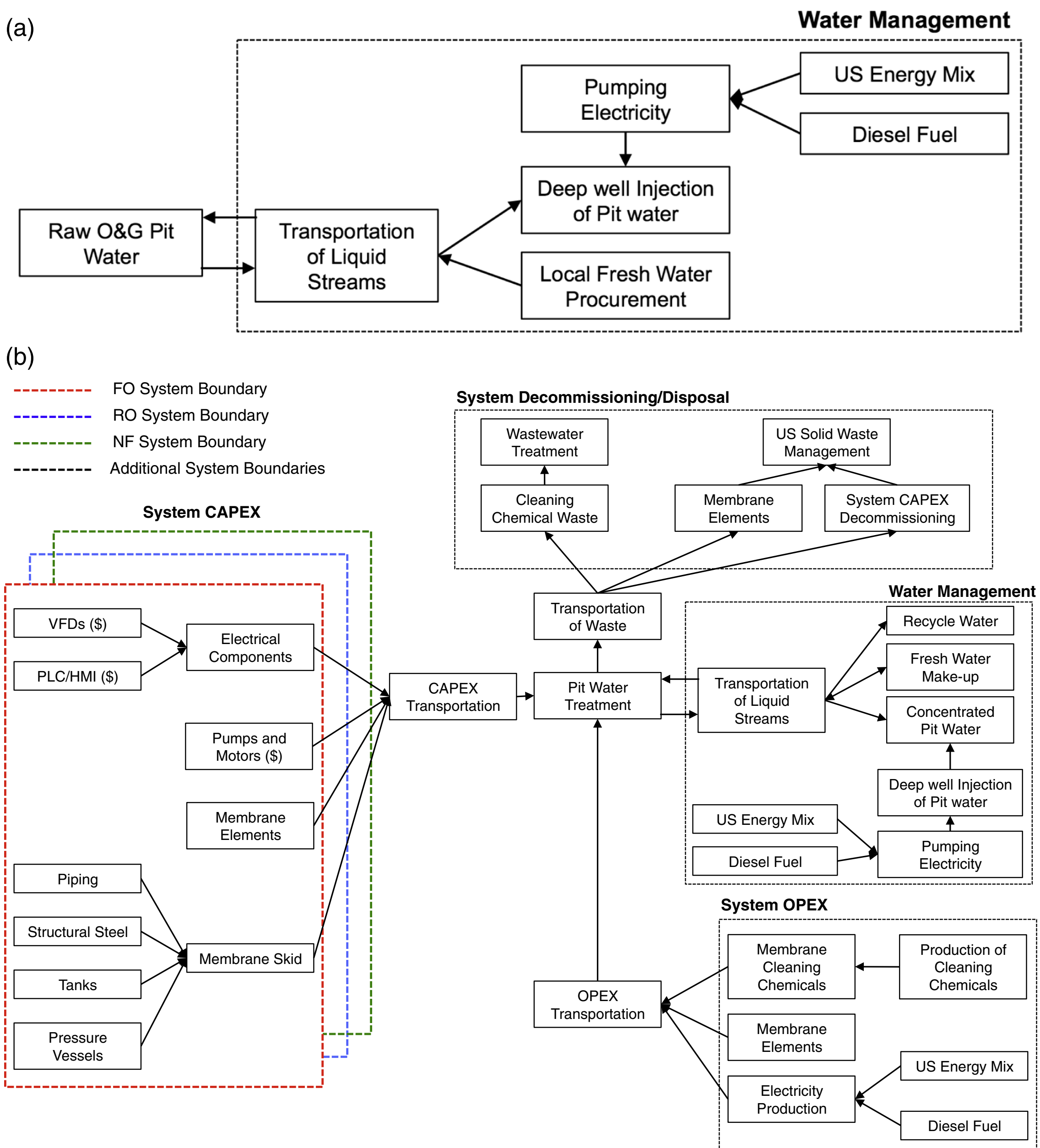


**Fig. 2.** LCI system boundaries for (a) deep well disposal at a Class II injection well ((scenario A) gate-to-gate), (b) pit water treatment using engineered osmosis ((scenario B) cradle-to-grave), and (c) pit water treatment using osmotic dilution ((scenario C) cradle-to-grave). The engineered osmosis system assumes system manufacturing and capital expenditures for the FO (red), RO (blue), and NF (green) membrane systems, while the osmotic dilution system only includes those inputs from an FO system.

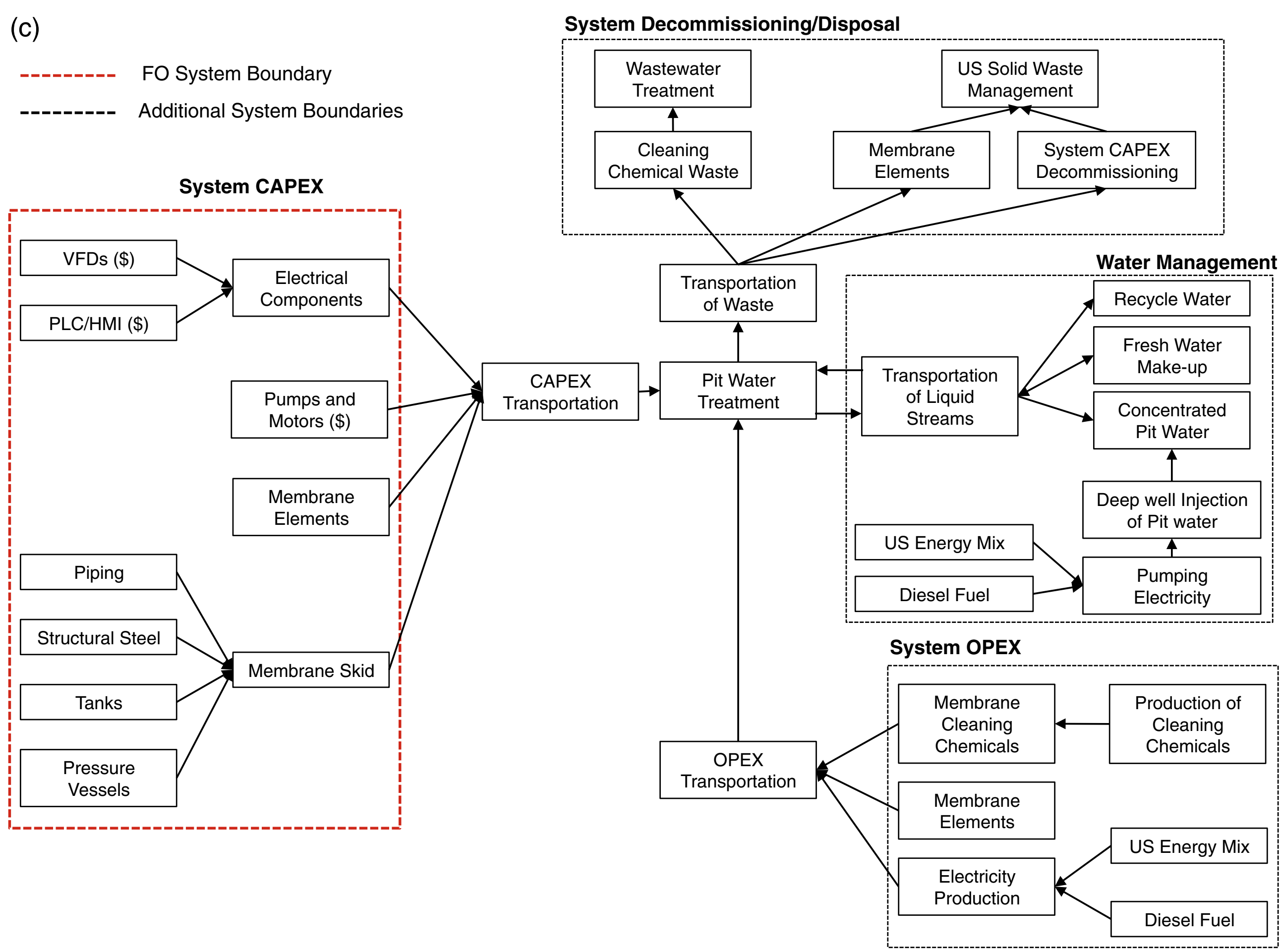


**Fig. 2** (*continued*).

effects (RE), ecotoxicity potential (EcP), and fossil fuel depletion (FFD). A complete description of the impact categories and of the methodologies used for their interpretation can be found elsewhere [45]. While site specificity is available for many of the above impact categories using TRACI 2.1, the U.S. average values were used in this study.

In cases where no water treatment was employed (scenario A), all pit water was trucked 50 miles one-way for disposal in a Class II injection well, where 0.54 kWh/bbl of pit water was required to operate a high-pressure pump [41,42]. Subsequent to pit water disposal, an equal volume of local fresh water was purchased and trucked back to the field (15 miles) for use during the hydraulic fracturing process [41, 42]. Due to the current lack of comprehensive data on deep well injection facilities, no other inputs (e.g., facility construction, maintenance of the well or high pressure pump, chemical inputs used during injection) were assumed. Furthermore, only the transportation impacts associated with truck operation for water transport were considered. LCI components such as truck maintenance and road damage were not included due to minimal information in the literature. Combination trucks in the U.S. were assumed to operate at half-loads for round-trip distances to account for empty and loaded trips.

The system operating parameters employed for scenarios B and C for pit water treatment are shown in Table 1. The system permeate flow of 0.1 bbl/min (~16 L/min) was maintained for 120 h of continuous operation during pilot-scale testing and is equal to an average CTA water flux of 5.7 LMH. Similar average water flux was demonstrated by Hickenbottom et al. (~6.2 LMH) when testing the same CTA FO membranes in osmotic dilution mode using pit water feed and 26% w/w NaCl draw solution [23]. The environmental impacts associated with brine procurement for the FO processes are not included in this study due to the presence of readily available NaCl brine used for hydraulic fracturing in the Haynesville basin [22]. The energy consumption for each membrane process is derived from pilot-scale test data, where the energy demand of the FO, RO, and NF system was 2.38 kWh/bbl, 1.03 kWh/bbl, and 0.08 kWh/bbl of product water produced, respectively. The environmental impacts of operating each scenario when powered by a diesel generator (genset) or by energy supplied by the United States Electricity mix ((USEM) Electricity, production mix) is compared (e.g., scenario B1 or scenario B2 if powered by a genset system or the USEM, respectively). The fuel consumption of each scenario when powered by a genset system was calculated assuming that a diesel engine consumes fuel at a rate of 0.84 gal/h/kW [42,46]. It should be noted that the RO system used during pilot testing did not employ an energy recovery device (ERD). It should also be noted that to achieve

**Table 1**
Second generation FO treatment system operating parameters.

| Parameter | Unit | Amount |
|---|---|---|
| System service life | Years | 10 |
| Average system perm flow | bbl/min (gpm) | 0.1 (4.2) |
| System recovery | % | 75 |
| Membrane service life | Years | 3 |
| FO energy demand | kWh/bbl (kWh/$m^3$)[a] | 2.38 (15) |
| RO energy demand | kWh/bbl (kWh/$m^3$)[a] | 1.03 (6.5) |
| NF energy demand | kWh/bbl (kWh/$m^3$)[a] | 0.08 (0.5) |
| FO/RO/NF cleaning events | Event/month | 1/4/4 |
| Membrane cleaning duration | Hours/event | 8 |
| KL7330 chemical concentration | kg/bbl[b] | 1.91 |

[a] Per bbl ($m^3$) of product water.
[b] Per bbl of water required to for system cleaning.

dewatering of pit water without pretreatment, the FO elements must be operated with 100 mil corrugated feed spacers and maintain a minimum cross-flow velocity to avoid high concentration polarization [47–50] and membrane fouling [23,51–53]. Therefore, an FO energy demand greater than that of high-pressure RO was observed. Subsequent to pit water treatment, 25% of the total pit water volume (concentrate) is trucked for disposal (50 miles) in a Class II injection well (0.54 kWh/bbl) and an equal amount of local fresh water is procured and returned for hydraulic fracturing (15 miles one-way) [41,42]. The volume recovered by the FO treatment processes (75%) is recycled for hydraulic fracturing (10 miles one-way) [41]. Similar to scenario A, only the transportation impacts associated with the operation of the combination truck used for water transport are considered.

### 2.3. Life cycle costing

LCC analyses are based on the sum of economic expenses incurred during water management (trucking and wastewater disposal), capital expenses, and yearly operation and maintenance (O&M) expenses. The costs associated with water management during each LCIA scenario are shown in Table 2. All cost values and transportation distances are specific to O&G and water treatment operations within the Haynesville basin; however, similar values are possible in other shale gas plays. The expenses associated with deep well disposal include the cost of energy required for operation and maintenance of the high-pressure pump. It should also be noted that values in Table 2 could change significantly with time, location within the basin, level of basin activity, and government regulations. For that reason, all economic values used in the LCC are adjusted to the year 2012 to match the year that cost data were collected and to ensure the most accurate economic comparison to deep well disposal at the time of pilot testing.

The total capital costs associated with scenarios B and C were calculated based on the complete bill-of-materials used for the LCA. Total capital costs are the sum of fixed capital costs, overhead costs, and civil labor costs associated with system fabrication. Fixed capital expenditures include the cost of membranes, pumps and motors, pipes and valves, electrical and instrumentation, tanks, and system frames. Overhead costs are assumed as 10% of the fixed capital expenditures and civil labor costs are assumed as 20% of the total capital costs. Total capital costs are amortized over the design life of the system using assumed values in Table 3 and are normalized by the functional unit. An external service provider is assumed to handle wastewater disposal and therefore the capital costs of the deep well injection facility are not considered.

Yearly O&M costs associated with scenarios B and C are calculated based on the rates of membrane replacement and chemical cleaning presented in Table 1. The costs of each FO, RO, and NF membrane element are assumed as \$750, \$585, and \$350, respectively. The cost of KL7330 cleaning chemical (membrane CC) is approximately \$19/kg of powdered chemical. The costs associated with O&M labor (\$0.13/$m^3$ of product water) and spare parts (\$0.04/$m^3$) are estimated using values proposed by Helal et al. [54], which are adjusted from the year 2003 to 2012 based on a 3% inflation rate.

**Table 2**
Water management cost values and transportation distances [41,42].

| Parameter | Unit | Amount |
|---|---|---|
| Fresh water price | \$/bbl | \$0.30 |
| Fresh water transportation cost | \$/bbl/mile | \$0.03 |
| Fresh water transportation distance | Miles | 15 |
| Pit water transportation cost | \$/bbl/mile | \$0.03 |
| Pit water transportation distance | Miles | 50 |
| Deep well disposal cost | \$/bbl | \$1.88 |
| Recycle transportation cost | \$/bbl/mile | \$0.03 |
| Recycle transportation distance | Miles | 10 |

**Table 3**
Economic values used for calculation of capital costs.

| Parameter | Unit | Amount |
|---|---|---|
| Plant availability | % | 90 |
| Inflation rate | % | 3 |
| Annual interest rate | % | 8 |
| Annual amortization factor | – | 0.14 |

## 3. Results and discussion

### 3.1. Comparative analyses of FO pit water treatment technologies

A baseline comparative analysis was performed to elucidate the potential environmental impacts and financial expenses associated with the three-pit water management scenarios. Results from the LCIA and LCC are specific to the operating conditions and performance of FO systems observed in recent pilot-scale tests in the Haynesville basin. In the baseline analyses, power is supplied by on-site genset systems, where only the energy production from the combustion of diesel fuel is considered.

#### 3.1.1. Baseline life cycle impact assessment

The relative impacts from the baseline LCIA of the three scenarios are shown in Fig. 3. The environmental impacts of each scenario are normalized by the maximum value observed between the three scenarios and are compared across the ten environmental impact categories (Fig. 3a). For each category, the dominant water management scenario assumes 100% of the relative impact compared to the other scenarios. The maximum values observed for each environmental impact category are also shown (Fig. 3b), using a logarithmic scale and different units of measurement for each impact category. Results in Fig. 3 indicate that engineered osmosis (scenario B1) yields the highest relative environmental impacts in nine of the ten categories. The relative environmental impacts of water management using osmotic dilution (scenario C1) are consistently 30% below those observed for scenario B1 and are similar to the impacts associated with scenario A1. Scenario A1 has the highest impact potential in the smog formation category, which is a result of the excessive transportation of water in this scenario compared to scenarios B1 and C1. In fact, transportation accounted for approximately 91% of the potential environmental impacts in smog formation compared to only 9% associated with energy required for pumping during deep well injection (data not shown).

Normalized scoring of the ten impact categories in Fig. 3a are shown in Fig. S1 of the Supplementary Data document. Normalization is performed by the SimaPro software and TRACI 2.1 impact assessment method by dividing the impacts of each environmental category by a reference value to better compare their relative importance. Reference values proposed by Ryberg et al. [55] are employed by TRACI 2.1. Fig. S1 shows that the carcinogenic potential and non-carcinogenic potential are of the greatest relative importance for all three scenarios, followed closely by the relative importance of ecotoxicity potential and fossil fuel depletion. The relative importance of the remaining six impact categories is very similar.

Despite both FO systems exhibiting potentially higher negative environmental impacts than those associated with deep well disposal in many categories, the loading results for all three scenarios across nine of the ten impact categories are within one order of magnitude (Fig. 3b). This finding is significant, especially considering the lack of detailed information regarding the additional LCI components associated with deep well injection beyond pumping energy and transportation of water. In other words, these findings strongly suggest that the environmental sustainability of FO treatment of O&G pit water is competitive with current deep well disposal practices. It is highly possible that the negative environmental impacts of scenarios B1 and C1 are lower

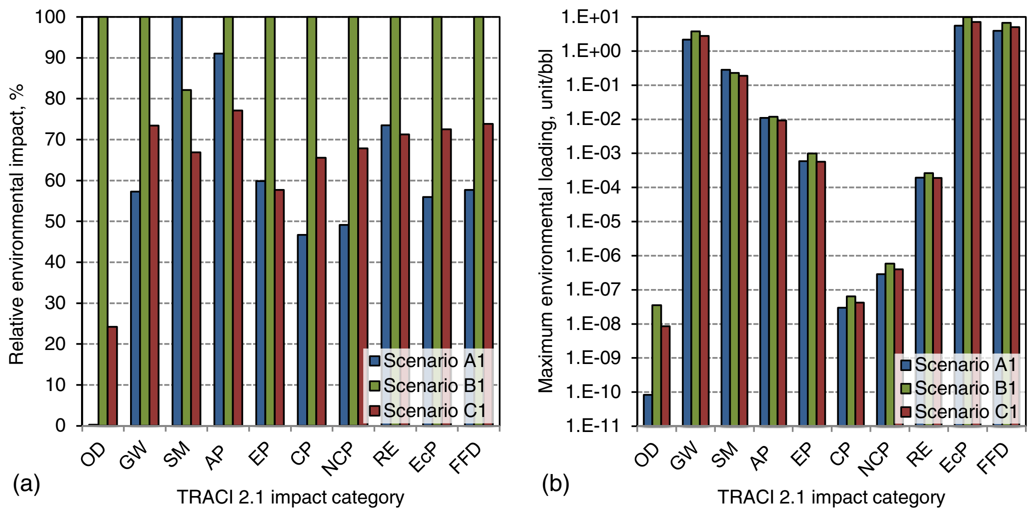


**Fig. 3.** The (a) relative environmental impacts and (b) maximum environmental loading of deep well disposal (scenario A1), engineered osmosis (scenario B1), and osmotic dilution (scenario C1) for management of O&G pit water. System energy demand is supplied by an on-site genset system. The environmental impacts of each water management option were evaluated using ten impact categories. Normalized scoring of the ten impact categories in Fig. 3a are shown in Fig. S1 of the Supplementary Data document. OD: Ozone Depletion (kg CFC-11); GW: Global Warming (kg $CO_2$); SM: Smog Formation (kg $O_3$); AP: Acidification Potential (kg $SO_2$); EP: Eutrophication Potential (kg N); CP: Carcinogenic Potential (CTUh); NCP: Noncarcinogenic Potential (CTUh); RE: Respiratory Effects (kg PM2.5); EcP: Ecotoxicity Potential (CTUe); FFD: Fossil Fuel Depletion (MJ surplus).

than those of scenario A1 if a cradle-to-grave LCI becomes available for deep well disposal (as opposed to the current gate-to-gate LCI). Additional LCI components such as capital construction and land procurement, chemical demands during system operation, equipment replacement at the end of its service life, and injection well shut-in and facility decommissioning will likely increase the expected environmental impacts of deep well disposal.

The contributions of the dominant LCI components of engineered osmosis (scenario B1) and osmotic dilution (scenario C1) FO systems to the potential environmental impacts of each category are shown in Fig. 4. The energy requirement for the FO subsystem dominates most impact categories, on average accounting for 40% of the total category contribution in the engineered osmosis system (Fig. 4a) and 56% in the osmotic dilution system (Fig. 4b). These findings are similar to those of Hancock et al. [37], who reported that the energy-related impacts were dominant in hybrid osmotic dilution processes across all impact categories investigated. The energy requirements for the RO subsystem and the impacts associated with transportation and pumping energy for pit water disposal also contribute substantially to nearly all impact categories in scenario B1 — on average accounting for 19% and 23% of the environmental impacts, respectively. The only impact category in which these LCI components do not contribute significantly to the environmental impacts is ozone depletion, where impacts due to infrastructure components of the FO and RO subsystems (e.g., pumps, motors, VFDs, PLCs) are dominant. The materials and manufacturing associated with pumping equipment and of all electrical components accounted for 49% and 29% of the total infrastructure impacts, respectively. Because the osmotic dilution system does not include an RO subsystem, the FO subsystem and the transportation and pumping energy for pit water disposal are the dominant LCI components in scenario C1 — transportation and pit water disposal account for 29% of the total category contribution. These data indicate that the environmental impacts associated with capital construction and decommissioning for each cradle-to-grave LCI are negligible compared to those associated with the operation and periodic maintenance of each system. This finding is consistent with those presented by Hancock et al. [37] and Raluy et al. [56]. Therefore, the potential environmental impacts associated with the FO processes are best managed with improvements to each system's operation phase (i.e., system energy supply and overall energy consumption).

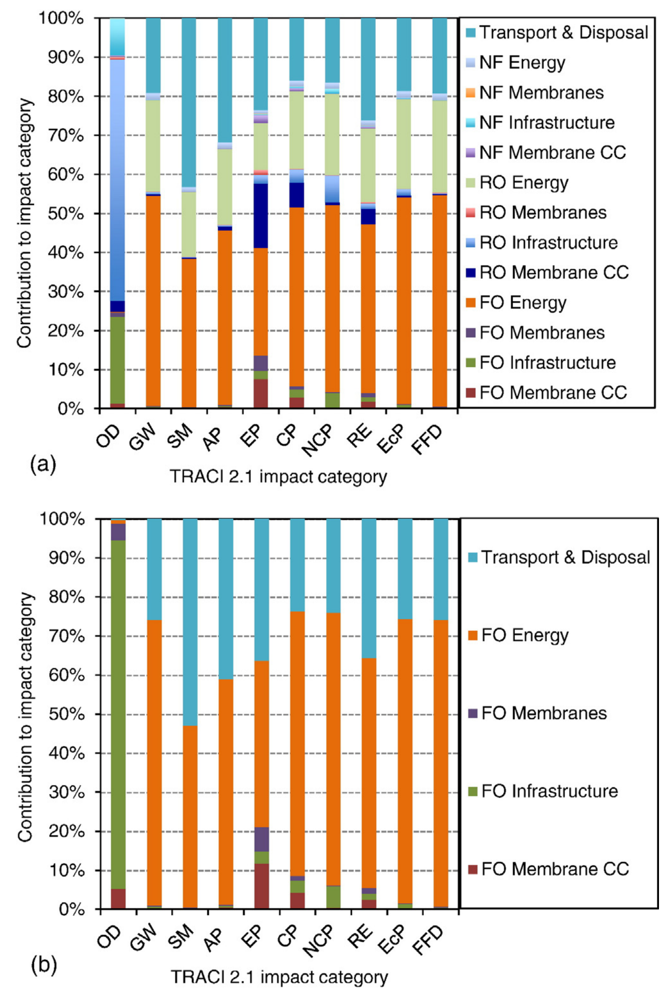


**Fig. 4.** Contribution analysis of various components of the (a) engineered osmosis (scenario B1) and (b) osmotic dilution (scenario C1) processes for treatment of O&G pit water.

*3.1.2. Baseline life cycle costing assessment*

A LCC of the inventories collected for each of the three pit water management scenarios was conducted using the system performance criteria outlined in Table 1 and economic values provided in Tables 2 and 3. Baseline economic evaluations resulting from the LCC of the three scenarios are shown in Table 4. Pit water management expenses are divided into six economic categories, where the final sum is expressed in dollars per year ($/year) of operation. The categories include fresh water procurement cost, fresh water transportation cost, OPEX treatment cost, treated water transportation cost, disposal transportation cost, and deep well disposal cost. Operation expenses incurred during deep well disposal are included in the total cost suggested in the literature for injection ($1.88/bbl of pit water) [41]. The total amortized capital costs for scenarios B1 and C1 are calculated based on values presented in Table 3. The total costs (water management costs plus amortized capital costs) are summarized at the bottom of the table and then normalized to the functional unit (1 bbl of pit water).

Results in Table 4 indicate that scenarios B1 and C1 can provide significant economic benefits to the O&G exploration industry compared to scenario A1. The total water management costs of scenario B1 ($3.01/bbl pit water) and scenario C1 ($2.27/bbl pit water) are lower than that of scenario A1 ($4.13) by 27% and 45%, respectively, and are in agreement with the range of water recycle costs proposed by Slutz et al. [41]. Included is these cost savings are those resulting from reduced water transportation requirements, where the miles of trucking required for water management fall by 63% for both scenarios B1 and C1 compared to scenario A1 (assuming an average truck volume of 130 bbl of water [38,41]). In general, the OPEX of treatment were the greatest contributors to the total costs associated with the FO processes, with significantly lower expenses associated with water transportation and disposal compared to scenario A1. At the estimated pit water management costs ($/bbl) and the economic values summarized in Table 2, the expenses associated with scenario A1 will be competitive with scenario B1 (no cost savings from water treatment) only if the cost of injection at deep well disposal facilities falls below $0.24/bbl in the Haynesville basin, all else held constant. Scenario A1 is not competitive with scenario C1 at any cost of deep well injection. These findings are significant considering that the costs associated with pit water management can account for up to 15% of well development and completion costs [41]. Therefore, cost savings during pit water management can help to maximize short-term profits for O&G exploration companies.

Similar to the LCIA of the FO processes, it is important to identify the dominant financial components of scenarios B1 and C1 to better understand what improvements might increase the economic sustainability of the processes. Therefore, the cumulative OPEX of scenarios B1 and C1, normalized by the functional unit, are shown in Fig. 5. The cumulative OPEX is the sum of costs associated with membrane replacement, intermittent chemical cleaning of the membranes systems, energy, labor, spare parts, and amortized fixed capital costs. Results in Fig. 5 demonstrate that cost associated with the operation of an on-site genset system to provide energy to the membrane skids was the highest financial contributor (>60% of OPEX), followed by amortized fixed capital costs. Intermittent chemical cleaning and FO membrane replacement were also dominant financial components, though substantially less than that of energy. Note that nearly all of the financial components shown, excluding the replacement of FO membranes, are less in scenario C1 due to the lack of RO and NF membrane processes. It is important to note the relatively high cost of FO membrane replacement ($750 per 8040 element) compared to that of RO ($585 per 8040 element) and NF ($350 per 4040 element) membrane replacement, which will likely fall given the rapid advancements in FO membrane research and FO companies entering the market.

**Table 4**
Cost comparison for O&G pit water management using disposal, engineered osmosis, and osmotic dilution. System energy demand is supplied by an on-site genset system. All values are discounted to the year 2012, during which pilot testing occurred.

| | | Scenario A1 | Scenario B1 | Scenario C1 |
|---|---|---|---|---|
| Pit water volume | bbl/year | 66,754 | 66,754 | 66,754 |
| Treated water for recycle | bbl/year | – | 50,066 | 50,066 |
| Fresh water make-up | bbl/year | 66,754 | 16,689 | 16,689 |
| Fresh water price | $/bbl | 0.30 | 0.30 | 0.30 |
| Fresh water procurement cost | $/year | $20,026 | $5007 | $5007 |
| Fresh water make-up | bbl/year | 66,754 | 16,689 | 16,689 |
| Fresh water Transportation cost | $/bbl/mile | 0.03 | 0.03 | 0.03 |
| Fresh water transportation distance | Miles | 15 | 15 | 15 |
| Fresh water transportation cost | $/year | $30,039 | $7510 | $7510 |
| Replacement — FO membranes | $/year | – | 6000 | 6000 |
| Replacement — RO membranes | $/year | – | 2340 | – |
| Replacement — NF membranes | $/year | – | 350 | – |
| Chemical cleaning | $/year | – | 12,439 | 3617 |
| Spares | $/year | – | 343 | 343 |
| Labor | $/year | – | 1040 | 1040 |
| Energy (60 Hz diesel genset) | $/year | – | 61,096 | 41,656 |
| Opex treatment cost | $/year | – | $83,608 | $52,656 |
| Volume of treated water | bbl/year | – | 50,066 | 50,066 |
| Treated water Transportation price | $/bbl/mile | 0.03 | 0.03 | 0.03 |
| Treated water transportation distance | Miles | – | 10 | 10 |
| Treated water transportation cost | $/year | – | $15,020 | $15,020 |
| Disposal volume | bbl/year | 66,754 | 16,689 | 16,689 |
| Disposal transportation price | $/bbl/mile | 0.03 | 0.03 | 0.03 |
| Disposal transportation distance | Miles | 50 | 50 | 50 |
| Disposal transportation cost | $/year | $100,131 | $25,033 | $25,033 |
| Disposal volume | bbl | 66,754 | 16,689 | 16,689 |
| Injection costs | $/bbl | 1.88 | 1.88 | 1.88 |
| Deep well disposal cost | $/year | $125,498 | $31,374 | $31,374 |
| Water management cost | $/year | $275,695 | $167,551 | $136,599 |
| Total amortized capital costs | $/bbl pit water | – | $0.50 | $0.23 |
| **Total water management cost** | **$/bbl pit water** | **$4.13** | **$3.01** | **$2.27** |

because energy contributed substantially to impacts in the baseline

*3.2. LCIA contribution analysis: energy source and energy recovery*

Before attempting to optimize the FO processes to reduce the baseline environmental and economic impacts, it is important to examine the impacts associated with system operating conditions. In particular, because energy contributed substantially to impacts in the baseline

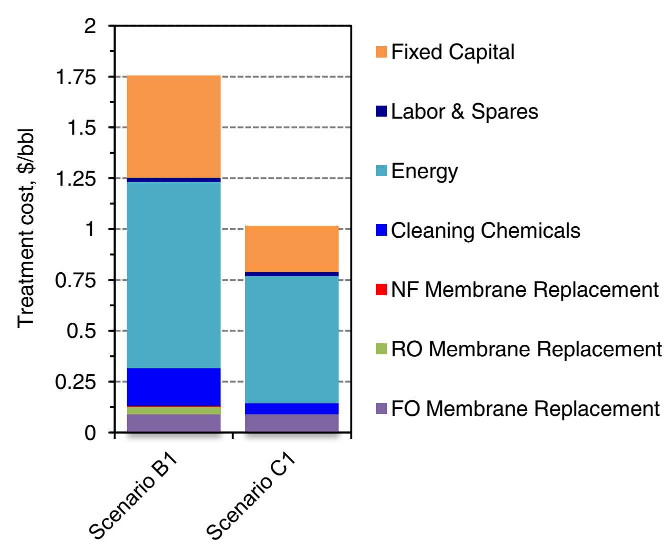


**Fig. 5.** System OPEX of engineered osmosis (scenario B1) and osmotic dilution (scenario C1) when powered on-site with a genset system (pilot testing conditions). Amortized fixed capital costs and the O&M cost associated with labor and spare parts are included.

scenario, the sensitivity to energy source was evaluated. An analysis was performed with electricity supplied by the USEM rather than on-site diesel genset systems. On-site power supplied by the USEM is representative of potential operating conditions for permanent treatment facility installations and readily available electrical infrastructure within the shale play. The USEM is the sum of energy production from a variety of sources, including hard coal (47.7% of total contribution), nuclear (19.8%), natural gas (17.5%), hydropower (6.9%), and oil (3.3%). The remaining 4.8% is comprised of seven additional minor energy sources [57].

*3.2.1. LCIA: impacts of energy source and energy recovery*

The relative and maximum environmental impacts of each scenario when operated with power supplied by the USEM are shown in Fig. 6. The results and general trends in potential environmental impacts shown in Fig. 6a are similar to those shown in Fig. 3a; however, engineered osmosis (scenario B2) now produces the highest relative environmental impacts in seven of the ten impact categories (compared to 9/10 in scenario B1). Overall, the relative environmental impacts of water management using osmotic dilution (scenario C2) also remain consistently 30% below those observed for scenario B2. Scenario A2 has the highest impact potential in the smog formation, ecotoxicity potential, and fossil fuel depletion categories and no longer exhibits higher impact potentials than scenario C2 in the acidification and eutrophication categories (compared to scenario C1 in Fig. 3a). As a whole, the maximum environmental impacts observed for each scenario (Fig. 6b) increased for the ozone depletion and acidification, eutrophication, and carcinogenic potential impact categories. The maximum environmental impacts decreased for the global warming, smog formation, non-carcinogenic potential, eutrophication potential, and fossil fuel depletion categories. The shift in all impact potentials was less than one order of magnitude total change in either direction.

As expected, the greatest overall percent change in impact potential occurred between scenarios B1 and B2 due to the high-energy demand of the engineered osmosis system compared to the C scenarios (<1.5 times lower energy demand) and A scenarios (<5 times lower energy demand). The difference in the relative impacts between scenario B2 and C2 only slightly decreases because the majority of system energy demand is generated by the FO subsystem. Despite substantially lower energy demand of scenario A2 compared to scenario B2, the comparative change in relative impacts between these scenarios does not reflect a significant difference in overall environmental loading (Fig. 6b). Indeed, the differences in LCIA results for all three scenarios across the ten impact categories are all within one order of magnitude. Normalized scoring of the ten impact categories presented in Fig. 6 (Fig. S2) shows that the carcinogenic potential is of the greatest relative importance for all three scenarios. The relative importance of the remaining nine impact categories was very similar. The contributions of the dominant LCI components of the engineered osmosis (scenario B2) and osmotic dilution (scenario C2) systems to the potential environmental impacts of each category were similar to those when operated with a genset system (Fig. S3). The energy requirement of the FO subsystem again dominates all impact categories, on average accounting for 47% of the total category contribution in the engineered osmosis system (Fig. S3a) and 63% in the osmotic dilution system (Fig. S3b).

Because the choice of energy source might only minimally influence the potential environmental impacts of each scenario, and especially the engineered osmosis process, an analysis was performed to determine the impact of system improvements through the inclusion of energy recovery in the RO system (which was not included in pilot-scale testing). The normalized and maximum environmental impact values from various energy configurations of scenario B are shown in Fig. 7. The impacts of operating the engineered osmosis system are compared when employing an on-site genset system and the USEM, and with or without an ERD. The inclusion of energy recovery in the RO subsystem in scenario B effectively lowers the total system energy demand by approximately 0.42 kWh/bbl (2.5 kWh/m$^3$ or 11.4%). Results in Fig. 7a show that the relative environmental impacts of engineered osmosis decline when powered by the USEM and when employing an ERD. Negative environmental impacts decrease in the order of scenario B1 > scenario B2 > scenario B1-ERD > scenario B2-ERD. Similar to Fig. 6, the maximum environmental impacts observed for engineered osmosis (Fig. 7b) increased for the ozone depletion, acidification potential, eutrophication potential, carcinogenic potential, and respiratory effects impact categories when engineered osmosis was powered by the USEM. The maximum environmental impacts decreased for all other impact categories. These findings suggest that RO energy recovery marginally affected the potential environmental impacts of the engineered osmosis system when operated without upstream pretreatment and did not effectively reduce the impacts of each category below that of osmotic dilution or deep well disposal (data not shown).

It is apparent that any potential reductions in the environmental impacts of FO, especially engineered osmosis, will result only from a focused effort to change system operating conditions in order to reduce

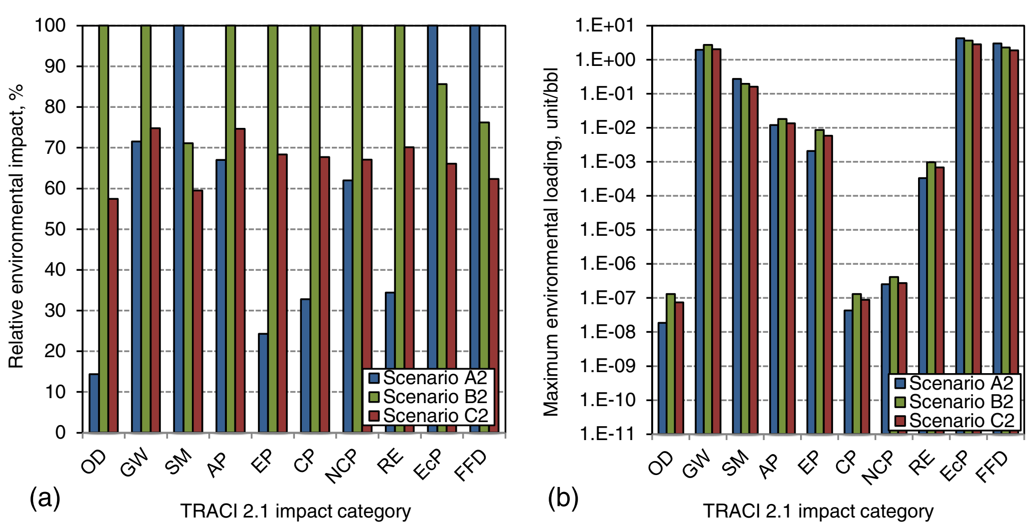


**Fig. 6.** The (a) relative environmental impacts and (b) maximum environmental loading of deep well disposal (scenario A), engineered osmosis (scenario B2), and osmotic dilution (scenario C2) for management of O&G pit water. System energy demand is supplied by USEM. The environmental impacts of each water management option were evaluated using ten impact categories. The abbreviations and units for each impact category are defined in Fig. 3.

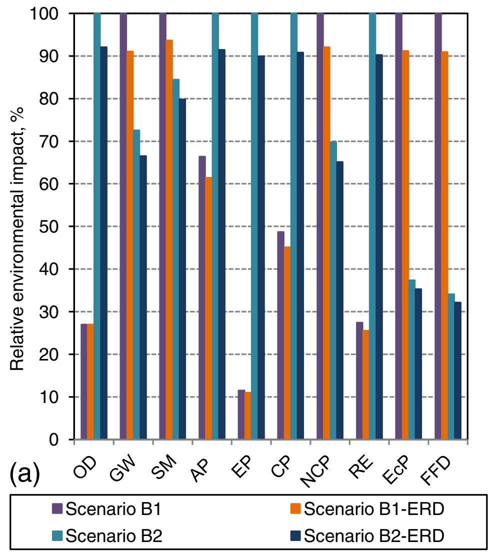


**Fig. 7.** The (a) relative environmental impacts and (b) lifetime environmental loading of deep well disposal, engineered osmosis, and osmotic dilution for management of O&G pit water. The environmental impacts of each treatment process are investigated using a variety of energy demand scenarios. The environmental impacts of each water management option were evaluated using ten impact categories. The abbreviations and units for each impact category are defined in Fig. 3.

the overall energy demand; however, it is highly unlikely that increasing membrane packing density, membrane service life, or cleaning frequency will significantly impact the overall environmental impacts observed for these FO systems. For example, Hancock et al. [37] demonstrated that, in a hybrid osmotic dilution system for seawater desalination, the contribution of system energy demand (<2.5 kWh/m$^3$ throughout their study) to the negative environmental impacts was greater than 70% compared to other dominant LCI components of the modeled system. The authors showed that the relative impacts of doubling FO membrane packing density (9.5 m$^2$ per element to 20 m$^2$ per element), while simultaneously increasing FO membrane permeability (0.36 L m$^{-2}$ h$^{-1}$ bar$^{-1}$ to 1.08 L m$^{-2}$ h$^{-1}$ bar$^{-1}$), only reduced the relative environmental impact of membrane materials (which contributed to the environmental impacts of the entire system by less than 5%) by approximately 30% over their five year service. The authors further showed that reducing clean-in-place frequency of the membrane systems (once per month to biannual) by implementing ultrafiltration prior to FO reduced the relative environmental impacts of cleaning chemicals (which contributed less than 20% to the system total) by approximately 5%. Based on those findings, and the overwhelming contribution of FO energy demand to the environmental impacts of engineered osmosis (~70% without transport and disposal impacts) and osmotic dilution (>90% without transport and disposal impacts) demonstrated during treatment of pit water, radical improvements to the current FO membranes (~7 m$^2$ per element, 0.36 L m$^{-2}$ h$^{-1}$ bar$^{-1}$, and 3 year service life) and membrane cleaning frequency will only marginally impact the environmental impacts presented here.

*3.2.2. Life cycle costing assessment: impacts of energy source and energy recovery*

Results from the economic evaluation of the three pit water management scenarios when powered by the USEM are shown in Table 5. Pit water management expenses are divided into the same categories as described in Section 3.2 (Table 4). The same OPEX for deep well disposal are assumed in the total cost ($1.88/bbl of wastewater) [10]. Results in Table 5 show that despite marginal changes in the potential environmental impacts of each FO system, significant cost savings might still result from employing power from the USEM. The total water management cost of scenario B2 ($2.32/bbl pit water) and scenario C2 ($1.82/bbl pit water) are lower than that of deep well disposal by 44% and 56%, respectively. At these management costs, the expenses associated with scenario A will be greater than both FO processes, regardless of the price charged for injection at the disposal facility. Even at increased USEM energy costs ($0.30/kWh), the cost of injection

**Table 5**
Cost comparison for O&G pit water management using disposal, engineered osmosis, and osmotic dilution. System energy demand is supplied by the USEM. All values are discounted to the year 2012, during which pilot testing occurred.

| | | Scenario A2 | Scenario B2 | Scenario C2 |
|---|---|---|---|---|
| Pit water volume | bbl/year | 66,754 | 66,754 | 66,754 |
| Treated water for recycle | bbl/year | – | 50,066 | 50,066 |
| Fresh water make-up | bbl/year | 66,754 | 16,689 | 16,689 |
| Fresh water price | $/bbl | 0.30 | 0.30 | 0.30 |
| Fresh water supply cost | $/year | $20,026 | $5007 | $5007 |
| Fresh water make-up | bbl/year | 66,754 | 16,689 | 16,689 |
| Fresh water transportation cost | $/bbl/mile | 0.03 | 0.03 | 0.03 |
| Fresh water transportation distance | Miles | 15 | 15 | 15 |
| Fresh water transportation cost | $/year | $30,039 | $7510 | $7510 |
| Replacement — FO membranes | $/year | – | 6000 | 6000 |
| Replacement — RO membranes | $/year | – | 2340 | – |
| Replacement — NF membranes | $/year | – | 350 | – |
| Chemical cleaning | $/year | – | 12,439 | 3617 |
| Spares | $/year | – | 343 | 343 |
| Labor | $/year | – | 1040 | 1040 |
| Energy | $/year | – | 14,919 | 11,476 |
| Opex treatment cost | $/year | – | $37,431 | $22,476 |
| Volume of treated water | bbl/year | – | 50,066 | 50,066 |
| Treated water transportation price | $/bbl/mile | 0.03 | 0.03 | 0.03 |
| Treated water transportation distance | Miles | – | 10 | 10 |
| Treated water transportation cost | $/year | – | $15,020 | $15,020 |
| Disposal volume | bbl/year | 66,754 | 16,689 | 16,689 |
| Disposal transportation price | $/bbl/mile | 0.03 | 0.03 | 0.03 |
| Disposal transportation distance | Miles | 50 | 50 | 50 |
| Disposal transportation cost | $/year | $100,131 | $25,033 | $25,033 |
| Disposal volume | bbl/year | 66,754 | 16,689 | 16,689 |
| Injection costs | $/bbl | 1.88 | 1.88 | 1.88 |
| Deep well disposal cost | $/year | $125,498 | $31,374 | $31,374 |
| Water management cost | $/year | $275,695 | $121,374 | $106,419 |
| Total amortized capital costs | $/bbl pit water | – | $0.50 | $0.23 |
| **Total water management cost** | **$/bbl pit water** | **$4.13** | **$2.32** | **$1.82** |

would need to decrease dramatically ($0.25/bbl versus $1.88/bbl) for deep well disposal to be competitive with engineered osmosis for pit water treatment. The OPEX remain the greatest contributors to the total costs associated with engineered osmosis, while the OPEX of osmotic dilution are slightly less than the transportation costs of concentrated pit water for disposal.

The water management costs associated with scenario A and with the two energy configurations for scenario B and scenario C are compared in Fig. 8. Similar to Tables 3 and 4, the total cost of pit water management for each scenario is the sum of costs associated with fresh water procurement, fresh water transportation, expenses associated with pit water treatment for reuse (scenarios B and C), transportation of treated water, transportation of water for disposal, and disposal in a Class II injection well. The water management costs of scenario C are compared when operated with an on-site genset (scenario C1) and with the USEM (scenario C2). The water management costs of scenario B are shown for the same energy sources; however, the management costs of each energy source for scenario B are also shown with and without ERD in the RO subsystem. The choice of energy source has significant impact on the water management costs associated with scenarios B and C, which is contrary to the minimal changes in environmental impacts shown in Fig. 7. Yet, the addition of ERD to the economic impacts provided minimal economic benefits, which is similar to the environmental impact trends previously shown. The costs of osmotic dilution when powered with a genset system (scenario C1) are lower than the costs of engineered osmosis even when powered by the USEM (scenario B2 and B2-ERD). The costs of osmotic dilution when powered by the USEM (scenario C2) provide the most economic savings compared to the other scenarios of this study.

## 4. Conclusions

The comparative LCIA of the three different pit water management scenarios demonstrates that the potential environmental impacts of engineered osmosis (scenario B) are highest compared to osmotic dilution (scenario C) and deep well disposal (scenario A). However, the overall environmental impacts of the FO treatment processes are very similar to those modeled for deep well disposal (only water transportation and pumping energy). In fact, the difference between the maximum values observed for each scenario across the ten TRACI 2.1 impact categories are consistently within one order of magnitude. At the current state of the technology, the energy demand of the FO subsystems operated with no upstream pretreatment is the single greatest contributor to the negative environmental impacts. The environmental impacts associated with system capital construction, membrane chemical cleaning, periodic membrane replacement, and system decommissioning minimally contribute to the observed environmental impacts. Analysis of two probable electricity sources demonstrates that the source of energy to the systems might lead to lower environmental impact values, yet such changes are unlikely to significantly impact the order of relative environmental impacts observed between the three pit water management scenarios. Only with radical changes in the US energy portfolio, or an energy supply dominated by renewable sources, like those previously presented in the literature, are substantial improvements likely achievable. The inclusion of pretreatment prior to scenarios B and C might reduce the need for high pumping rates through the FO membranes to reduce fouling and concentration polarization, thereby reducing the environmental impacts associated with system energy demand; however, the inclusion of pretreatment processes will surely lead to additional environmental impacts. The potential environmental trade-offs associated with the inclusion and enhancement of pit water pretreatment scenarios are not included in this study.

Economic evaluations of the three scenarios show that the employment of FO technologies for treatment of pit water could lead to considerable cost savings compared to deep well disposal practices. The financial snapshot of pit water management in the Haynesville basin suggests that FO technologies can have a potential economic benefit of nearly 60% compared to the deep well disposal scenario. Furthermore, transportation requirements could be reduced as much as 63% within the basin given adoption of water recycling technologies. Both the engineered osmosis and osmotic dilution processes could effectively buffer future economic variations associated with changes in injection costs at deep well disposal facilities and changes in transportation due to fluctuating automotive fuel costs.

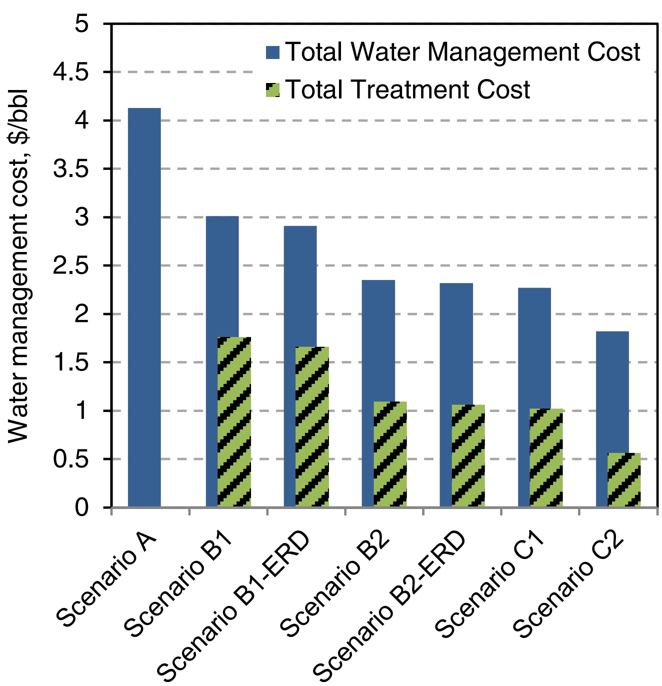


**Fig. 8.** Water management costs ($/bbl pit water) for deep well disposal and the energy scenarios for the engineered osmosis and osmotic dilution processes. The solid data bars represent the total cost of pit water management for each scenario, including the cost of wastewater trucking and disposal at a deep well injection facility. The hashed data bars represent only the costs associated with operating each FO treatment system; the costs of wastewater trucking and deep well injection are removed.

## Abbreviations

| | |
|---|---|
| AP | acidification potential |
| CAPEX | capital expenditure |
| CP | carcinogenic potential |
| CTA | cellulose triacetate |
| EcP | ecotoxicity potential |
| EP | eutrophication potential |
| ERD | energy recovery device |
| FFD | fossil fuel depletion |
| FO | forward osmosis |
| LCA | life cycle assessment |
| LCC | life cycle costing |
| LCI | life cycle inventory |
| LCIA | life cycle impact analysis |
| GW | global warming |
| ISO | International Standards Organization |
| NCP | non-carcinogenic potential |
| NF | nanofiltration |
| OD | ozone depletion |
| O&G | oil and gas |
| O&M | operation and maintenance |
| OPEX | operational expenditure |
| PLCs | programmable logic controllers |
| RE | respiratory effects |

RO reverse osmosis
SM smog formation
TDS total dissolved solids
TFC thin-film composite
TRACI tool for the reduction and assessment of chemical and other environmental impacts
USEM United States electricity mix
U.S. EPA U.S. Environmental Protection Agency
VFDs variable frequency drives

## Acknowledgments

Support of this investigation was provided by DOE/RPSEA project 10122-39 and the National Science Foundation Engineering Research Center Program under Cooperative Agreement EEC-1028968. Special thanks to DOW Chemical Company and King Lee Technologies for providing supporting information. The authors would also like to thank Kerri Hickenbottom for her assistance with life cycle costing methodology, John Veil for his invaluable expertise on and shale gas development and water treatment practices in the industry, and Nathan Walker, Alex Vian, Dr. David Stewart, and Dr. Wayne Buschmann for their role in data acquisition and technical review.

## Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.desal.2015.04.028.

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