Assessing the energy and carbon footprints of exploiting and treating brackish groundwater in Cape Town

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ABSTRACT

South Africa has been facing significant challenges in meeting demands in its water and energy sectors in recent years and planning for both sectors has mostly been done separately. The City of Cape Town has started to supplement its dwindling conventional freshwater supplies with groundwater, wastewater and seawater, in light of the drought that commenced in 2015. The Cape Flats Aquifer in Cape Town represents an important resource whose yield could be increased to 85 000 m^3/day through artificial stormwater recharge in the Zeekoe Catchment alone. The abstraction and treatment of this water would require significant amounts of energy and thus this paper explores the links between energy usage in the water sector and its carbon footprint. The three alternatives investigated were 'centralised', 'desalination' and 'decentralised' approaches. The former two are centralised treatment mechanisms to produce potable water utilising existing and new treatment infrastructure, respectively, and the latter proposed minimal treatment for non-potable end-users. The energy intensities of the alternatives were evaluated by identifying energy-intensive components and carrying out a preliminary design of the networks and the required treatment mechanisms. South Africa's future potential electricity mixes were used to conceptualise the significance of the associated energy demand. The centralised approach's energy intensity was found to be the lowest of the three, ranging from 1.16 to 1.57 MJ/m^3, while those of the decentralised and desalination approaches ranged from 3.57 to 7.31 MJ/m^3 and 7.41 to 9.62 MJ/m^3, respectively. The Western Cape Water Supply System has an installed capacity of 47.6 MW which could potentially increase by at least 2.7%, 5.7% and 12.3% through the centralised, decentralised and desalination options, respectively. This paper contributes to a growing knowledge on the water–energy nexus in South Africa.

Keywords: Cape Flats Aquifer, water–energy nexus, stormwater recharge, brackish water desalination, carbon footprint

INTRODUCTION

The existing freshwater and energy resources worldwide have been exploited extensively and unsustainably over the past decades creating a heavy dependency on surface water and fossil fuels, while planning for both sectors has been historically carried out independently (IEA, 2016; Hussey & Pittock, 2012). However, with growing concerns for both water scarcity and the impacts of fossil fuel energy sources on the environment, the implications of the linkages between the two sectors are now becoming increasingly important in planning for future water and energy mixes.

As a freshwater-scarce country with an energy-intensive economy, South African resources must be managed judiciously to meet the needs of its growing population, while simultaneously mitigating its greenhouse gas emissions (GHG). The South African energy sector contributes 88% to the national carbon emissions and these are mainly generated by highly water-intensive ageing coal power plants (DEA, 2013). The water sector is also a significant user of energy, both in the form of liquid fuels and electricity, and comprises the third-largest demand for energy in the country (17%) (SACN, 2014). It is therefore important that the energy implications of introducing alternative water sources and treatment mechanisms are quantified and evaluated in economic and environmental terms. South Africa has committed itself to decrease its greenhouse gas (GHG) emissions through the Peak Plateau and Decline (PPD) trajectory, requiring compliance from all sectors to achieve its targets (RSA, 2015). Nonetheless, available information on the water–energy nexus in the South African context is limited. Given the country's status as one of the top 20 polluting countries, constrained energy supplies and sensitivity to drought – which is being considered as the 'new normal' based on a projected drier future according to climate change prediction models – holistic planning between sectors is crucial (WRI, 2017).

Surface water accounts for 77% of South Africa's supply, while groundwater and water reuse account for the remaining 22% (CSIR, 2015; DWA, 2013). The City of Cape Town (CCT), in particular, is supplied by six major dams situated in the mountains surrounding the City with a total storage capacity of 898 GL and an extensive distribution network (CCT, 2017). During the 2015–2018 drought, the CCT was forced to implement several measures to virtually halve water use (CCT, 2017). The CCT is thus considering alternative water sources such as seawater desalination, groundwater and recycled water to supplement freshwater supply (CCT, 2017).

One alternative water supply is through the artificial recharge of the Cape Flats Aquifer (CFA) using stormwater (Okedi, 2018). According to Okedi (2018), with recharge of the CFA using stormwater, it is possible to abstract substantial amounts of groundwater, especially in the winter months, due to availability of rainfall. The abstracted water would meet a portion of Cape Town's water demand and assist in the recovery of bulk storage in the existing surface water dams for use in the dry summer months. Accordingly, three alternative approaches, termed 'centralised', 'decentralised' and 'desalination', were investigated to determine the energy required from the abstraction to treatment stages. The centralised approach proposed pumping the groundwater to two existing water treatment plants, namely Blackheath and Faure, to produce

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potable water that would then be distributed through the existing system. The decentralised approach proposed the use of four smaller networks and the associated water treatment plants to produce lower quality water for non-potable end-users identified in the catchment. The proposed desalination approach would treat the groundwater to potable water levels using reverse osmosis and then distribute the treated potable water through the existing reticulation system. This paper contributes to a broader study by Okedi (2018) by evaluating the direct and embodied energy intensities of the three approaches' abstraction, conveyance and treatment stages. The potential current and future costs and carbon footprints of the alternatives are then used to compare their viability.

LITERATURE REVIEW

The water and energy sectors, considered as being vital to economies, are both facing urgent challenges worldwide (Hussey and Pittock, 2012). Despite the considerable progress made in past decades to improve access to water and energy, nearly 16% of the world's population still lack access to electricity, while 9% lack access to safe water and more than 40% are affected by water scarcity (World Bank, 2017; IEA, 2016). Demand for clean water services and energy, not only in the form of electricity but also liquid fuels, is projected to increase with growing global population, improved accessibility to services and economic growth (IEA, 2016). Such increases will likely result in growths in the production and supply of water and energy, as well as deepening the link between the water and energy sectors. The future water and energy mixes include energy-intensive alternative water sources such as desalination and wastewater re-use, and water-intensive energy conversion mechanisms, including nuclear power and biofuel production (IEA, 2016).

The water–energy nexus has been recognised as being crucial in holistic planning for sustainable development and associated frameworks, but planning for both sectors has historically been carried out in parallel with minimal interaction (Siddiqi and Anadon, 2011; Hussey and Pittock, 2012). While there are rising concerns of resource depletion and climate change globally, the implications of the water–energy nexus have largely been focused on developed countries – and then mainly on the role of water in the energy sector. Various studies (e.g. Wilkinson, 2000; Stokes & Horvath, 2011; Bakhshi et al., 2012) have extensively investigated the effects of energy on the water sector in the United States and Canada. The nexus in developing regions such as the Middle East and Africa has also been explored to a certain extent in studies such as: Madhlopa et al. (2016); Ahjum and Stewart (2014); Sparks et al. (2014); Siddiqi and Anadon (2011); Bazilian et al. (2011) and Friedrich (2009).

Energy production in various forms can be highly water intensive, with water being used both in primary energy production and power generation. The extraction of fossil fuel resources has many water-intensive processes including drilling, hydraulic fracturing for shale gas and oil, refining and washing. As new mechanisms are developed to extract more primary energy resources, water demands in the energy sector are constantly changing. For instance, the water requirements of hydraulic fracking for the extraction of locked natural gas exceeds those of conventional methods, whilst the water footprint of exploiting the Canadian oil sands is 20 times that of petroleum produced in the Middle East (Glassman and Wucker, 2011).

On the other side of the nexus, energy is not only needed for water extraction, conveyance, storage, treatment and distribution but also for on-site water pumping, thermal requirements and wastewater collection, treatment and discharge (Wilkinson and Kost, 2006). Almost 60% of the water sector's global energy consumption is in the form of electricity, while the remainder is in the form of fossil fuels in pumps and as thermal inputs in desalination treatment (IEA, 2016). Considerable energy is required for the treatment processes before treatment depending on the degree of impurity (depending on the concentration of contaminants) and the targeted end-uses (Plappally and Lienhard, 2012).

The energy and water sectors are intricately linked in South Africa. The highly coal-dependent electricity sector, on average, requires substantial amounts of water from extraction to generation, while energy is required throughout the conventional water cycle and wastewater treatment and management. Eskom is one of the largest users of freshwater in South Africa with some 2% (292 million m^3 per annum) of the total national supply delivered to its power stations (Eskom, 2017). The energy sector is also considered as one of the main causes of degradation of water resource quality, due to the generation of highly polluted water and greenhouse gas emissions produced from the burning of fossil fuels (Madhlopa et al., 2016).

The projected electricity mixes given by the Integrated Resources Plan (IRP) propose new build programmes centred on additional coal and nuclear power stations that will considerably increase Eskom's water demands. In an attempt to curb these, Eskom has, through its long-term water strategy, targeted a decrease in the water intensity of its plants from 0.383 L/MJ to 0.358 L/MJ by making use of dry-cooling systems in new power plants, retrofitting existing ones, desalination of effluents from mines, demand-side management and technical improvements (Madhlopa et al., 2016).

Globally, water supply systems make up 2% to 3% of total electricity consumption, of which motor pumps generally account for 80% to 90%, depending on the available water sources, climatic conditions and type of technologies used for treatment (Vilanova and Balestieri, 2014). The movement of water in water supply systems requires energy which, in the absence of potential energy (from gravity flow), is generally provided by means of pumps driven by electricity (Plappally and Lienhard, 2012). Over and above the operational needs of the water sector, the embodied energy of the materials used during the service lives of the water supply systems (WSSs) also needs to be accounted for. These can often be compared to direct energy consumption of water systems and must be included in the determination of the total embodied energy of the treated water (Mo, 2012; Wilkinson, 2000).

The South African water sector, including wastewater management, creates the third-largest demand for energy in the country (SACN, 2014). Electricity costs range between 5% and 30% of the total operational costs of both water and wastewater treatment plants (SACN, 2014). As freshwater resources are being exploited to their limits, alternative water treatment mechanisms such as desalination plants are being set up around the country, increasing the sector's energy demands since desalination processes are highly energy intensive (Karagiannis and Soldatos, 2008).

The energy consumption of water supply systems is related to the topography and spatial distribution of the network, climatic conditions, the location of available water resources and their demand sites and the quantity and quality of the water (Plappally and Lienhard, 2012; Pelli and Hitz, 2000). Energy is required at each step of the water supply systems to

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treat water to various levels and drive it through the network. It can be quantified using several methods. Pelli and Hitz (2000) estimated the energy consumption and performance of water supply systems using two energy indicators suitable for small- to medium-sized utilities. The structural indicator considers the energy required to move water across the spatial distribution of the water supply system, whilst the quality indicator assesses the efficiency of a water utility.

The integration of energy production with hydraulic energy recovery in water supply systems can contribute to increasing the efficiency and sustainability of WSSs since electricity and water usage profiles have similar peak times (Ramos et al., 2010). For example, the CCT produces 5% of its internal electricity demands from micro-hydro generation using turbines fitted at its bulk water treatment works with a total installed capacity of 2.775 MW (CCT, 2015). Furthermore, the time of use of energy-intensive components, such as pumps, can be shifted to off-peak electricity usage periods (Ramos et al., 2010; CCT, 2015).

While surface water resources have been extensively developed, alternative water sources such as brackish water – including groundwater and treated wastewater effluents – and seawater are now increasingly being investigated and exploited to varying extents. Despite the fact that so-called brackish water only accounts for 0.5% of the available water resources, it represents a relatively cheap and energy efficient source (Voutchkov, 2013). It is widely used for irrigation purposes without treatment (Winter et al., 1998). However treatment, typically advanced aeration and chemical dosing, is required to produce potable water (CSIRO, 2007). The treated effluent TDS levels achieved by most wastewater treatment plants operated by CCT also fall within the brackish water salinity ranges, but in this instance advanced treatment in the form of ultra-filtration and desalination methods is often required out of concern for pathogenic organisms and pharmaceuticals.

Seawater desalination, rainwater harvesting, greywater recycling and wastewater reuse systems are other alternative water resources, each with different economic and environmental implications (Gleick, 2000). The ranges of energy intensities of water produced from these sources are given in Table 1 and vary according to the design of the systems, the technology used and the water quality required for its targeted end-uses (Lazarova et al., 2012).

TABLE 1
Typical energy intensities of alternative water systems (Lazarova et al., 2012)

Processes	Typical energy intensities (MJ/m³)
Rainwater harvesting systems	1.15–4.32
Greywater reuse	0.72–9.0
Membrane bioreactors (MBR) for wastewater treatment	1.8–9.0

Seawater desalination, in particular, is highly energy intensive compared with conventional treatment mechanisms due to the high salinity content of the feedwater – but is a viable alternative in coastal water-scarce countries. The reverse osmosis (RO) process is the most common technology used for desalination and is employed in more than 60% of existing desalination plants. It is far less energy-intensive than thermal processes such as multi-stage flash distillation (MSF) and multiple-effect distillation (MED) (Ghaffour et al., 2013), since for these the feedwater has to be heated up to 100°C and then cooled back over multiple stages (Voutchkov, 2013), and hence the energy intensity can reach 72 MJ/m³ (Goga et al., 2015). The electricity consumption of electro-dialysis is comparable to reverse osmosis but the process can only be used for feedwater having lower ranges of salinity. The energy intensities of treated water from the different processes are indicated in Table 2.

The costs of desalinating water have decreased over the years as a result of advances in the treatment technologies as well as the use of energy recovery devices (ERDs) to improve the efficiency of the mechanisms. Combined power and desalination plants improve the efficiency of both energy and water (Qiu and Davies, 2012; WWDR, 2015). ERDs installed in existing desalination plants in South Africa can yield savings of up to 50% through the use of pressure exchangers and hydraulic turbines (Plessis et al., 2005).

DATA AND METHODS

This paper considers the energy requirements for abstraction, conveyance and treatment of groundwater to be extracted from the CFA between March and November, which accounts for almost all rainfall in Cape Town. The calculations were based on several factors including the topography, spatial layout of the proposed networks and water quality of the resource.

Abstraction points for pumping the groundwater were envisaged as being placed around several existing stormwater ponds in the catchment that had been identified as being suitable for artificial recharge of stormwater in the Zeekoe Catchment (Okedi, 2017). The Zeekoe Catchment covers about 100 km² of the CFA and is found in the south-eastern part of Cape Town as shown in Fig. 1.

Overview of the various approaches to the delivery of treated groundwater

Three alternative water supply options were considered, as follows:

- The ‘centralised’ approach consists of abstraction of groundwater from the CFA with subsequent conveyance through two main transmission lines to Blackheath and Faure Water Treatment Plants (WTPs) (Fig. 2), for treatment

TABLE 2
Desalination technologies’ energy intensities (Voutchkov, 2013; Ghaffour et al., 2015; Turner et al., 2015)

Process	Thermal energy (MJ/m³)	Electrical energy (MJ/m³)	Total energy (MJ/m³)
Multi-stage flash (MSF) distillation	9–43.2	9–14.4	18–57.6
Multiple-effect distillation (MED)	0.72–25.2	4.32–7.2	5.04–32.4
Seawater reverse osmosis (SWRO)		9–16.6	9–16.6
Brackish water reverse osmosis (BWRO)		1.08–9	1.08–9

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to potable water quality levels. The treated water would then be distributed using the existing reticulation systems.

- The 'decentralised approach' was chosen due to available non-potable water uses in the catchment. Four theoretical decentralised WTPs with minimum basic treatment of groundwater to minimise health risks from contact were assumed. The treated water would be pumped through dual reticulation networks to the various users in the study area.
- The proposed brackish water 'desalination approach' assumed a plant was placed to the south of the study area, near the surface water bodies where RO would be used to treat the groundwater to potable water quality levels and distributed through existing reticulation systems.

The 'centralised' and 'decentralised' approaches essentially compared the coupling of the existing potable water system with the alternative of small decentralised water treatment works and the associated dual reticulation networks providing non-potable water. The brackish water 'desalination' approach was chosen as the third alternative because desalination had been proposed in various plans for future water mixes for the CCT (CCT, 2017). An abstraction rate of 85 000 m^3/day was used as the yield of the CFA augmented through artificial recharge using stormwater as proposed by Okedi (2017).

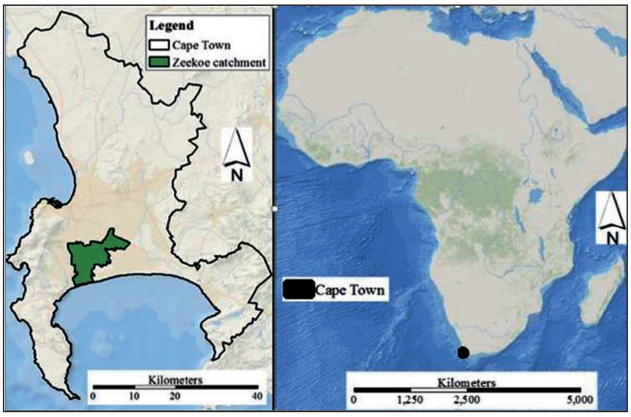

Figure 1
CoCT boundary and Zeekoe catchment location (CoCT, 2013; Google Maps, 2017)

Assumptions and limitations

The study focused on the operational stages (abstraction, conveyance and treatment) only. The addition of the construction and decommissioning phases of the alternatives would be an interesting follow-up study that would require in-depth sizing, design and costing of the alternatives. The energy demands generated by the different components, at their operational stage, of the three alternatives are summarised in Fig. 3.

Due to the limited data available on the energy intensities of the different chemicals used in the local water supply systems in South Africa, the analysis was carried out the using embodied energy data of chemicals extracted from international life cycle assessment tools such as GaBi and WEST (GaBi, 2017; WEST, 2017). The production processes of the various materials which would be used during each water treatment stage are fairly standard and thus the data was deemed to be applicable in the South African context.

Energy losses occurring across distribution lines and upstream during electricity production were not directly accounted for. The study only estimated the probable direct electricity demands and embodied energy demands of the options considering their likely efficiencies. The calculations of the carbon footprints caused by the calculated energy usages were based on EPRI (2015) data, where the emissions in

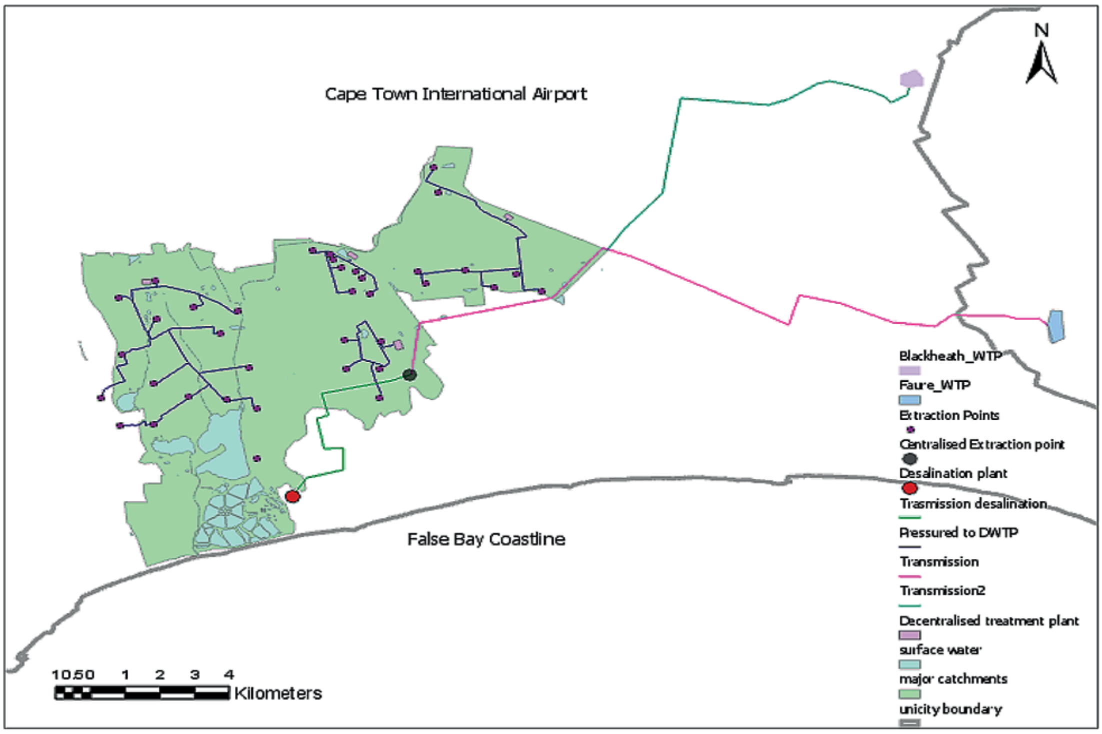

Figure 2
Map of the key aspects of the approaches (CCT, 2013)

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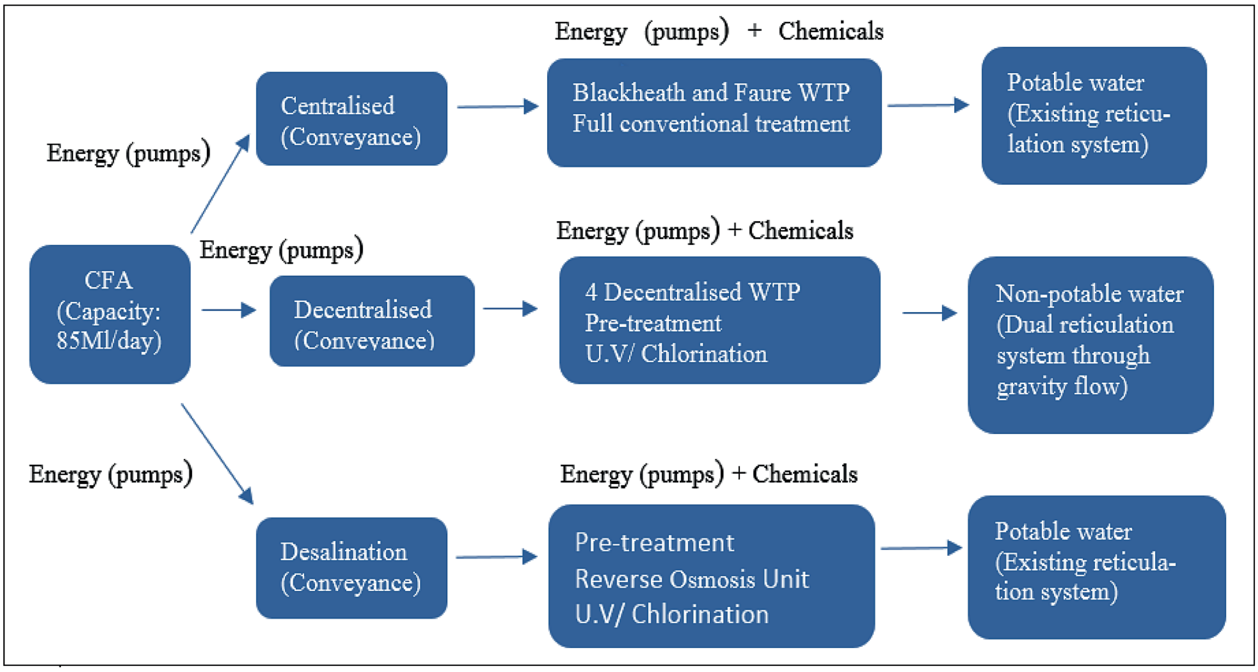

Figure 3

Overview of the energy demands for the three alternative water-supply approaches

kg/MWh (converted to kg/MJ) from each energy technology were given for the electricity produced. The fluctuations in groundwater level were also limited to 1 m since it was assumed that stormwater recharge would be used to supplement the aquifer.

Determining the energy demands of the three approaches

The theoretical direct power required to pump the groundwater depends on the flow rate and the total hydraulic head. Ahmed et al. (2014) give the direct output power of the pump, P_{out}(kW) as a function of the total dynamic head, *h*, (m), the flowrate of the water, Q, (m^3/s), the density of the water ρ, (kg/m^3), and gravitational acceleration, *g* (m/s^2) as given in Eq. 1:

$$P_{\text{out}} = \frac{\rho g Q h}{1000} \quad (1)$$

The total dynamic head was computed from the total drawdown in the well, the gravitational lift of the water, friction and secondary losses in the pipes, and the exit velocity head. The pipe friction head loss, h_f, was obtained by using the Darcy-Weisbach equation while the exit velocity head, h_e, was computed from Eq. 2 where *v* is the velocity in the pipes (Ahmed et al., 2014; Finnemore and Franzini, 2002). Secondary losses were also accounted for by estimating the loss coefficient, *K*, of fittings, bends, elbow, valves and exits of pipes over different segments of the systems (ibid).

$$h_e = \frac{v^2}{2g} \quad (2)$$

The input power required by a motor is the product of the pump power requirement and the motor efficiency. The pump power requirement, P_{in}, is the product of the output power (Eq. 1) and the pump efficiency, *n*, which, in turn, depends on the flow rate and head profile of the pump and individual power-capacity (P-Q) and efficiency-capacity (E-Q) curves of each system, generally ranging from 44% to 85%. A system efficiency of 70% was ultimately used to calculate the lower limit of the abstraction electricity demand for the transmission pumps whilst 50% was used for submersible borehole pumps due to changes in static and dynamic heads across each stage. The efficiency varies with changes in water levels in the borehole which in turn influence the flow rate. An overall system efficiency of 85% was used to account for energy losses such as motor efficiencies of the pumps used.

$$P_{in} = n.P_{out} \quad (3)$$

The energy intensity calculations for the treatment stage were carried out similarly. The flows in the centralised and decentralised approaches' treatment processes were assumed to be mostly gravity driven. The backwash pumps' energy intensities were estimated from EPRI (2013) and appropriate UV lights ratings, based on the turbidity and the microbial content of the feedwater, were used to calculate the electricity usage required for their operation.

The direct energy demand in the brackish water desalination alternative is also generated by backwash pumps and, mostly, input feedwater pressure in the RO unit. Pre-treatment was assumed to comprise of the oxidation of iron and manganese followed by gravity filtration through manganese greensand. Centrifugal pumps were assumed for the provision of the head required to overcome the pressure difference between the feedwater and permeate in the RO unit. The minimum applied feed pressure F_p has to be greater than the osmotic pressure, on the permeate side of the RO membrane, the permeate pressure P_p and the pressure drop across both sides, $P_{d,}$ to create the net driving pressure (*NDP*) (Voutchkov, 2013; Kucera, 2012).

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$$NDP = F_p - (O_p + P_p + 0.5\ P_d) \quad (4)$$

The minimum power required to abstract and pump water to the water treatment plants was based on the total dynamic head calculated using Eq. 3. The energy, *E*, (MJ), required to pump a given flow volume of the water, was calculated using the product of the flow, *Q*, and the operational hours, *T*, as shown in Eq. 5.

$$E_{min} = P_{in}\ T \cdot 3.6 \quad (5)$$

The energy intensity of the treated water in MJ/m^3 was therefore obtained by using the total treated water over time, *T*, and the energy required over the same time period.

$$\text{Energy intensity}_{min} = \frac{E_{min}\ (\text{MJ})}{\text{Total Volume of water treated}\ (\text{m}^3)} \quad (6)$$

Pumps matching the required flow rates were then chosen and their pump, motor and electrical systems' efficiencies were factored in their power ratings, P_{pump}. The total upper end of the ranges of the energy intensities for abstraction and conveyance were calculated using the chosen pump power rating.

$$\text{Energy intensity}_{max} = \frac{P_{pump}\ T\ (\text{MJ})}{\text{Total Volume of water treated}\ (\text{m}^3)} \quad (7)$$

A considerable amount of energy is also required to produce materials and products and to transport these to their final consumers. The embodied energy can often be compared to direct energy usage of water supply systems (Mo, 2012). The embodied energy demands of the three approaches were calculated using a bottom-up approach. Actual chemical usage data obtained from Blackheath WTP were used in all three approaches due to the similar raw water qualities fed to the treatment plants. The total primary energy used for the manufacturing of unit mass of each chemical used during the processes was retrieved from the life cycle assessment tool GaBi as well as local and international literature (GaBi, 2017).

The consumables considered for the study included the filter material (both silica and manganese greensand) and the RO membrane. Regeneration of manganese greensand can be carried out using potassium permanganate as an oxidising agent for the removal of iron and manganese ions from the raw water at a concentration ratio of approximately of 1:1 for iron and 1:2 for manganese (Kucera, 2010). The main materials required for the treatment stage of the three approaches were identified and are summarised in Table 3.

The energy intensity of each chemical used per m^3 (W_e) was calculated using the manufacturing energy intensity and the dosage through each process (Eq. 8).

$$W_e \left(\frac{\text{MJ}}{\text{m}^3}\right) = \text{primary energy intensity} \left(\frac{\text{MJ}}{\text{Kg}}\right) \cdot \text{dosage} \left(\frac{\text{Kg}}{\text{m}^3}\right) \quad (8)$$

Production costs and carbon footprint of the evaluated components

While conventional water technologies have been developed extensively, the largest potential to improve the sustainability

TABLE 3
Proposed chemicals usage in the three approaches

Consumables	Centralised	Decentralised	Desalination
Chlorine	✓	✓	✓
Lime	✓		✓
Aluminium sulphate	✓		
Carbon dioxide	✓		✓
PAC	✓		
Sand	✓		
Manganese greensand		✓	✓
Potassium permanganate		✓	✓
Fluoride			✓

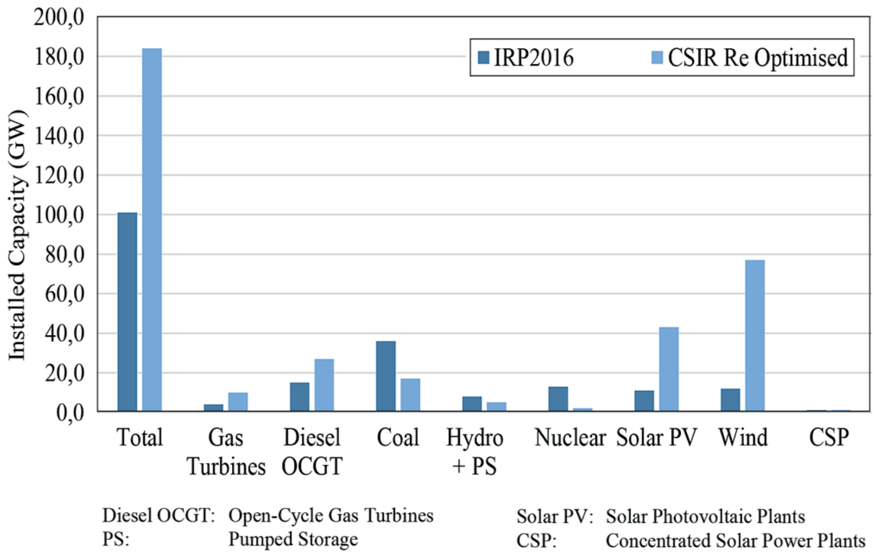

Figure 4
IRP 2016 & CSIR 2016 electricity mixes for 2030 (CSIR, 2016; DoE, 2016)

of the sector is to examine the energy sources. All three alternative electricity consumptions were matched to the current South African electricity mix and compared to the future electricity mixes as described in the updated IRP reports and CSIR's (2016) least-cost electricity mix scenario.

The likely future electricity mix of South Africa was laid out by the Integrated Resource Plan (IRP) developed by the Department of Energy in 2010. The IRP (2010) proposes new build programmes for South Africa from 2010 and 2030 but the plan was later revised in 2013 and 2016 and the next review is due in 2018. The IRP 2016 electricity mix has a higher share of coal and nuclear (DoE, 2016). There have been other studies carried out using the base case of the IRP with different parameters. The CSIR (2016) scenario is considered as being in line with current trends in the local and global renewable energy sector and the modelling of the resulting electricity mix adopted a least-cost approach for the energy technologies considered. (CSIR, 2016). The resulting electricity mix proposes no new coal and nuclear capacity added but higher renewable energy and gas capacity over the next 25 years.

The carbon footprints of the three alternatives were estimated using the current carbon emission intensities of the materials used and the current electricity usage during the operational stages. The future possible emissions associated with the approaches were also calculated using the CSIR (2016) and IRP (2016) future electricity mixes. Their possible respective carbon emissions were estimated using EPRI (2015) emissions from each energy technology used in the mixes (EPRI, 2015).

RESULTS

Energy intensities of the three approaches

The energy intensities of the abstraction, conveyance and treatment stages were estimated and their respective total electricity and embodied energy intensities were compared as shown in Fig. 5. The estimated abstraction stage electricity demands were based on the requirements of the submersible pumps and were found to be similar in all three alternatives. Conveyance pumps accounted for the electricity demands of the conveyance process, which was dependent on the distance and elevation differences between the abstraction points and the water treatment mechanisms used. This, in turn, depended on the spatial layout of the networks of the three approaches and varied with the combination of static and dynamic heads. The elevation differences between the boreholes and the water treatment plants at Blackheath and Faure in the centralised approach were larger than those of the other two alternatives, i.e., the decentralised and desalination approaches' total dynamic heads mainly consisted of friction losses created in the transmission networks.

The electricity demands for the treatment stage were the lowest in the centralised approach where gravity flow, mechanical and chemical processes were used to treat the groundwater. The electricity intensity of the decentralised approach was largely a consequence of the backwash systems and the use of UV for water disinfection, while the electricity demands for the desalination approach were mostly created by the use of UV and the feedwater pumps needed to produce the large pressure gradients required for the reverse osmosis (RO) unit. The decentralised approach's lower end of its electricity intensity range is less than that of the centralised approach and the largest difference between the two occurs in the conveyance stage. The distance and elevations between the abstraction points and treatment plants are significant in determining the viability of both options as the decentralised approach could have a smaller energy demand with smaller networks or onsite treatment plants.

The design pressure gradient used across the membrane in the RO unit depends on the concentration of dissolved solids of the feedwater and the targeted water quality levels. Despite a relatively low TDS concentration of the groundwater as compared to feedwater concentrations (such as seawater) normally used in desalination plants, the energy intensities were found to be higher than those obtained from the literature review. The high salt rejection rate (97.7%) used in the estimation of electricity usage could explain the differences, since only one RO unit was used in the treatment chain,

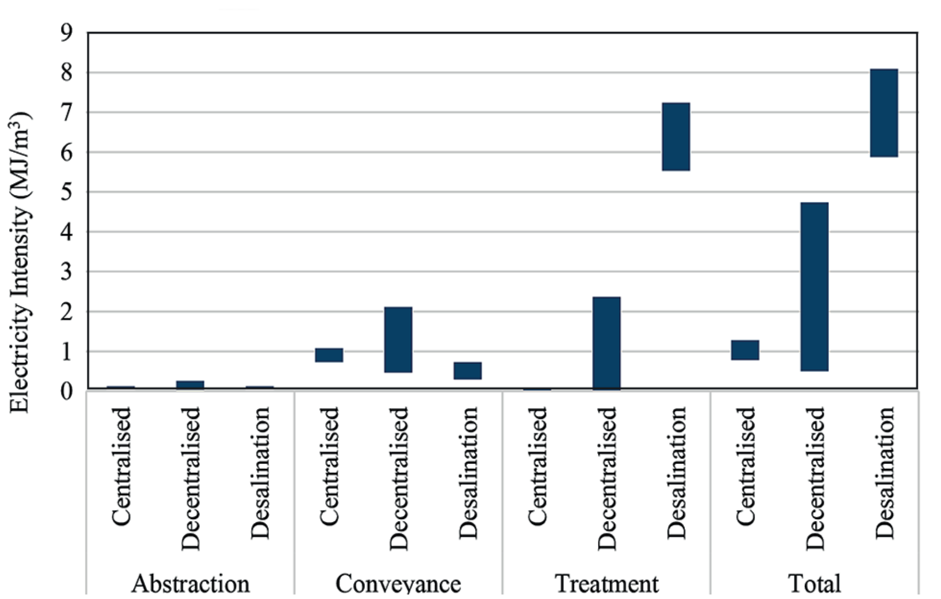

Figure 5
Electricity intensities of the three alternatives (MJ/m³)

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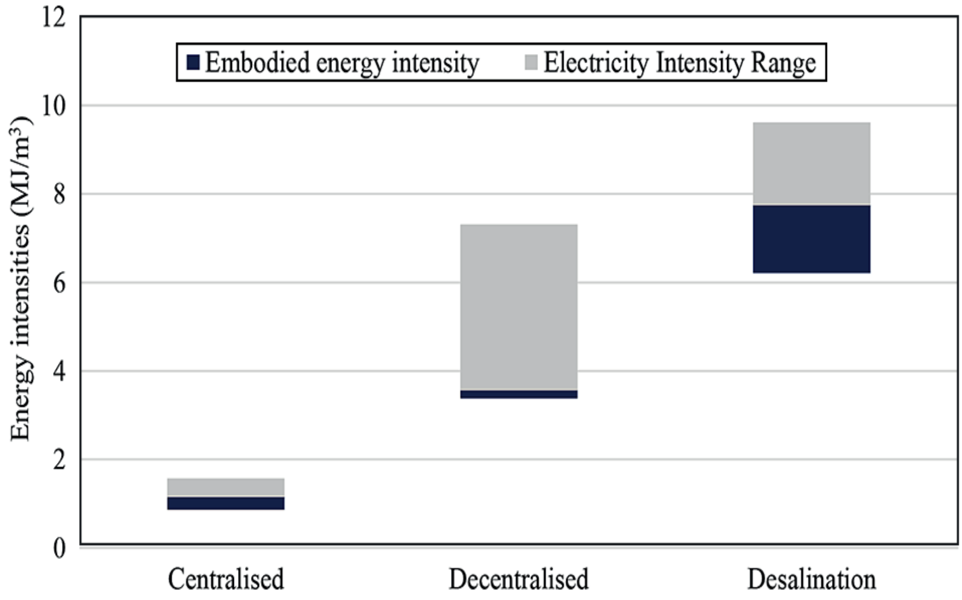

Figure 6
Comparison of the two types of energy intensities of the three approaches

resulting in the need for a higher osmotic pressure gradient across the membrane.

The proposed daily abstraction rate of 85 ML/day was assumed to offset an equivalent quantity of freshwater drawn from the existing dams. However, the implementation of alternative sources of supply such as those proposed here during winter months would increase the electricity usage, which peaks during this period of the year. The centralised approach would involve water infrastructure requiring an installed capacity of 1.3 to 2.8 MW while the decentralised and desalination approaches would require infrastructure with an energy requirement ranging from 2.7 to 2.9 MW and 5.8 to 6.3 MW, respectively. The existing Western Cape Water Supply System electrical installed capacity is 47.6 MW and the implementation of the centralised approach would result in an increase of 2.7 to 5.9% while the decentralised and desalination approaches would cause increases of 5.7 to 6.1% and 12.3 to 13.2%, respectively.

The electrical energy required to operate the three approaches, however, does not account for the entire energy footprints of these alternatives. To this, must be added the embodied energy of the chemicals used during treatment stage of the approaches, which was quantified in MJ/m^3 of treated water and the two components were compared in Fig. 6.

The total embodied energy intensity of the centralised approach ranged between 22% to 34% higher than that of the decentralised approach due to larger quantities of chemicals required to produce potable water. The use of lime, to remove hardness from the raw water, contributes the most to the total embodied energy intensity of the chemicals used in the centralised approach. The high total energy intensity of the desalination approach is mainly due to its electricity demand. However, its comparatively high embodied energy from the chemical usage also makes a significant contribution. Considerable chemical use (such as lime, carbon dioxide and fluoride) is required in the post-treatment to achieve potable water quality levels.

The different treatment trains used in the three alternatives have significantly different energy requirements. Desalination was the most energy intensive of the three approaches investigated. It is highly dependent on electricity for purification of the feedwater. The electricity demands of the centralised approach are the least due to the use of chemical processes for the removal of contaminants (during coagulation and sedimentation steps). The share of electricity (0.08 MJ/m^3) of the centralised approach at its treatment stage was found to be 22% of its total energy intensity while its embodied energy intensity amounted to 0.21 MJ/m^3 (78%); the embodied energy component shares of the decentralised and desalination approaches were 7% and 18% of their total energy intensities, respectively. The decentralised approach has the largest conveyance component compared with the other two alternatives owing to the extensive pressure pipeline system required to link the proposed well-points to the proposed decentralised water treatment plants.

Water production costs and carbon footprint of the approaches

The costs of pumping and treating the feedwater, and the carbon footprint of the treated water from the three approaches, were calculated using both the current and future electricity generation mixes and their respective costs, as well as the prices of chemicals used during the operational phase.

Table 4 indicates the range of expected (2017 rates) chemical (embodied energy during the operational phase) and electricity costs of producing water through the three options.

TABLE 4
Individual component costs (2017 R/m^3) of the alternatives

Approaches	Electricity costs		Chemicals costs	Total	
	Min	Max		Min	Max
Centralised	0.38	0.55	0.37	0.75	0.92
Decentralised	1.40	2.74	0.28	1.68	3.01
Desalination	2.47	3.40	0.55	3.03	3.96

The desalination approach was found to have the highest costs of water production due to the high requirement for chemicals and electricity. The electrical component of the operating costs of the desalination treatment process make up nearly 51% of the total operating costs and falls within the range of the reported values (Swartz et al., 2013).

The global warming potential of the treated water was calculated using GHG emissions (quantified as $kgCO_2eq/m^3$) from the use of electricity and chemicals and it includes carbon dioxide, methane and nitrous oxides as shown in Fig. 7.

The centralised approach employs a higher concentration of chemicals (0.09 kg/m^3) during the treatment process while the desalination approach (0.079 $kg/m^3$of chemicals) emits 40 gCO_2eq per unit of treated water more than the former. A higher usage of lime in the desalination option to stabilise the treated water results in emissions of approximately 74 gCO_2eq/m^3, representing the highest footprint of the chemicals used in all three alternatives. The results also show that emissions from the electricity sector outweigh the associated emissions from the production of the chemicals.

The electricity component is the largest of the carbon footprints in all three approaches since the electricity component's emissions are mainly produced by coal-powered stations. The higher electricity consumption of the desalination approach consequently results in a higher carbon footprint of the treated water. The abstraction stage's electricity demands were similar across the three options while their conveyance stage's electricity intensities affected their respective total electricity intensities.

The distance and the networks between the source and the water treatment plants influence the power required to convey water and therefore greatly impact on the resulting carbon footprint of the centralised and decentralised approaches. The carbon intensity of the conveyance stage of the desalination approach is smaller than the other two, owing to the proximity of the abstraction points to the proposed desalination plant. A similar result was obtained in a study conducted in the United States, where seawater desalination was found to be the better option when compared to conventional treatment methods, due to the long conveyance distances of the latter (Shrestha et al., 2011). Despite the high total energy and carbon intensities of the desalination approach, the energy required to convey of water over long distances for conventional treatment could make desalination a viable alternative in certain circumstances where the desalination plant is located in close proximity to its source and end-users.

The Peak Plateau Decline emissions trajectory, that South Africa has committed itself to, requires a significant cut in emissions from the energy sector and more particularly from its electricity generation plants. The two possible electricity mixes used for the study, the IRP (2016) and CSIR (2016), have lower shares of fossil fuel–based generation plants than the current electricity mix. The CSIR (2016) scenario proposes a more significant emission cut than the IRP (2016) over the next 25 years at lower electricity generation costs. Table 5 shows the reduction in emission intensities of the treated water with the two future electricity mixes.

With greater uptake of renewable energy sources for electricity generation in the future, the embodied energy component of the options would contribute more towards the total GHG emissions than the electricity demand components. The emissions of all three options decrease with both alternatives by 47% and 79% using the IRP (2016) and CSIR (2016) electricity mixes, respectively, by 2040. The embodied emissions' share in the centralised option would increase to nearly 30% in 2040 as compared to 8% in 2017; the embodied energy emission shares of the decentralised and desalination options also increase to 5% and 14%, respectively, as the electricity mix changes. The IRP (2016) scenario has a higher share of fossil fuel sources in its mix, which results in higher predicted carbon emissions than the CSIR (2016) scenario.

The CSIR (2016) results in lower electricity prices as the costs of renewable energy technologies such as PV and wind turbines have been decreasing over the past few years and

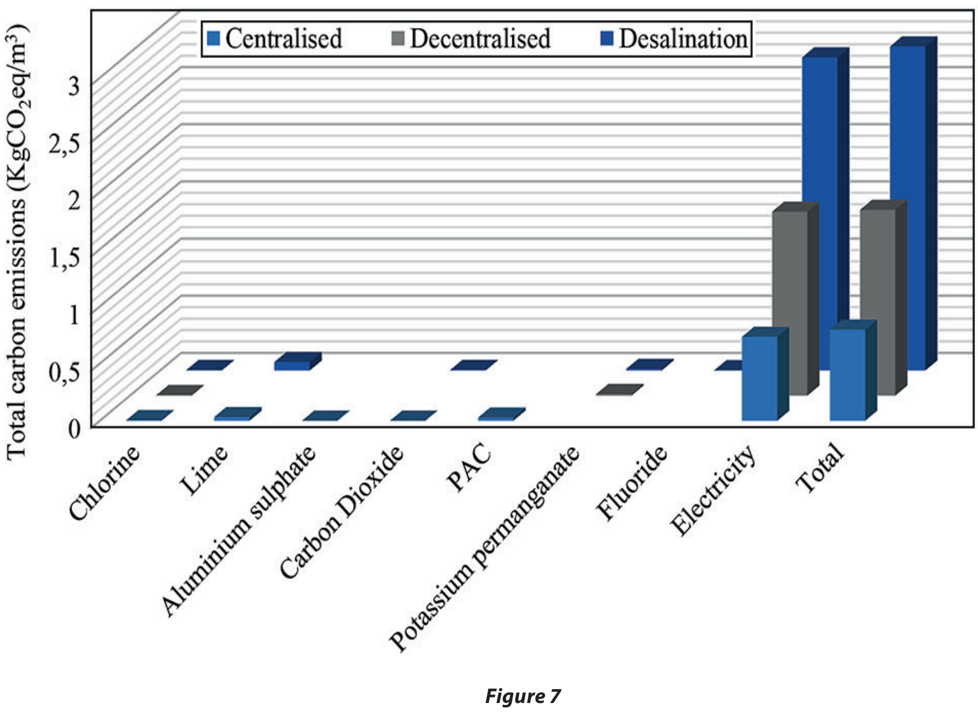

Figure 7
Total emission intensities of the water supply alternatives (2017)

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TABLE 5 Comparison of the implications of the alternatives				
Element		**Approaches**		
		Centralised	**Decentralised**	**Desalination**
Energy intensities (MJ/m^3)	Min	1.15	3.57	7.75
	Max	1.57	7.31	9.62
Production costs using 2017 electricity generation costs (R/m^3)	Min	0.20	0.38	0.78
	Max	0.28	0.63	1.08
Production costs using 2040 electricity generation costs (R/m^3)	Min	0.35	0.67	1.37
	Max	0.62	1.36	2.31
2017 Carbon footprint (kgCO_2eq/m^3)		0.80	1.62	2.83
2040 Carbon footprint (kgCO_2eq/m^3)	CSIR (2016)	0.15	0.34	0.58
	IRP (2016)	0.39	0.85	1.45

have become more cost-effective compared to conventional energy technologies. The production costs of the three options subsequently decrease as the penetration rates increase in the future energy mix scenarios. The CSIR (2016) future production costs are represented by the minimum 2040 production costs while the IRP (2016) future production costs are represented by the upper end due to its comparatively smaller share of RE.

The centralised approach has the lowest energy intensity (1.07 to 1.57 MJ/m^3) of the three which results in the lowest possible production costs and the lowest carbon footprint of them all, making it the most viable alternative from financial, energy and environmental perspectives. The carbon footprints of the approaches are dependent on their electricity intensities and thus the desalination approach, with its high energy requirement, results in the most polluting form of water production. Larger uptakes of renewable energy technologies in the electricity mixes could alleviate this, but are currently unlikely to decrease carbon emissions from the desalination approach below those of the decentralised and centralised approaches.

CONCLUSIONS AND RECOMMENDATIONS

The importance of the water–energy nexus is being realised as a result of the crises experienced in recent years, both in South Africa and globally, as countries strive towards sustainable development across sectors. The water sector is evolving as alternative water sources such as seawater and wastewater are being increasingly added to water mixes to supplement scarce freshwater resources. However, the treatment mechanisms required for these alternative sources differ from conventional water treatment chains and the effects of implementing such measures have yet to be considered. In the South African context, the energy sector is heavily reliant on fossil fuel sources for electricity despite the introduction of renewable energy technologies such as PV and wind over the past few years. In light of the commitment of the country to decrease its GHG emissions, it is important that choices made in the water sector account for their impacts on the energy sector as well as the potential emissions possible from the uptake of these investigated approaches. This paper has contributed quantitatively to the links between the alternative water treatment mechanisms and the energy sector, in the form of the potential increases in electricity loads from the three approaches investigated, and their possible current and future contribution to the country's emissions.

In this case study, the desalination approach appears to be an expensive, energy and carbon intensive option. It can considerably increase the supply of freshwater but this will come at the cost of a high energy demand generated. The centralised approach has the lowest energy and carbon intensities and has the potential to produce water at the lowest cost as it makes use of existing facilities. However, potable water produced from both the proposed desalination and centralised treatment plants would still be supplied for non-potable uses and would be unnecessarily treated to potable levels. The decentralised approach uses a different perspective by proposing that the water would only be rendered safe and distributed for non-potable use in a dual reticulation system. However, the decentralised approach has higher costs and carbon footprints than the more conventional centralised approach due to its higher electricity demand. The design of the options' networks and their spatial layout influences their energy consumption and solutions thus have to be adapted and optimised for each specific area. Their resulting treated water production costs and carbon footprints depend essentially on the electricity mixes of the country.

The paper quantified, both environmentally and economically, the potential implications of implementing three different approaches to exploit the CFA and accentuates the importance of the water–energy nexus in South Africa.

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