

REVIEW

The water industry and the decarbonisation of cities: A comprehensive review in the context of Cop26

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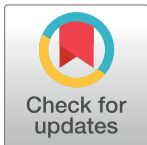
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Abstract

The urban water industry is a very energy intensive industry. Higher water quality standards are driving a level of energy growth that is threatening to move it to the top rank. Climate change is further exacerbating this situation: Growing aridity is variously imposing an enhanced carbon burden through water recycling, trans-regional pipelines and desalination plants. Natural disasters too can often affect water quality, requiring energy hungry mitigations. There's clear evidence that a failure to appropriately weight energy considerations in water infrastructure is commonplace and that this is an unsustainable position for the industry and is prejudicial to working towards zero carbon cities targeting net zero by 2030. Real time tracking of CO₂e emissions is an important starting point in raising operator consciousness and introducing rivalry between utilities in attaining abatement. So too is reaching out to the resource and manufacturing sectors to form strategic alliances, as well as seeking to enter into closer relationships with the energy sector.



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1 Introduction

The aim of this review article is to identify the material, technological and behavioural possibilities for substantially lessening the water industry's CO₂e footprint and to bring it into line with mitigation in buildings, transportation and the fixed energy sectors having regard to the catastrophic effects of global heating most recently highlighted by Cop26. Achieving net zero in its wake will require overcoming traditional orthodoxies and ways of working and this is no less true for a traditionally risk adverse industry.

It embodies a close knit energy/emissions accounting across the whole of the water-in-use cycle, viz. collection → treatment → conveyance → use → treatment → disposal/reclamation.

The high water quality standards demanded by regulatory authorities and the public alike in Australia, North America, Europe, Britain, *etc.* coupled with the fact that the industry in these places is under increasing scrutiny as to how it uses water, have intensified its energy usage. American data for example, reveal a 39 per cent increase for drinking water supply and treatment and a massive 74 per cent increase in wastewater treatment over the period 1996–2013 [1]. Moreover, desalination plants and long-distance piping of supplies, as climate change adaptation responses, have the potential to further add to the impost.

Radcliffe [2] has noted that

There are many variables which influence water/energy (“nexus”) relationships including natural resources availability and governance, the potential for climate change, increased urbanisation, the preferred built urban form, and domestic and industrial demands.

The experience, practices, methods and technologies residing in these locations, principally Australia, provide a sound basis for the framing of prescriptive measures. Further, as issues of drought, water contamination, safe disposal or reclamation know no borders, especially in the face of climate change, they have global relevance. Achieving net zero in the wake of Cop26 will require overcoming traditional orthodoxies and ways of working, which is of equal importance within a traditionally risk adverse industry.

Finally, our review recognises that developments are in a state of flux, both within the seven stages of the public water-in-use cycle and further afield. In order to capture the full story, we have drawn upon a combination of direct practitioner sourcing. This includes research papers from within each of the seven stages over the last 10–15 years, the broader research and commentary on city sustainability, as well as the grey literature that can capture the mainstream developments and thinking before it enters the literature base. Our Australian focus in part derives from its Western perspective, with special attention to the UK and the USA, given their similar water industry processes.

2 Article logic

This broad ranging review proceeds along the following lines and should be read cognisant of such disaggregation:

- Surveys the literature on decarbonising cities including the water supply and treatment context—see §3.
- Asks what global heating could have in store for the water industry—see §4.
- Examines the energy burdens associated with key elements in the water cycle—see §5
- Identifies energy “hot spots” in this cycle and sets them aside for closer attention—see §6.
- Unpacks contemporary initiatives undertaken by water authorities to deal with the incidence of drought; redress energy black holes in their operating systems; or simply lessen operating costs—see §7.
- Identifies initiatives that will or could affect energy budgets in significant ways, such as pressure sewers are also set aside for scrutiny. The resultant fine grain understanding then allows a pinpointing of pathways to lessen emissions—see §8.
- Makes conclusions about the prospects for the industry acquiring zero carbon status—see §9,
- Finally, discusses options for technology transfer to newly industrialised and middle band countries are examined—see §10,

3 Decarbonising the urban form

An extensive body of material has been and continues to be generated concerned with zero carbon &/or low carbon human settlements and pathways to them [3–7].

Such decarbonisation strategies are pitched to transitioning societies off coal and oil by substituting renewables. Most take a continuance of economic and population growth as a

given, but some recognise that this is leading to an exceedance of the planet's carrying capacity [8–11].

The focus of these strategies has variously been on transport (rail, cycling, walkable cities, etc.), buildings (LEED/Green Star), fixed energy sources (windmills, solar, wave and tidal power, etc.) and occasionally, industry. Whilst the first two are clearly important insofar as future designs for 21st C cities are concerned, water supply and sewerage for the main part, continue to be passed over. However, they are down every street and under every roadway, and it's thus important that these critical infrastructures be brought into mainstream thinking about the decarbonisation of settlements. City form such as the presence or absence of fall in land contours, affects the amount of energy needed for drinking water distribution, as well as wastewater collection. Further, zero or neutral carbon strategies pursued by local or regional governments more often than not overlook the role of water.

Despite this the water industry, alias the urban water sector, has been thrust into the forefront of climate change: The reliability and quality of its principal resource, bulk water, has been challenged by an increasing incidence of drought as well as disruption to supplies by extreme weather events. Thus, an unusually high rainfall event in July 2007 rendered most of Melbourne's catchment water storage unusable (due to high turbidity) for a period of months causing flow balance storages to be drastically drawn down and some fringe suburbs to be placed on a boil water alert.

At the same time, the industry faces increased energy demand on account of higher water quality standards; rising people numbers; and in more arid parts of the world such as Australia and Western United States, an existing or evolving requirement to transfer water between water basins and resort to drinking water-making from the sea with Reverse Osmosis (RO) desalination plants. Indeed, the change from traditional gravity-fed potable water supply via mountain dams towards energy ravenous processes has increased reliance on the conventional power sector.

One U.S. estimate has water-related energy use at least 521 million MWh a year amounting to a carbon footprint of at least 290 million tonnes a year [12]. Other estimates place the water and wastewater share of the American municipal energy bill at 40 to 60 per cent [13]. Similarly, in Japan approximately 7.9 billion kWh of electricity is needed each year to transport water from source, purify it, and supply it to people's homes. Likewise, to collect wastewater, process it, and release the discharge consumes a further 7.1 billion kWh each year. Together, water supply and treatment in Japan consumes 15 billion kWh each year, equivalent to the total energy generated by 1.5 nuclear reactors [14].

As noted above, conventional thinking on transitioning to carbon neutrality has focussed on transport, buildings and the primary energy sector. It has assumed that water supply and disposal &/or reclamation constitute such a small proportion of overall energy usage that the industry's role in the scheme of things is somewhat marginal [15]. And, what energy burden does exist is largely attributed to domestic hot water heating [16,17]. But, looking at the water industry's energy burden in this light is contextually problematic and analogous to adding the domestic cooking of food to the greenhouse footprint of the meat or poultry industry.

A review of the energy ↔ water nexus by the Congressional Research Office [18] has further concluded that this reasoning is deficient in other respects:

- It relies on secondary source data.
- It does not include future projections of electricity requirements for water supplies in the thermoelectric sector (because it assumed that energy for water use in this sector would decline).

- It does not consider on-site heating, cooling, pumping, and softening of water for end-use.
- It does not consider that in the future a large proportion of new water demands will be met by sources with greater energy intensities, such as groundwater pumped from greater depths and seawater desalination.

The respective benefits of energy saving and water conservation are well established. Less understood when holistic evaluative frameworks aren't applied and exploited are the prospective savings in water during the course of pursuing savings in energy and vice-versa. Dr. Penny Sackett, (then) Australia's chief scientist, in referring to the report of her office, [19] expressed doubts as to whether energy, water and carbon budgets are being dealt with holistically, adding that treating one independently could harm the others. If poorly handled that interdependency runs the danger that apart from being a 'victim' of climate disruption the industry also becomes a contributor.

4 The impact of climate change on water security

Global heating is expected to have both incremental and abrupt effects on the industry. The scale of these changes is best summarised by a few paragraphs drawn from the fifth IPCC report [IPCC, 20]:

Climate change is projected to reduce raw water quality and pose risks to drinking water quality, due to interacting factors: increased temperature; increased sediment, nutrient, and pollutant loadings from heavy rainfall; reduced dilution of pollutants during droughts; and disruption of treatment facilities during floods.” “Each degree of warming is projected to decrease renewable water resources by at least 20 per cent for an additional 7 per cent of the global population.

Drought lies in the incremental category (although it is capable of inducing catastrophic wildfires per the below) and is emerging as a critical problem for the industry especially in Australia and Western United States [21] It has in turn prompted energy intensive desalination hedges on the eastern seaboard of Australia, which periodically comes under the influence of *El Niño* events and where aridity is growing over the long run as a result of anthropocentric climate change.

Ribes and co-workers [22] have noted that,

In the mid-latitudes, the emerging picture of enhanced evapotranspiration confirms the end of the dimming decades (from sulphates) and highlights the possible threat posed by increasing drought frequency to managing water resources and achieving food security in a changing climate.

Global megatrend research is further suggesting that by 2030 there could be a 40 per cent shortfall between water supply and water demand [23] with other challenges [24].

Climate change is also believed to affect water quality in promoting nuisance and toxic algae species requiring supplementary treatment, whilst floods and wildfire, pose short term but no less critical threats [1]. With floods toxic chemicals can be released into soils and waterways from immersed surfaces. Moreover, industrial containers can be punctured, sewerage lines broken, and latrines smashed. Unpicking the pollutants from this witch's brew becomes near impossible.

Coastal storm surges are yet another headache. Apart from the physical damage to infrastructure, storm surges can leave surface and ground water adulterated by seawater. Stripping surfaces

of salt, alone, requires [reverse osmosis treatment](#) at considerable carbon and financial cost, which doesn't go ahead in most cases because the sheer scale of the remediation effort is prohibitive [25].

At the height of the Millennium Drought that afflicted eastern Australia for well over a decade, viz. 1996–2010 [26], household water saving and to a lesser extent, water restrictions, lowered sewer volumes (flows were, for example, down by up to 40% from pre-drought figures in Brisbane, Queensland) raising salt concentrations, and thereby placing an extra load on water reclamation facilities. Non domestic salinity in sewers stems from industrial processes including tanneries, food, and dishwasher detergents, as well as seawater infiltration into sewerage plants. Lowered volumes in sewers also concentrated wastewater contaminants, which then required additional energy during processing, thus leading to higher carbon emissions.

The pernicious sequence of drought → heatwave → drought [27] experienced in North America in 2012–2013 and 2020, and Australia in 2009 and 2019–2020 posed yet another threat to water security, notably, wildfire.

Fire in reservoir catchments can lead to a significant contamination drinking water, should heavy rainfall follow. Over the past decade, post-fire debris flows have been identified as a key erosion process resulting in extreme water quality impacts in the western US [28].

The Canberra, Australia, fires of January 2003 burnt more than 47,500 ha or 98% of the Cotter catchment, destroying ground cover and large areas of riparian vegetation and, in the process, greatly increasing the potential for of hill slope and stream bank erosion [29]. Huge quantities of charred organic matter also resulted. Unfortunately, highly-localised and intense rainfall occurred in early February and March 2003, transporting fire debris and sediment from denuded slopes into the Bendora Dam, the integrator storage for Canberra's reticulation system. These inflows vastly increased turbidity, thereby making the water unfit for human consumption for many months after the fire. An A\$40 million Membrane Bioreactor treatment plant was built to return water quality to pre-existing levels—equating to the eco-services value of the pristine catchment [30].

Further south, the Black Saturday wildfire contagion of February 2009 killed 173 people, and burnt out 30% of Melbourne's water catchments during a period when water consumption had trebled. Wised by the earlier Canberra event, local water authorities acted to protect the metropolis' drinking water supplies by sending water from dams in fire-affected catchments to those that were not affected [31]. Similar to the Canberra circumstance, the aim was to save as much clean water as possible by relocation before a storm event rendered the fire-affected dam water too turbid from ash and other run-off pollutants.

If not already, the industry is steadily entering a first responder world—one laden with incidents, rampaging uncertainty and emergency warnings—experienced firsthand during the recent extremely hot Eastern Australian fires. Many have to do with contamination in one form or another and the ability to check its entry points into the water supply at source. A sector potentially grappling with a *big dry* will have its work cut out coping with powerful storms, including flooding sewers and the commensurate overloading of wastewater treatment plants. And, of course, brimming sewers also offer to return the compliment by discharging their pernicious contents into waterways and the sea.

In this context a *tool* has been developed by Sydney Water to identify what infrastructure is likely to be at risk from floods, bushfires, high winds and heatwaves, and assess different costed adaptation options to manage that risk [32].

5 Utility energy usage overview

Energy consumption generally comprises 10–12 per cent of the cost of providing water and wastewater services to the public in Australia, [Fig 1](#). The equivalent American figure is higher at 25 per cent [33].

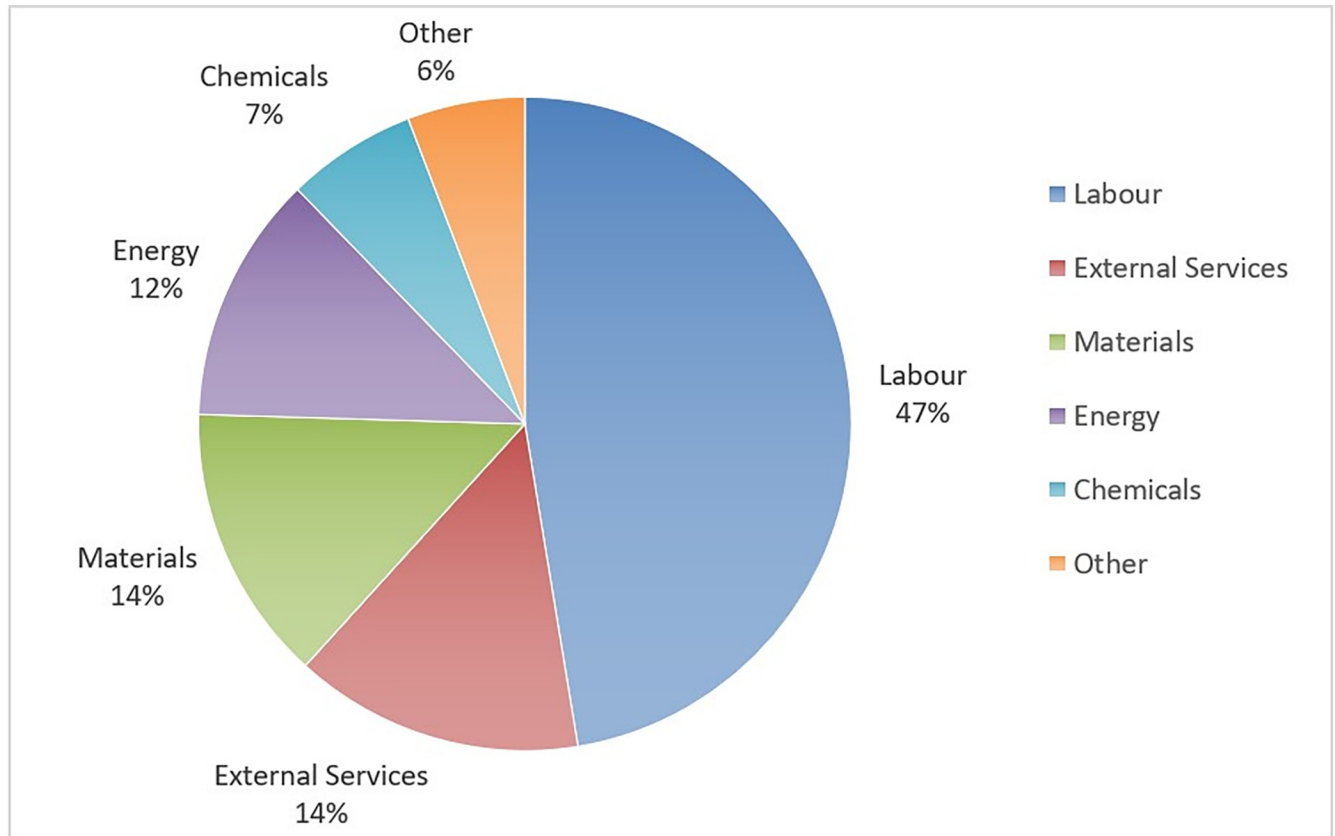


Fig 1. Typical budgetary outlays for a water utility. Source: Internal document, Gold Coast Water.

<https://doi.org/10.1371/journal.pwat.0000023.g001>

Energy is the largest controllable item outside of employment. It's on the par with 'materials' and 'external services'—although if chemicals are added the figure is even larger due to embedded energy involved in (for example) chlorine production.

This energy consumption is primarily in the form of electricity as reflected in CO₂e emission terms in Fig 2. Its seat is represented by the mechanical work performed by pumps [34] acting on water and air with a further component comprising disinfection technologies especially ultraviolet and ozone.

Electrical power is consumed over seven stages, Fig 3.

It is needed to:

- Pump water from rivers, aquifers or run desalination plants or water-recycling and convey it to storages to be distributed. Pumping is often needed on account of intervening hills and this tends to be a very energy intensive task.
- Treat water to a potable standard which usually takes place in situ. This may be minimal where dam catchments are enclosed (although global warming may change this situation) rising to significant when water is taken from groundwater, rivers and lakes which have pollutants from surface water or upstream discharges. Here it not only involves pumping but other energy intensive processes for purification. This is especially the case with later developments involving desalination and recycling.
- Distribute water by local pumping and pressurisation when reservoirs aren't sufficiently elevated above customers.

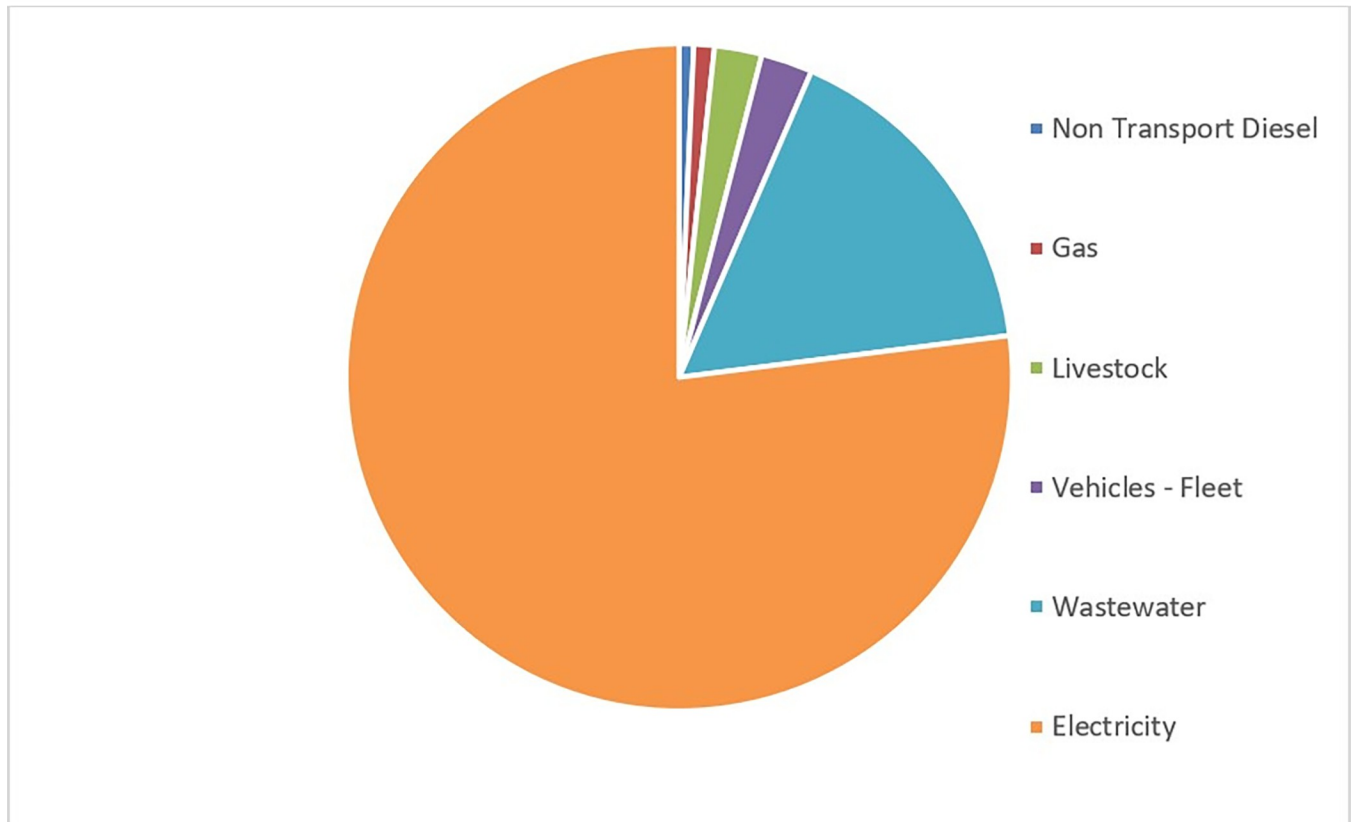


Fig 2. Emissions according to origin. Source: Internal document South East Water.

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- Heat water at the consumer end and (privately) elevate it to provide further “head” in high rise tower buildings as need be.
- Convey sewage to sewerage plants alias Waste Water Treatment Plants (WWTPs) when pressure sewers are being used or settlement is flat preventing gravity flow.
- Treat wastewater involving pumping, aeration, and other processes found in sewerage plants. Additional energy requirements will exist if the water is to be recycled esp. to water standards for fresh produce horticulture.
- Discharge treated effluent to receiving waters. The delivery of irrigation water is not often by gravity as sewerage plants tend to be located in low spots and almost every irrigation location will be on higher ground.

Data drawn from an Australian water retailer, South East Water, reveal that as much as 60 per cent of emissions are directly related to supply and End-of-Life treatment, Fig 4. These figures are however likely to be conservative as they do not include embedded energy in the water supply chain.

6 Pinpointing energy hotspots

6.1 Water delivery

It may be necessary to convey water over considerable distances and challenging terrain; pump it from rivers; and through a distribution network—all utilities do the latter every day.

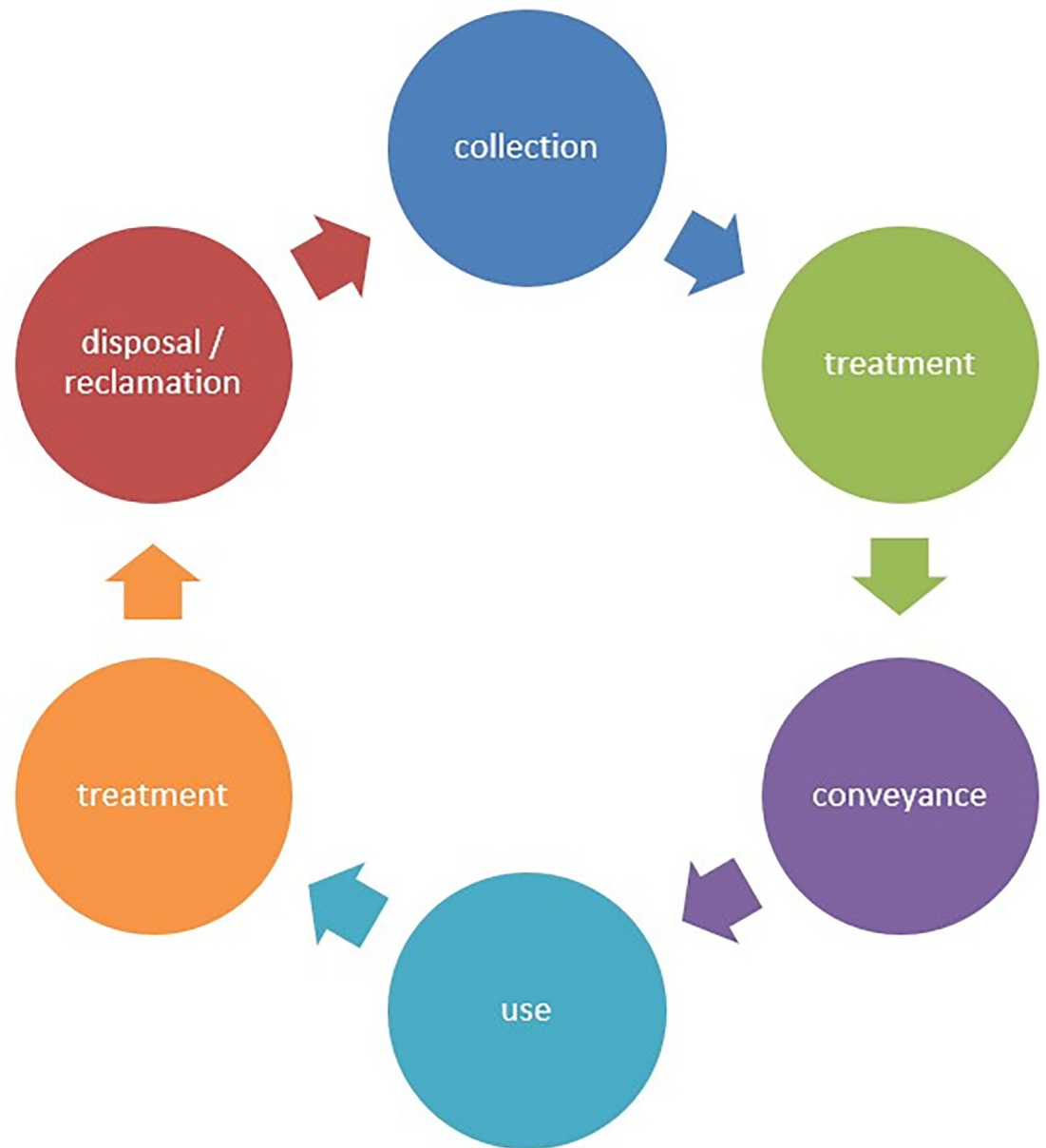


Fig 3. 'Straight through' water-in-use cycle for public supply.

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Melbourne's water network, Fig 5, has all three aspects; viz. A North-South Pipeline (now mothballed) from the Goulburn River over the Great Dividing Range as a response to the Millennium Drought; various pump stations for drinking water distribution; and the raising of water 60 metres from the nearby Yarra River to the Sugarloaf Holding Reservoir, constituting a similar drought response measure.

In addition there is, as required, the pumping of desalinated water from Wonthaggi on the Victorian coastline over a distance of 150 kilometres to the Cardinia Reservoir situated 167 metres above sea level, also shown in Fig 5.

Further north, an extensive 'water grid' was built in South East Queensland /Brisbane in the late 2000s which involves, on as required basis, the sending of water and tertiary treated

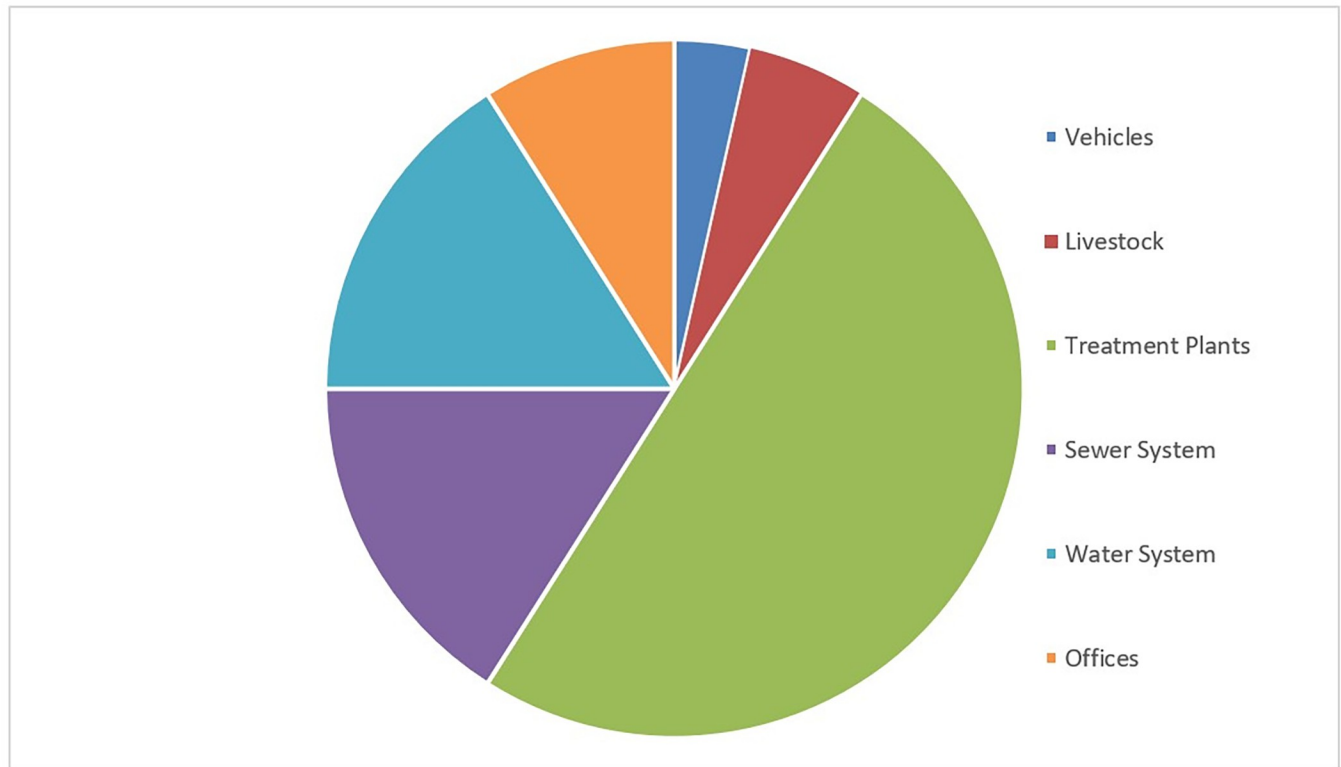


Fig 4. Characteristic water utility emissions. Source: Internal document South East Water.

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effluent throughout the region including to the Swanbank power station for cooling purposes, Fig 6.

Bulk water pipelines in, or feeding into, Australia's capital cities however are relatively short and don't involve any major elevation of water compared with those feeding Southern California, Table 1.

Central to bulk water conveyance is the role of the pump, which can be markedly improved by variable speed drives, low friction coatings and mechanical seals, premium efficiency motors, and electronic controls. Monitoring is a prerequisite as performance can deteriorate over time.

A national survey by the Water Services Association of Australia (WSAA) 'to develop a common energy benchmarking approach for water and sewage pump stations and collect a robust first data set' found that there was a considerable variance as to pump efficiency across utilities [34]. A number of pump stations were estimated to have an energy efficiency less than 10.9 kWh/ML/m (25 per cent) including many of the sewage pump stations, while a further number had efficiencies between 5.5 and 10.9 kWh/ML/m. Only in a few cases at this point was there any comprehensive real time monitoring of performance and energy usage. If the data for these pump stations is accurate, then they represent a potential for significant energy cost savings and carbon mitigation [34]

Interestingly, the proportion of energy used for the conveyance of water as opposed to that used for wastewater treatment (below) can vary widely depending upon the utility in question, e.g. some may be abstracting water from rivers; others from groundwater; and yet others from dams, as revealed by American data in Fig 7 [36]. Later American data show that this figure can be as much as 80 per cent of total electricity usage [1]. Interestingly, in many US cities, the

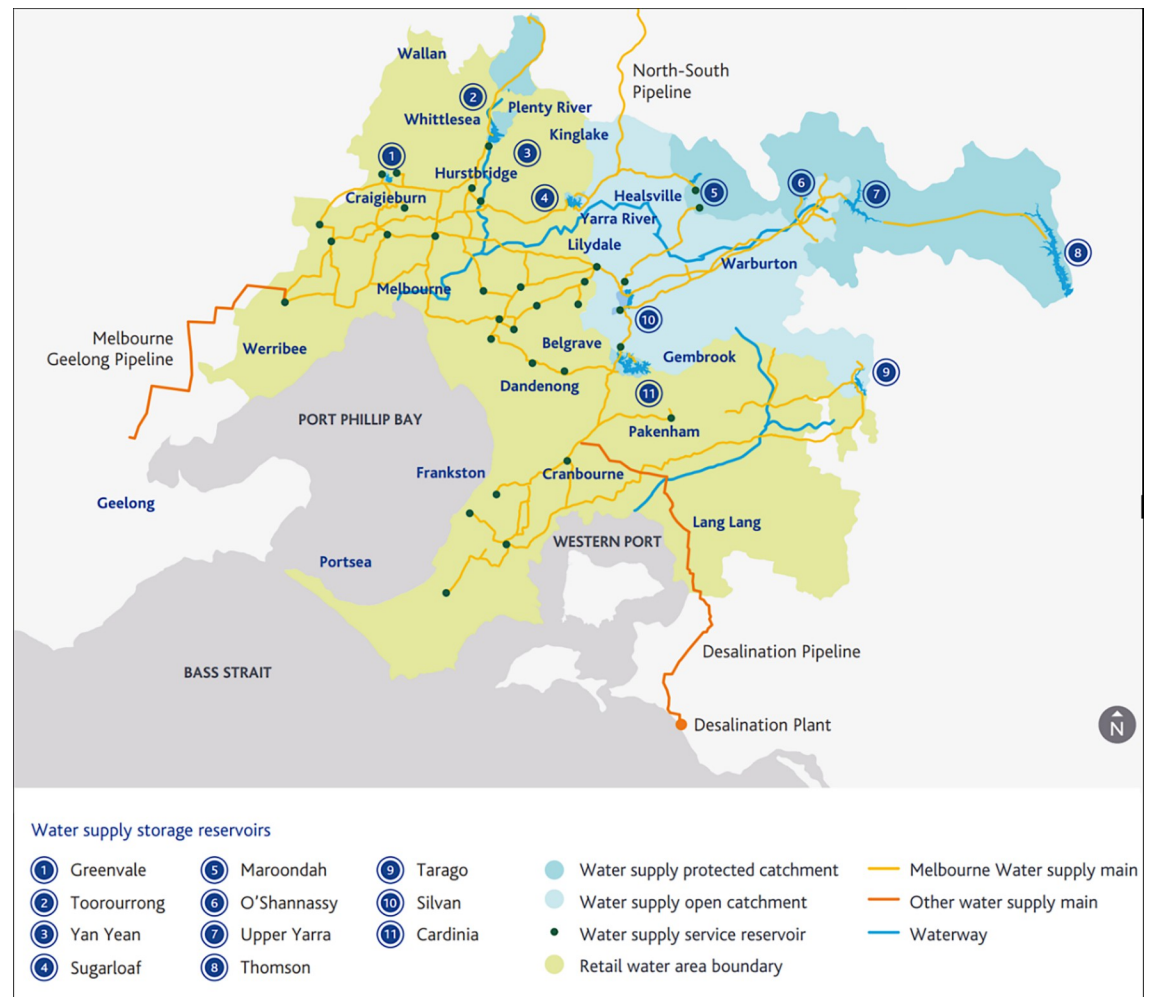


Fig 5. Melbourne's water distribution network. Source: Rohan Fisher.

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'sanitation district' may be a different utility from the water utility, though in most of Australia, both functions are run by a single utility, notable exceptions being Bunbury and Busselton in Western Australia.

6.2 Wastewater treatment

Another stage in the water-in-use cycle, Fig 3, warranting closer attention is the energy needed for wastewater treatment. It's a stage averaging two thirds of utility operating costs according to Reekie [33] and where more exacting standards applied to discharge to the environment or reclamation, are beginning to bite. For instance, 'increased treatment under the UK's Water Framework Directive—an overarching piece of legislation to achieve 'good ecological status' in inland and coastal waters—was estimated to raise carbon emissions by more than 110,000 tonnes a year due to operational matters [37]. While this may be considered a small increase with respect to the industry's overall carbon footprint, it is significant with respect to the wastewater function.

No longer is it acceptable in our case study countries (viz, Australia, the UK and America) merely treat effluent to a secondary level, especially where drinking water abstraction from

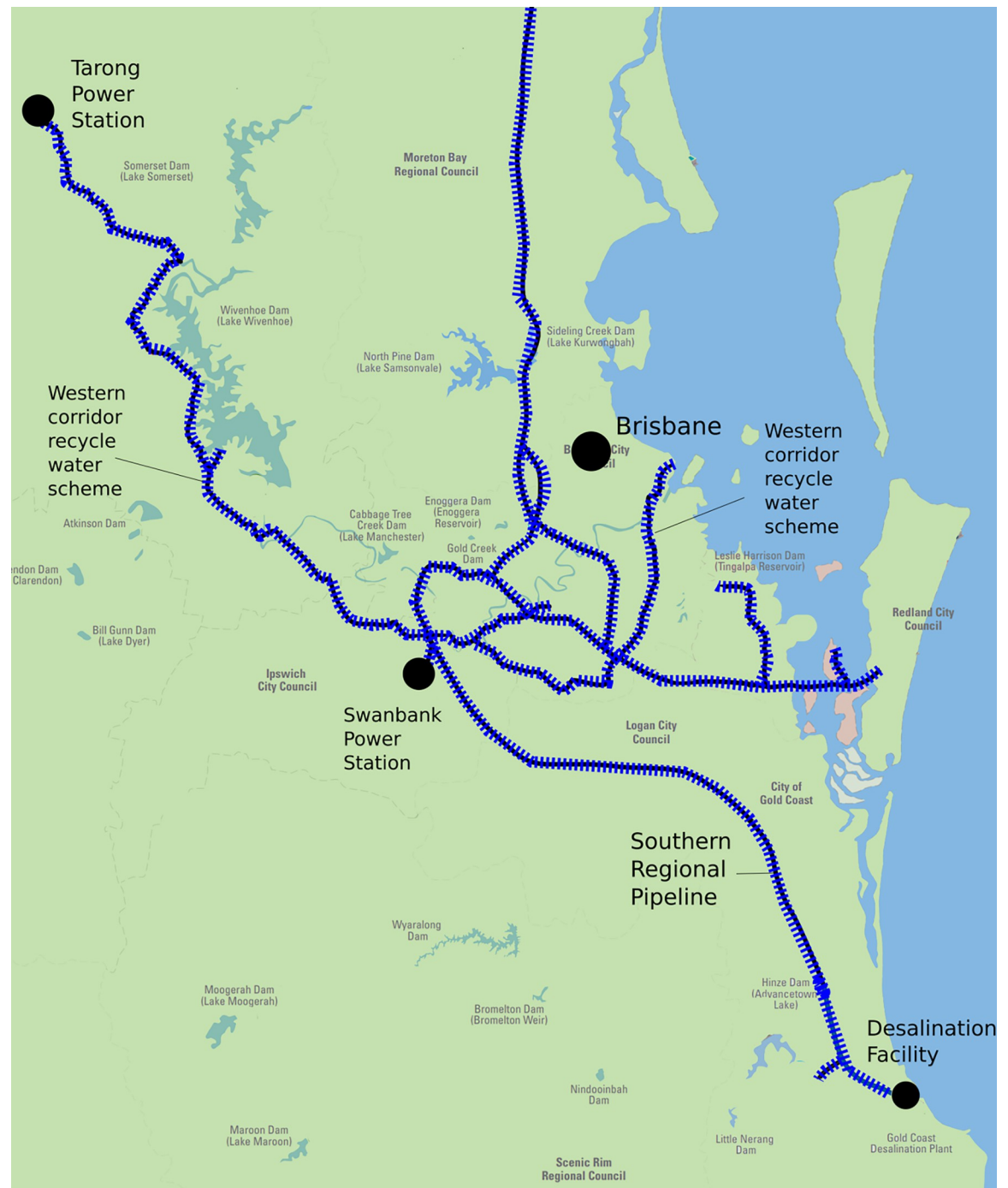


Fig 6. Transfer system for moving water and tertiary treated wastewater in South Queensland built as a response to the 1996–2010 drought. Source: Rohan Fisher.

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rivers occurs downstream (although discharge of low quality effluent to the ocean—deep water outfalls—in large cities like Sydney [38] and Los Angeles is still practiced).

A preminent reason for this high usage is aeration via air pumps consuming up to 60 per cent of total WWTP energy use according to Swiss research [39,40]. Significant efficiencies however have accrued by the recent adoption of turbo technologies.

Table 1. Long distance conveyance of bulk water to Southern California—includes pumping water up 1500 metres over the Tehachapi Mountains.

Source	Construction period	Conveyance distance
Colorado River Aqueduct	1930s	390 km
State Water Project	1960s	718 km

Source: California Department of Water Resources [35].

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American data presented in Fig 8 confirm that aeration is the main energy ‘black hole’ accounting for a significant portion of the 3 per cent of national GHG emissions attributed to the sector [41,42].

However, abatement of GHG emissions depends not only on electricity usage from fossil fuel sources but also on (any) harvesting of methane produced from the treatment process [44]. Prior to installation of methane capture at Melbourne Water’s Western Treatment Plant settlement ponds in 2004–05, its ‘feral CO₂e emissions’ were roughly equal to those from electricity usage.

6.3 Water-making: Desalination

This is the most energy intensive activity and deployed where rainfall is permanently low, e.g. the Middle East; or has become particularly unreliable in recent years e.g. Spain, Chile, Brazil, etc.; &/or is used as a hedge against severe drought e.g. Australia.

Three different technologies are in existence: Multi Stage Flash (MSF), Multi Effect Distillation (MED) and Reverse Osmosis (RO)—the last two being the most common. Table 2 shows the comparative energy burden for each method of water-making.

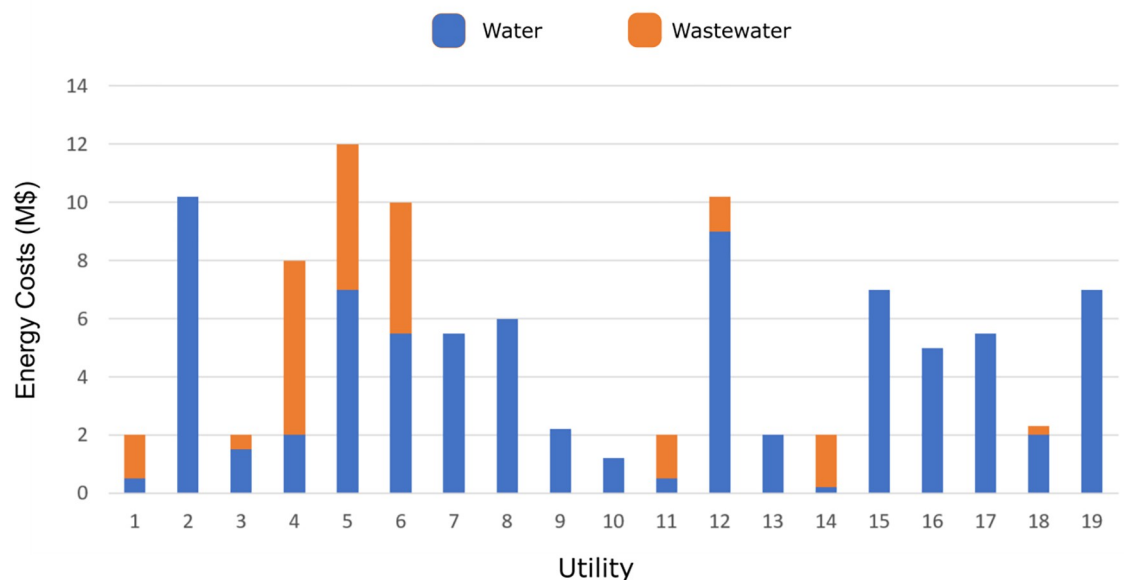


Fig 7. Best Practice Energy Costs (M\$) as a proxy for energy usage according to water (delivery) and wastewater treatment for 19 US utilities. Note that utilities 1, 3, 4, 5, 6, 11, 14, & 15 represent a combined cost of water supply and wastewater treatment. Source: <https://www.waterrf.org/research/projects/electricity-use-and-management-municipal-water-supply-and-wastewater-industries> Reekie, Pabi [1].

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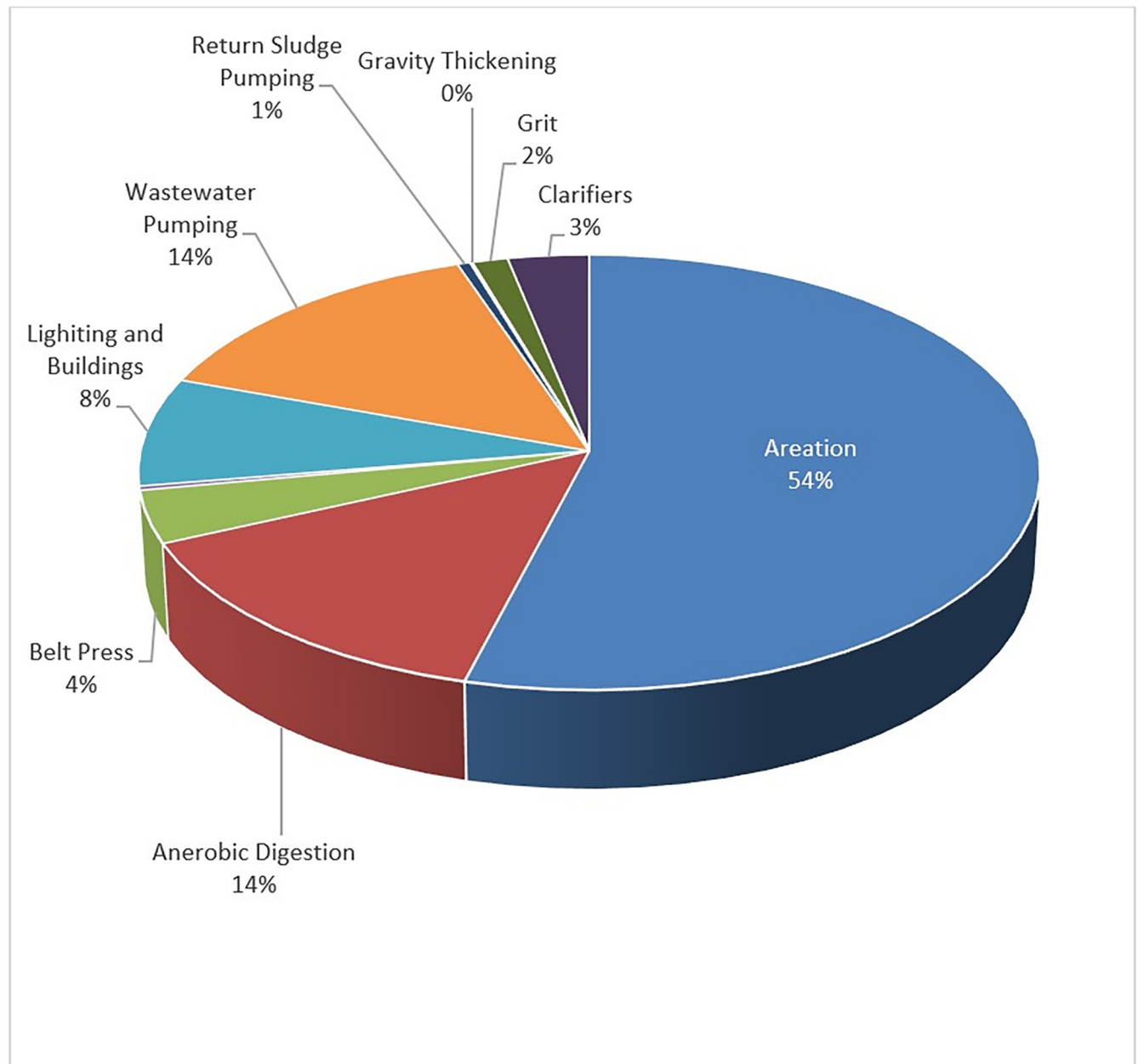


Fig 8. Electricity Requirements for Activated Sludge Wastewater. Source: Li, Curtis [43].

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Note that the overall costs are about the same for RO and some forms of distillation plants provided the latter are receiving low cost, quality waste heat (as is the case for cogeneration or co-processing). So, if distillation plants have a waste heat feed they are competitive with RO. In the case of waste heat from electricity generation it's assumed that the most efficient combined cycle plants are used. This is especially true when the heat comes from a high-efficiency combined cycle gas-fired power station. The coupling here is typically with a Multiple Effect Distillation plant. However, if this is not the case, then the overall cost of water from an RO plant is less than half of that produced by means of distillation. The energy cost for desalinating

Table 2. Total energy use of differing desalination methods.

Process	Gain Output Ratio (GOR)	Electrical Energy Consumption (kWh/kL)	Thermal Energy Consumption (kWh/kL)	Total Energy (kWh/kL)
MSF	8–12	3.25–3.75	9.75–6.75	13–10.5
MED	8–12	2.5–2.9	6.5–4.5	9–7.4
BWRO	N/A	1.0–2.5	N/A	1.0–2.5
SWRO	N/A	4.5–8.5	N/A	4.5–8.5

Source: Frontier Engineers. Key: GOR: Gain Output Ratio—the ratio of fresh water output (distillate) to steam; BWRO: brackish water reverse osmosis; SWRO: seawater reverse osmosis.

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seawater is about four times over that for brackish water for the same size RO plant. Distillation plants are suited to fairly large seawater desalination.

Meanwhile, it has been estimated that Australian water utilities could use four times as much electricity in their growing reliance on RO desalination, Table 3 [32].

For some time now it's been possible to integrate electricity generation and water-making into the one facility. The ploy as noted above is to use the waste heat from a high-efficiency combined cycle gas-fired power station to run an MED plant, which operates by progressively lowering the pressure at which water boils [45]. Earlier a similar arrangement in Adelaide might have led to a distillation plant added to the nearby gas-fired power station eliminating the need for the; Port Stanvac RO plant or at least improving its efficiency by linking the two water-making technologies, as exists with the ground breaking hybrid in Fujairah, Saudi Arabia [46,47].

A failure to take up (or at least examine) the efficiencies arising from the proximity of gas fired power stations to Australian desalination plants is a pointer to a lack of dialogue between water and power engineers. A contemporary caveat is that gas fired installations incur feral emissions and are not now viewed as compatible with a rapid transition to low carbon economies, as highlighted by Cop26.

7 Review of modern developments

Before identifying the specifics of enhanced zero carbon pathways it's important to take note of some of the current initiatives undertaken by water utilities to deal with the incidence of drought; redress cost/energy black holes in their operating systems; or simply lessen operating costs.

7.1 'Out-sectoring #1'—Introduction of pressure sewers

Pressure sewers represent a shift away from gravity based systems to convey effluent to Waste Water Treatment Plants (WWTPs). Under this system each household has a pump to

Table 3. Australian capital city RO desalination plants built in response to the 1997–2011 drought.

City	Location	Capacity (ML/annum)	Ability to increase capacity (ML/annum)
Sydney	Kurnell	90,000	Double capacity if needed
Melbourne	Wonthaggi	150,000	Up to 200,000
South East Queensland	Tugun	45,000	
Perth	Kwinana	45,000	
	Binninyup	50,000	Double capacity if needed
Adelaide	Port Stanvac	100,000	

Source: Water Services Association of Australia [32].

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discharge its sewage to a pressurised pipe network before which it gravitates to a tank where it's ground-up. The pipes are located in shallow trenches and are of fairly small diameter. Since the operation of the household unit can be remotely controlled by the utility, withholding of effluent can be effected smoothing the load reaching the plant and consequently lessening the energy burden at that end. Pressure sewers are especially suited to rocky, hilly or densely populated areas but are now finding wider application.

No detailed analysis appears to exist as to whether they use more energy over their conventional gravitational counterpart.

Arguments for pressure sewage systems using less energy are:

1. There is less infiltration, and therefore less water has to be pumped.
2. Water can be temporarily stored at the household, and with 'system smarts' this means there is less flow rate variation in the system. And since pipe friction loss is proportional to velocity squared, this will result in less pumping energy.
3. For a gravity system, in a catchment area, flow gravitates to a low point (which may well be in the reverse direction to where the treatment plant is located) and is then pumped towards the treatment plant.
4. A pressure sewer system can save energy back at the plant due to load smoothing.

Arguments for gravity sewage systems using less energy are:

1. A smaller number of large pumps compared to a huge number of small pumps is more energy efficient.
2. Gravity systems may have less wetted surface area.
3. The pressure sewer system although far more direct may not be a viable alternative in conveying water to a remote treatment plant because of intervening pipe friction (wet surfaces).
4. Can be a vehicle towards a greater degree of distributed treatment.

It's clear that this is complicated and could well be site specific.

Interestingly, the power cost of the pressure sewer is borne by the household effectively 'out-sectoring' this energy burden, an element reflected in the fact that Net Present Cost for pressure systems is less than for gravity systems. In the circumstances it would appear that the contemporary shift to the former is driven by cost.

Note that should a pressure system use more energy than an equivalent gravity system, but all other costs for it are significantly lower, the savings could be spent on other abatement measures.

The sheer complexity of the situation is the best argument for having a carbon price and for a utility to assess options based on Net Present Cost.

7.2 'Out-sectoring #2'—Industrial waste stream pre-treatment

Water may enter an industrial process by way of raw materials such as brines, acids and alkalis. But the most common entry points are to cleanse a product; assist in product formulation as a heat exchange agent or thermodynamic fluid; act as an ingredient or catalyst; act as a solvent; or provide heat by way of steam. Fabrics, glass, paper, beverages, pharmaceuticals, electronics, ceramics, polymers and many other products all require water in their manufacture. At a more general level, water is used to clean vessels or the overall plant and, as single processes, synergistic effects with energy are more than likely.

The practice of major industrial plants installing on-site wastewater treatment has become commonplace. Actual recovery of ‘industrial water’ facilitates operating efficiencies including energy savings [48,49] and serves to lessen mains water usage through trade waste charges imposed by water authorities on discharge to sewer. This leads to a reduction of the pollutant load reaching WWTPs with concomitant treatment/energy benefits for the utility. However, it’s unclear as to whether it lessens overall emissions since on-site treatments incorporating systems like Reverse Osmosis, Ultra Filtration, *etc.*, can be very energy intensive and unlikely to be totally fuelled by *in situ* renewables. In some cases the WWTP receives unwanted residuals like salt which are especially intractable.

Interestingly, the synergies commonly observed between energy and water savings in simple, single processes, can be scrambled when many processes are linked &/or interfaced. Further, processes offering the best energy-water savings combinations may not always do justice to other considerations relating to the embedded energy and resource drawdown in the manufacture of equipment/componentry or their end-of-life costs. Toxics are a further case in point, although they may not be viewed as important to industrialists as they are for regulators.

7.3 Exploitable resources

A treatment plant’s liquid and solid waste products can be regarded as exploitable ‘resources’ [1,50]) The corresponding responses fall into three main categories—water recycling, energy recovery and nutrient recovery, as shown in Fig 9 [41].

In Australia, there has been a marked emphasis on water recycling—a reflection of supply shortages arising from the Millennium Drought and a general decline in rainfall. Energy recovery via biogas through conventional anaerobic digestion and co-digestion also exists in a number of places such as Yarra Valley Water’s Aurora Estate in Melbourne [51].

The growing global popularity of water recycling has led to subtle changes to the ‘straight through’ scenario depicted in Fig 3. A revised representation is shown in Fig 10.

Improvements to the performance of wastewater treatment plants in particular have facilitated their recruitment for ‘purple pipe’/ ‘third pipe networks’ often on model residential estates for toilet flushing &/or garden irrigation which are commonly laid out along ‘water sensitive urban design’ lines. Golf courses and sports ovals, *etc.* may be recipients of their Class A effluent too. Contemporary residential developments may deploy *in situ* tertiary treatment systems like the Aurora Estate in Melbourne. In addition to such entities there’s fresh produce

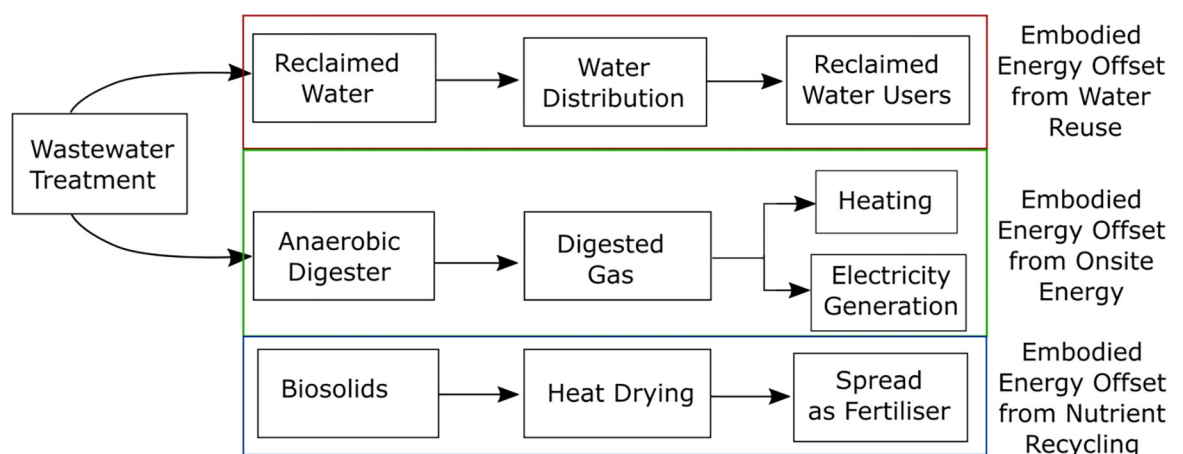


Fig 9. Resource recovery methods in the Howard F. Curren Advanced Wastewater Treatment Plant. Source: Mo and Zhang [41].

<https://doi.org/10.1371/journal.pwat.0000023.g009>

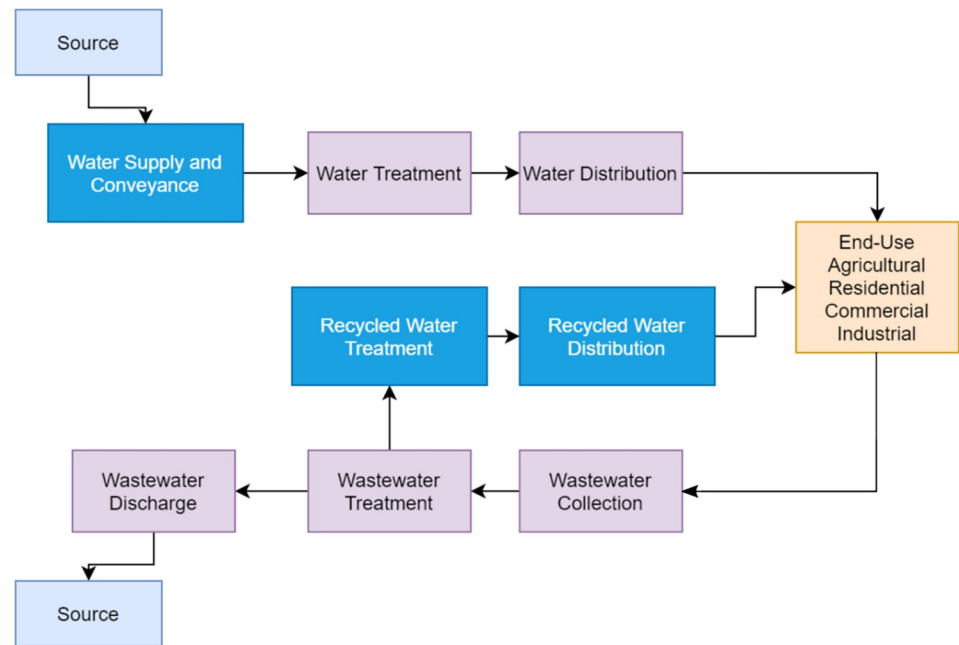


Fig 10. A contemporary water supply sequence allowing for water recycling. Source: The carbon footprint of water [12].

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growing farms using tertiary treated effluent such as at Virginia in South Australia [52]. Some of these projects could have issues in regard to the presence of PFAS [53–55]

7.3.1 Waste to energy/combined heat & power (CHP). There are a number of energy recovery technologies in existence notably, sludge to biogas; sludge-to- syn-gas; sludge-to-oil; and sludge-to-liquid. The simplest and one in most common usage is sludge-to-biogas where methane is used to run (spark ignition) engines to drive generators which can supplement mains supplies—although impurities like H₂S need to be scrubbed from the methane. Flow smoothing pumps here can result in more continuous biogas production due to fewer shutdowns.

However, the Australian experience is that the energy produced onsite through any of these means alone is not sufficient to supply all of the direct operational energy needs of the sewerage plant. Utilising biogas to run fuel cells offers greater efficiencies but has to be offset against a much higher CAPEX [56].

7.3.2 Nutrient recovery. ‘Nutrient recycling’ often takes the form of adding sewage sludge to farmland as is historically the case in the Central Highlands of New South Wales and the Darling Downs in Queensland. Recent refinements to this practice includes Barwon Water’s Renewable Organics Network program at Geelong, Victoria; using pelletised sludge as a source of inoculum for bio-hydrogen gas production; and the recovery of bio-pesticides from sludge [42].

It is unclear what the resulting energy balance is for these diversions but the growing body of research into the impacts of micro contaminants [54,57,58] would suggest that exacting standards need to apply if soils, waterways and food sources are to be fully protected.

But, there are in existence technologies for extracting just the phosphorous (thus avoiding the micro contaminants) although most use sulphuric acid which has life cycle and health issues [59,60].

7.3.3 Integrating waste streams. In contrast to Europe, notably Germany and Spain, where a significant degree of integration is in place between the waste streams of wastewater treatment plants and that of the general community, a degree of institutional separation persists in Australia. Organic wastes in the form of putrescibles (food scraps, etc.) *are* recovered through composting, basically privately at the household level if at all. Municipal Materials Recovery Facilities or MRFs predominantly handle hard waste in the form of paper, plastics, glass, batteries and Waste Electrical & Electronic Equipment or WEEE. Some early local experimentation included a joint venture between Sydney Water and the City of Randwick [61]; the development of specialised recovery technologies for ammonia by Degremont-South Australian Water Corporation; and a strategic integration initiative by the Victorian Government, etc. [62]. The issue of integrating waste streams with sewage sludge aka resource recovery, continues to be explored by Australian utilities as discussed in Holmgren [9] hopefully cognisant of not introducing toxins to food webs and biota.

7.4 Renewables

The use of renewables to offset the heavy power demands of the industry offers much promise. In Australia solar arrays have historically been largely absent from water utility properties and likewise wind turbine installations. However this situation is now changing with, for example, the installation of a 200MW solar facility at Melbourne Water's Eastern Treatment Plant. A number of wind turbines were earlier installed up the coast from the Kwinana desalination plant in Perth to offset its heavy power demand whilst Melbourne's Wonthaggi desalination plant is said to be partially offset by a windfarm at Glen Thompson.

Furthermore, Sydney Water, Melbourne Water and South East Water, among others, have installed mini-hydro in lieu of pressure reduction valves. Melbourne Water also operates a full scale hydro system on its largest reservoir, the Thomson Dam, and has the capacity to recapture 30–40 per cent of the energy used in broaching the Great Dividing Range on its mothballed North South Pipeline. In the case of South East Water, about 900 MWh per annum is generated and sold back into the electricity grid.

While these developments are encouraging they do not come anywhere near the degree of innovative thought/experimentation characteristic of the industry's American counterpart [56,63]; where for instance sewage methane is being tried to power fuel cells to generate electricity [64]. There is a larger level of institutional flexibility, too, such as leasing facility surrounds to renewable energy companies via purchase power agreements, or buying offsets from off-site parties, when there are high-energy applications such as desalination [65].

7.5 Supply augmentation via urban rainwater capture

Rainwater is increasingly being utilised to augment supplies during drought at both domestic and municipal levels via water tanks attached to houses [66] or underground tanks to capture street runoff [67]. Hybrid mains water-tank systems are also available deploying sensor valves to top up the levels.

7.6 Stormwater and water sensitive urban design

Drainage isn't normally the purview of water utilities but there are clear implications for the functional integrity of sewerage plants. Even if a plant is not actually flooded, high rainfall events will cause a 'loss of solids' or 'loss of biomass' and it may take the plant a week or two weeks to regain normal function. Stormwater gets into the sewer through low point manholes or cracks in gravity sewers. The pipe volume is exceeded and the system will overflow at manholes and pump stations. The overflow points are often creeks or other stormwater drainage

systems. If large pulses of runoff can be prevented from entering a combined sewer, increased flows can lead to a reduction in concentration and lessen energy costs at the WWTP. Smaller pulses can also be beneficial to treatment by adding oxygen to the sewage water.

Water Sensitive Urban Design [Australia; 68] as it is known in Australia, or Sustainable Urban Drainage Systems [UK; 69] in the UK, or Integrated Development in the U.S., utilises swales, infiltration basins, wetlands and ponds, and aims to attenuate damaging off-land flows and harness these for landscape and recreational value. Such developments need to incorporate bypass systems to divert extreme storm flows to prevent them destroying their passive features. Water Sensitive Urban Design has other advantages not the least being the reintroduction of Nature values back into cities [70].

7.7 Cost versus emissions abatement

In the recent past, emission abatement was far more likely to proceed if, at the same time, it could be shown to improve an organisation's bottom line.

As previously noted, in order to ensure continuity of supply, governments have undertaken major capital works in the form of inter-basin pipelines, water grids, and desalination plants, as a hedge against rising (catchment) aridity brought on by global heating. In some instances, water recycling plants incorporating micro- or nano-filtration have been built, notably at Luggage Point in Brisbane, Australia; whilst rapidly growing urban populations have been a further spur for ensuring future drinking water supplies. The infrastructures identified earlier, can involve vast sums of money and governments have sought to recover a portion of their outlays from consumers through increased water prices. Melbourne's water retail utilities for example, began collecting payments from customers in 2012 to cover the costs of purchasing water from the privately owned Wonthaggi desalination plant. Melbourne Water had incurred an A\$300 million or 120 per cent increase in its finance costs following the desalination plant's completion on the 17th December 2012. At the time, these payments had to be returned because the plant was not being used [71].

8 Rewiring the industry to meet the challenges of carbon neutrality

Many of the design features of the energy needs found in six of the seven stages identified in Fig 3 which are the direct responsibility of the utilities were conceived of and developed years before energy efficiency and carbon emissions gained prominence and certainly before the onset of the Anthropocene, necessitating a retrofitting of infrastructure.

The following is thus a list of measures designed to abate emissions:

8.1 Optimising wastewater treatment plants

Treatment technologies provide significant opportunities for refining energy needs into future decades, particularly with respect to aeration requirements of WWTPs. UK's Environment Agency [63] has identified a multi-step program to help reduce such emissions, the key elements being:

1. Source control: In some situations, the greatest carbon savings may be achieved through the control, at source, of substances of concern, avoiding the need for treatment at the WWTP. Trade waste charges targeted to such problem chemicals can be instrumental for eliminating or limiting their receipt. In-pipe real time monitoring may also assist in identifying the origin of such chemicals.

2. Least CO₂e end-of-pipe/process addition: Least-carbon treatment solutions may be sought if high standards are mandated for using treated water for say, fresh produce horticulture, requiring removal of antibiotics and antibiotic resistant bacteria [57,72].
3. Redeveloping existing treatment processes: Switching conventional processes to lower energy alternatives which have the capacity to reduce the concentration of pollutants in effluent and reduce carbon. This should also encompass the introduction of efficiency improvements within individual stages, Table 4.
4. Renewable energy generation: On-site generation from biogas or other generation within the water industry mitigating the water-energy nexus [43,65] For example, micro-generation from effluent flows under gravity.

These show that carbon emission reduction has to be pursued on several fronts—attention to the maintenance and efficiency of the plant as a whole and that of its individual stages; coupled with harnessing of biogas for electricity generation [73]. Moreover, the fact that one estimate has the British water industry capable of producing 50 per cent of its energy from renewable sources by 2020 (renewables as a whole have now risen to 40 per cent of the energy mix) suggests that there is scope to implement low carbon measures across water networks [37]. In particular, the considerable number of flat surfaces—roofs, yards, *etc.*—at WWTPs lend themselves to the installation of solar panels apropos of the Eastern Treatment Plant in Melbourne.

In the first instance, many fine tunings have been identified such as those set out by the Water Environment Research Foundation in Table 4 and similarly by Crawford and Sandino [63] and Reekie [33]. Effective as they may be they also need to be ‘incentivised’ through real

Table 4. Savings from water energy efficiency applications.

Waste water sector energy efficiency practice	Savings observed
Switch to variable frequency drives to match output to load requirement	Savings of 10–40 per cent by replacing valve with a VFD
Operational flexibility	Savings typically 10–25 per cent
Manage for seasonal peak by flexible staged design	Savings can reach 50 per cent during off-season
Optimise aeration systems	Savings of 30–70 per cent of total aeration system energy consumption is typical
Fine bubble aeration	Savings between 20–75 per cent of total aeration unit’s energy consumption
DO monitoring of control equipment	Savings between 20–50 per cent of aeration unit’s energy consumption
Reuse of final effluent to replace potable water for tank rinsing	Savings may reach 50 per cent of total systems energy
Conduct annual energy survey	Savings range from 10–50 per cent of the total system energy. Several projects have resulted in energy savings of 65 per cent.
Use of fine energy monitoring	Range of energy savings is typically 5–20 per cent when energy efficiency is viewed as a daily performance goal
Install high efficiency motors	Savings of 5–10 per cent of the energy used by the lower efficiency motor to be replaced
Optimise pumping systems	Savings of 15–30 per cent are typical with up to 70 per cent available in retrofit situations where a service area has not grown as forecasted

Source: Crawford and Sandino [63].

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time monitoring/logging by plant operators of the performance of the components throughout a WWTP on a kWh/kL basis not altogether dissimilar to the America's 'Energy Index for Benchmarking Water and Wastewater Utilities' [74].

In the wake of Cop26 it can be anticipated that utilities will be persuaded to make their CO₂e footprint yet more transparent.

8.2 Distributed treatment

Distributed systems for electricity generation have become widespread [75] especially through the use of solar panels on buildings. Apart from their operational efficiencies panels offer security of supply against extreme weather events such as floods and fires (or terrorism) which can immobilise power stations, substations and transmission lines.

Significant off-grid developments in America, Germany, etc. assisted by rapid innovation in battery storage technologies have become a powerful metaphor for sustainability [76,77] suggesting that water utilities follow suit and begin to move away from centralised, large scale treatment works.

As noted above there's already a degree of distributed treatment/recycling of industrial water and this is closely regulated through trade waste charges on discharges. A similar degree of distributed treatment also exists with some model housing estates and at yet a smaller scale, some commercial buildings and households, but they amount to only a tiny proportion of the mix. There will always be small common effluent schemes and recycling. However, these are usually very heavy on maintenance requirements particularly where the system is reliant on the diligence of householders for upkeep. The gains needed won't be there.

Note that distributed treatment here has an important difference over distributed energy generation in that there can be health and environmental consequences should they not be properly maintained &/or operated.

So, could distributed treatment cover more of the treatment load in modern cities? One possibility is to use pressure sewers to feed localised treatment plants, reducing sewage pumping distances at the urban fringe as for instance, that currently operating in Rosebud, Melbourne. The energy calculus here is bound to be extremely complicated given that economies of scale may be foregone over centralised larger plants especially if resource recovery is to be practiced.

8.3 Furthering the energy↔water nexus

One avenue worth following is the significant quantity of low grade waste heat to be found both on- and off-site (in industrial establishments).

Applying a water source heat pump to WWTP effluent for example, could be a way to raise anaerobic digestion to thermophilic temperatures [78].

And, forming new partnerships with customers to tap into factory waste heat offers a low carbon opportunity to reclaim polluted industrial water via small MED plants. Or up a notch or two, using low pressure steam, often available at oil refineries, for co-located desalination plants such as at Kurnell, Sydney where such a facility already exists across the other side of Botany Bay, Table 3.

But these ideas remain at best piecemeal responses; one solution being that detailed by UK's Environment Agency [79] that water companies merge with energy producers to create more effective partnerships for tackling emissions or at the very least a form of association like the partnership between the Water Research Foundation and the California Energy Commission [33]. The efficiencies arising from integration of the two sectors should not be

underestimated. It's possible however that community operated microgrids will steadily reduce the potency of that connection.

9 Discussion

A key question arising from this overarching review is whether the water industry which, as we have seen, is becoming increasingly complex, can ever become fully decarbonised in its own right?

An integrated energy, nutrient and water recovery analysis of a treatment plant Mo and Zhang [41] has concluded that it “has the potential to offset all the direct operational energy; but it is not able to offset the total embodied energy of the plant to achieve carbon neutrality”. This finding moreover is for a single albeit energy intense stage of the cycle depicted in Fig 3. It should be cognisant of a ‘responsible care’ obligation to strip heavy metals, steroids, antibiotics [80,81] and other micro contaminants before administering treated effluent to land, receiving waters [82] or food crops [83] and likewise, sewage sludge.

A special report by the UK's Environment Agency [37] in pinpointing likely pollutants identifies the additional treatments that may be required, namely, biological (e.g. activated sludge, trickling filters, and membrane filtration); adsorption (e.g. GAC, sand filters); chemical treatment (e.g. pH adjustment, coagulation, precipitation); advanced oxidation (e.g. UV, hydrogen peroxide; and ultrafiltration (e.g. membrane filtration or reverse osmosis). Any of these will serve to readjust the energy budget away from carbon neutrality.

American data in fact shows that advanced treatment has grown from less than 1 per cent of the population in 1972 (dating from the Clean Water Act and the Safe Drinking Water Act) to 50 per cent in 2008 in spite of improvements in energy efficiency.

Before-&-after kWhr/kL data for the Eastern Treatment Plant in Melbourne for instance, would be an interesting case study. This large plant runs a conventional activated sludge process which is augmented by an additional treatment train of pre ozone, biological filter, post ozone, UV and chlorination, as its chosen technology to meet tighter discharge limits and the requirement for ‘Class A’ irrigation water (Class A is a somewhat imprecise water quality concept based on microbiological units with some grounds for chemicals but not for example, PFAS).

A similar finding to Mo and Zhang [41] above has been reported by Nowak, Enderlee [84], namely that an activated sludge process *can* be carbon neutral and acquire positive status with the importation of energy, provided “that the negative effects on the environment like insufficient wastewater treatment or the release of methane gas to the atmosphere be avoided”.

However, the scenario they describe appears to require certain circumstances that may not exist for many utilities. Lagoon plants which are commonplace in Victoria, Australia, are near neutral in energy consumption but they require vast amounts of land which are simply not available in most cities, e.g. >100 km² would be needed for a 5+ million metropolis like Melbourne. Further, their vulnerability to algal blooms and questionable ability to consistently produce very low nutrient water excludes their consideration.

Nonetheless, in the case of the Nowak examples, and those described by Torrie, Bryant [85], the desire to pursue at least an energy neutral situation led to changes in the design and operation of the facilities in question and it is this consciousness that is atypical in the water industry more broadly.

So there's a clear need to further progress R&D into water treatment methods and technologies which have much lighter carbon footprints [43], a process begun with low energy RO membranes [86] as well as drawing upon stratagems like a Cost of Carbon Abatement or CCA tool to permit differentiation between mitigation options [87]. The American Water Research

Foundation has similarly developed an energy management Decision Support System or DSS to help water utilities make better decisions for sustainable energy management [33].

We have seen in analysing one particular area, pressure sewers, an illustration of how a price on carbon could be influential in refocussing utilities on CO₂e mitigation rather than purely financial considerations, viz. Net Present Cost. Yet, a formative report devoted to improving economic regulation in the Australian urban water sector [88], whilst clearly valuable, dealt with climate change in just a few lines and had nothing at all to say about how abatement might fit into its reform agenda. At that point the drive was to divide infrastructure entities into more and more sub components (under the guise of competition and therefore efficiency) which had done nothing except erode the ability to make changes to global thinking at this level.

In Australia where a national carbon price was legislatively removed in 2014 that signal could take the form of a social cost in all business planning activities and to incentivise the utilities to outperform each other in carbon terms[89]. In the process it could competitively position the industry with front runners due to adopt a national emissions trading scheme in the current decade. Indeed, if more water authorities were to be privatised and operate outside their traditional jurisdictions, there may be a competitive advantage awaiting those that are quick to incorporate carbon footprint thinking into their future design and operational activities.

Central to that objective is a greater transparency deriving from real time tracking of CO₂e emissions throughout utility operations especially sewerage plants e.g. kWh/kL, in order to get energy reduction into designer and 'operator consciousness' *vis-à-vis* a willingness to change/innovate or focus on energy. It would further niche with a need for a fuller industry AI including the convergence of big data, metering, information systems and technologies enabling efficiency in operations [33]. There is now in existence a large number of generic applications suggesting that the industry could at first transition into small scale applications such as Melbourne Water's usage to identify and monitor vegetation in stormwater basins [90].

Part of the reason why the industry rarely shows up in discussions about zero carbon cities are historic American EPA figures that it contributes just 3 per cent to national CO₂e emissions [12]. Another estimate is 5 per cent whilst the Electric Power Research Institute of the Water Research Foundation [1] puts it at 2 per cent. As noted earlier, the Congressional Research Office [18] has now queried the cogency of such figures [13]. A further two caveats apply to these values:

The first is to caution against generalising this figure to other countries, even jurisdictions. Fig 8 for instance, implies a huge spread of energy cost by stage amongst 19 American utilities reflecting the fact that some may be abstracting water from rivers; others groundwater; and yet others from dams; coupled with a variability as to water quality requirements and therefore different treatment standards across States and jurisdictions; And, if California's supply was to be unpacked, the long distance pipelines identified in Table 2 would consume a considerable amount of pumping energy with only partial recovery via mini hydro on running downhill at various points. Of further note is the fact that part of this review has drawn upon Melbourne data where the fall of the land is ideal for gravity sewers but 2000 km to the north, Gold Coast Water (with only 15 per cent of Melbourne's population), has to deploy no fewer than 450 pumps to convey its sewage along a coastal plain.

The second is the role of global heating, itself, in making life more difficult for water authorities. Growing aridity in parts of the world like Australia (in temporary respite), California [91] and Spain, have driven countries to resort to desalination as hedges against these conditions. Chile is moving in the same direction [92].

As the World Bank Group [93] has previously recorded “once the soil has completely dried out due to strong evaporation during heat waves, no more heat can be converted into latent heat, thus further increasing temperatures. This effect is much more important during summers [27] and has been a characteristic of major heat and drought events in Europe and Western United States”. The extremely hot fires that devastated Eastern Australia in December 2019/January 2020 and more recently, Western United States, are testimony to this circumstance.

It’s unlikely however that the industry can acquire full zero carbon status in its own right while it has to resort to desalination and bulk water transfers especially if droughts on the scale of California and Australia are to be a recurrent feature of the Anthropocene. If even the most conservative predictions of the IPCC come to pass, RO plants will be steadily brought on-line transforming the energy burden of the sector. Unfortunately, such plants lie in the front line of advancing sea levels and storm surge. CSIRO modelling for instance, based upon a 19 per cent increase in winds forcing storm surge and 82 cm of sea level rise, suggests that Melbourne’s desalination plant at Wonthaggi is particularly vulnerable to inundation [94]. No less of concern is the precarious grip a glacier the size of Florida has on remaining anchored to the Antarctica land shelf which has the potential to remake the world’s coastlines! [95].

Extreme climatic conditions are clearly poised to make a significant energy impost as has been acknowledged by the Reekie, Pabi [1]. It does not appear that these risks have been fully factored into desalination plant siting and design [96]. In places like the Australian and American seaboard most of the heavy wastewater infrastructure is already situated close to the sea (often experiencing seawater infiltration) rendering it equally vulnerable.

The desalination burden in the Anthropocene will in all likelihood be added to by bulk water transfers through inter basin pipelines to counter drought conditions; not to mention trucking water to regional towns as has recently occurred in Australia; subtle changes in temperature regimes altering the prevalence of nuisance and toxic algal species requiring further treatment of supplies at source; similar treatment requirements should wildfires enter catchments producing post-fire debris resulting in extreme water quality impacts; and finally, growing community expectations and regulatory standards as to water quality.

Whilst many influences lie beyond the sector’s immediate control, e.g. population growth, design and operation of cities, household behaviour [15] etc., the industry should not be waiting around for leads from governments and other authorities before acting on those areas it does have some control over. An overdue move is to supplant unsullied competition policy with good management and governance sympathetic to carbon and long term resource allocation.

This is a traditional and conservative industry which, outside of North America and parts of Europe, has been interacting minimally with the energy sector. As the importance of carbon accounting grows that level of functional independence becomes less credible. This situation is unhelpful given that these sectors are becoming interdependent and need to work together especially in relation to demand management and harnessing renewables. The only entity in Australia integrative of the two is Northern Territory Power & Water.

The recruitment of climate modellers and water-power engineers by utilities for example would further help, serving to offset depleted in-house experience as a result of increased outsourcing of expertise over many years in Australia. The American Water Research Foundation- Electric Power Research Institute Reekie, Pabi [1] in like vein has . . . advocated development of a formal program directed by a mix of professionals from the water and wastewater industry along with electric utility representatives to study and demonstrate innovative energy management solutions.

But, this is not to lose sight of the fact that global CO₂e emissions need to be cut drastically rather than merely flat-lined and a reduction in carbon intensity alone will not be enough [97]. Can the industry therefore usefully contribute to that objective by generating more renewable power than it consumes?

The UK industry back in 2009, for example, managed to produce 8.5 per cent of its total energy from renewable sources, wind and hydro, with the vast majority drawn from water and wastewater companies many of whom anticipated reaching 20 per cent within a year. The target for the national economy at that point was to produce 15 per cent by 2020 whereas it's accomplished a staggering 40 per cent. In these circumstances it would appear that the aspirational targets of 50 per cent on wastewater sites could become practical by 2020 [98] could well have been achieved.

Nonetheless achieving energy self-sufficiency for WWTPs still faces serious technological hurdles thus being a work-in-progress [99–102]. And, if it can't be internally carbon neutral, as seems the case, then the industry will have to draw upon a partially or fully decarbonised centralised grid and where practicable, supply to it from its own renewable sources. Having said that, that grid in turn may be contracting as a result of defections due to rapid advances in battery storage technologies [76] if not palpable limits on its capacity to deal with the exigencies of climate change such as wildfires affecting lines in contrast to less exposed microgrids [103].

10 Knowledge and technology transfer to non-western countries

This review has focussed on the repository of knowledge and technologies vested in developed countries of the likes of Australia, America, Britain, *etc.* It's interesting to note here that there's now a measure of convergence between water problems encountered in these places and middle-band and developing countries due to rising incidence of punishing drought (Parts of Europe experiencing its worst for 2000 years), extreme climatic events, and population pressure. Serious contamination of ground and surface water, however, remains a major point of departure between the two, with only one third of wastewater treated to secondary standard in Asia, less than half of that in Latin America and the Caribbean and a miniscule amount in Africa [104]. Drought is also taking its toll on some of these countries where Chile for example, has been grappling with the establishment of desalination plants [92,105].

Extending conventional secondary treatment to full coverage to ensure health and environmental protection would have profound implications for global energy usage and affect the long-term goal of bringing net emissions to zero by 2030 or at least 2050 [97]. And, if recycled water is to relieve critical supply shortages affecting food production [105] as is advocated by the United Nations [25], then tertiary standards of treatment will be needed especially if micro-contaminants such as antibiotics producing resistant strains of bacteria [81,106,107] are to be stripped from effluent [57]. Whilst there's a clear benefit in 'source control' to stop all manner of pollutants entering waste streams in the first place, new plants and upgrades to existing plants are inevitable and these may use yet more energy.

The transfer of knowhow and technological advances to such countries is therefore critical to reaching clean energy transitions. And, pursuance of an energy neutral situation provides an unparalleled opportunity to make changes in the design and operation of new facilities. As noted above upon starting from scratch, how should a WWTP be (re-) designed for a degree of integration of sewerage and select municipal waste?

An immediate response is to centre on large emitter countries particularly those where there is a strong commitment for action on climate change such as China. The measures envisaged under the Reinventing Fire: China programs [4] are thus of special interest to the theme of this paper. That program aims to:

focus on an economy-wide analysis of the four major energy-producing and-consuming sectors of the economy: Buildings, Industry, Transportation, and Electricity. For each sector, the team will develop and use “bottom-up” models to estimate the potential for different technologies and approaches to shift the trajectory of China against an assumed “business as usual” scenario. Modelling will include both specific energy-saving and renewable technologies, and integrated benefits achieved by combining multiple options.

Our findings suggest that a fifth category, water, could be usefully added to the current four in this modelling exercise, viz. industry; buildings; transportation; water, and transformation/ electricity.

11 Conclusions

If the water industry—indisputably a growing energy user—is to play a part in cutting overall CO₂e emissions to lessen peak warming it needs to be highly creative and on the lookout for opportunities to form partnerships not only with the energy sector [1,33] but also the health, manufacturing and resource processing sectors. To some extent this is already happening at a small scale in Australia with a level of partnering, however basic and one sided, between the electricity and water sectors for at least a common ownership of consequences for performance of both entities. The notable exception to this de facto association is the combined governance under Northern Territory Power and Water.

Moreover, recognising that the industry’s service provisions are an integral part of on-going urban development, it’s important that it participate in the strategic planning and land use debates that affect its energy budgets. And, it has of late, a new found liaison with the health sector in identifying Covid19 pandemic hot spots by surveillance of sewer-sheds [108,109]. The social and medical value of this capability has been demonstrated by its detection (September 2020) in Adelaide sewage and subsequently in other states believed to include shedding of fragments of the virus. And, America’s Centers for Disease Control and Prevention [110] has now provided a tool to detect omicron in sewer sheds.

This presence underscores a wider need to monitor and deal with trace contaminants [111] including PFAS [54,55,112] and antimicrobials [57] There is precious little to see here insofar as a recognition of a need to have multiple treatment trains inclusive of ultra-filtration &/or RO applied to the production of ‘purified water’ [113] especially when it is used to irrigate vegetable crops [55,114] No less troublesome are findings that microplastics can be taken up by crop plants irrigated with treated effluent [115].

Despite such riders, gaining public acceptance of recycled water remains a focus of Australia’s water utilities [114,116].

Interestingly, a plan to install an RO component at South Australia’s New Bolivar Advanced Water Recycling Plant (AWRP) which provides treated water to farms on Adelaide’s Northern Plains [117] that grow fresh produce for local, national and international markets, derived from ‘a need to reduce salinity’ rather than mitigating any possible presence of emergent contaminants. It has not proceeded because farmers were not prepared to meet the costs.

The local industry of late has further turned its attention to ‘renewable organics’ [118] aimed at transforming sewage sludge (a feedstock sometimes augmented by food waste) into an energy source and an ‘agricultural enhancer’. The conventional tack employs anaerobic digestion to produce biogas aka methane, for electricity generation [51] whilst utilising the digestant as a fertiliser [119].

A further approach uses this same feedstock, or one sourced from outside of the industry, to produce biochar as a soil improver. There are a number of local experimental projects

variously in the modelling stage, underway or completed—viz. pyrolysis [120] or self-energising gasification-based at Logan, Queensland [121]. Further work is needed to establish the extent that the respective biochars are free of contaminants such as PAHs [122,123] PFAS [124], PCDD/Fs & PCBs. Currently there appears to be no firm detail as to how and where the products produced a) by different feedstocks and b) by different production methods, are safe to use as soil enhancers there being no comprehensive long-term trials.

Insofar as emerging countries are concerned there is an opportunity for early adoption of new systems bypassing a need to retrofit old technologies including promising advances in desalination [125].

Given the importance to such countries—their human and non-human populations across the globe of an adequate supply of water, it is to be expected that most fronting the sea will, or already have, turned to desalinated sources to enhance the quantity and quality of this primary resource. With that understanding always in mind, the authors have proceeded to underline many of the energy related dimensions for bringing about such an adequate and quality supply.

There's clear evidence that 'underweighting' energy considerations in water infrastructure is commonplace (outside of North America) and that this is an unsustainable position for the industry as a whole to maintain. Further, as strategies to reduce CO₂e emissions from buildings, the primary energy sector and transportation begin to bite, growing and unabated levels from the water industry could leave it as a non-conforming emitter. A change in mindset and a subsequent shift in behaviour is needed. In this way the industry can become an influential, as opposed to a passive player, in decarbonising the cities of this planet and most importantly, play a material role in reaching net zero emissions.

Further, it needs to be more on the front foot, joining the climate emergency call and taking ownership of its burgeoning energy needs, starting with lobbying for a water category in national emissions per Australia. If utilities were monitored on the amount of electricity used per kilolitre of water processed and then rewarded (or penalised) accordingly, it would encourage the entire sector to improve its carbon performance from water supply all the way through to sewage treatment. A symbolic beginning would be to real time accredit its 'product' with a carbon rating given measurement and disclosure becoming unavoidable; noting that using 'digital' means to create transparency can have benefits.

This keys with an approach advocated in a Cop26 Sustainability report [126], viz.

Achieving net zero will require overcoming traditional orthodoxies and ways of working and constructive actions taken during the pandemic have demonstrated the world's ability to innovate and intervene at scale to support both lives and livelihoods.

Supporting information

S1 Graphical abstract.

(TIF)

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