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Energy recovery in a commercial building using pico-hydropower turbines: An Australian case study

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ABSTRACT

Optimising energy use in systems and buildings is crucial to reduce climate change. This paper aims to address the gap in knowledge for pico-hydropower (<5 kW) that has been identified as an area of untapped potential in the water industries. A literature review and multivariate analysis are used to find a suitable pico-hydro turbine to install into a coral reef aquarium system in a government owned facility. Key findings from the literature review are untapped potential, gaps in knowledge and global quantification of small hydropower for energy recovery, and lack of enabling data contributing to slow uptake of small hydropower. The study showed a propeller pico-hydropower turbine could be used to recover approximately 10% of the energy used for pumping water through a filtration system. At 2.3 m available head, and 90 L/s water flow, power output up to 1.124 kW was achieved. The project was economically viable with financial and non-financial benefits for the life cycle of the product. There remain sparse case studies for energy recovery using small hydropower in the scientific literature. A growing number of authors see the potential of this renewable energy technology to reduce global greenhouse gas emissions and contribute to the UN Sustainable Development Goals to provide affordable clean energy and address climate change. This study helps to shine a light on opportunities to find value from waste using a novel application of hydropower in a water industry.

1. Introduction and background

Universal access to affordable, reliable, sustainable, and modern energy is at the centre of efforts to tackle climate change. The United Nations have established 17 Sustainable Development Goals (SDGs) in a worldwide agenda and a call to action to achieve global sustainability including 'Affordable and Clean Energy' (SDG7) and 'Climate Action' (SDG13) [1]. Of particular concern to Australia, is that climate change is the greatest threat to the Great Barrier Reef (GBR) and only the strongest and fastest possible actions to decrease greenhouse gas emissions will limit the impacts of climate change on the GBR [2]. Of particular concern in developing countries, is the importance of bringing clean affordable energy and water to all people, including those in remote regions [3]. An estimated 1.06 billion people (13% worldwide), a predominantly rural population, don't have access to electricity [4]. More efficient and cost-effective water networks and systems could reduce operational and end user costs and lower greenhouse gas emissions [5].

Globally, hydropower is the most mature type of renewable energy, and it plays an important role in providing electricity in more

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than 160 countries [6]. It is an efficient method for continuously generating up to 90% of mechanical energy into electrical power compared to around 60% efficiency of fossil fuel-based power plants [7]. The median life-cycle emissions for hydropower are between 18 and 24 g CO_2-e/kWh less than emissions from gas, coal, biomass, or geothermal [8]. Traditional small hydropower (SHP) for rural electrification (run-of-river, pumped hydro and reservoir) has been explored comprehensively [9] and represents approximately 1.5% of the world's total electricity generation. Installed hydropower capacity is estimated at 78 GW and yet 66% of the potential 229 GW capacity remains untapped [10]. Small hydropower has been described as the 'shyest' of renewable energy sources, due to a lack of knowledge about the technology and its applications [11]. Although SHP projects are predicted to add 11 GW from 2021 to 2030 [8] this may not include all small-scale plants and systems. SHP plants and systems including pico-hydropower (<5 kW) ('pico-hydro') are increasingly seen important for reaching the SDG7 targets including expanding access to clean and affordable electricity for basic living needs [3]. Small hydropower systems are likely to have significantly lower life-cycle cost, less residual and indirect greenhouse gas emissions, minimal transmission and construction costs, can have minimal hydrological risk, lower environmental impacts and can be easily accessible [12].

Traditional hydropower stations exist for the primary purpose of generating electricity. In this study, energy recovery hydropower is defined as hydropower installed into existing systems or structures, where water is already being diverting from a natural waterway for agricultural, municipal, industrial or building consumption and not primarily for the generation of electricity. Potential and existing hydropower for energy recovery can be found where energy is required to pump, treat, and deliver water [13] and in the energy sector for extraction, processing and for cooling [14]. The International Energy Agency estimates global electricity consumption could be reduced significantly if the economically available energy efficiency and energy recovery potentials in the water sector can be exploited [15].

Only 34% of traditional SHP potential is currently being utilised [10]. Energy use for water industries, agriculture and industry outflows represents global energy consumption of at least 4%, and reductions in these sectors may help to achieve SDG7 and SDG13 targets globally [15]. Numerous authors also draw attention to the water-energy-nexus and links to SDG6 (clean water and sanitation) where advances in the water industries using hydropower can also minimise water leaks [15]. Previous studies point to a narrow focus, and this prevents an understanding of how the whole water industry is performing as a renewable energy generator [16]. To help address this gap, this study includes a literature review that comprehensively examines the global use of SHP for energy recovery across the water industries, agriculture, industry outfalls and buildings. This review offers an overarching and up-to-date analysis of global studies for non-traditional SHP for energy recovery.

There is an immediate need to drastically reduce the energy consumption of buildings and water services, where there is no one solution to achieving net zero emissions for these sectors. More practical case studies are needed to demonstrate possible uses for micro- and pico-hydro systems that can optimise the use of energy in buildings. This study focused on pico-hydro turbines for energy recovery in a commercial setting, to address the gap in real world case studies for pico-hydro systems and raise awareness for the potential applications for this renewable energy source. The study examined the feasibility and efficacy of an energy recovery system integrated into a government owned building managed by the Great Barrier Reef Marine Park Authority (the Reef Authority). The subject of this study is a readily available pico-hydro turbine used for energy recovery in an aquarium filtration system used to support a coral reef exhibit. A targeted literature review was used to aid selection of a suitable pico-hydro generator unit.

Previous studies highlight the gap and need for more novel systems, and more demonstration sites to address lack of awareness for stakeholders [17,18]. A novel case study is presented here for an existing building, which may help fill the gap in real world studies for SHP energy recovery, particularly for buildings. No similar case study could be found in the peer-reviewed scientific journals. It adds to the work of others by examining an application for pico-hydropower which can recover of some energy used to continuously pump water in a commercial building mechanical system. Although the building is unusual, the global relevance will be explored. The study aims to highlight the diversity of SHP to increase energy efficiency where potential in some applications may be unknown.

An additional aim of the case study was to test the feasibility of feeding recovered energy back into the building's energy supply network.

2. Hydropower classification and theory

Hydropower has been categorised according to key design features, configuration and operating conditions as shown in Fig. 1 (adapted from YoosefDoost and Lubitz (2020) [19]). Several authors have classified hydropower systems by their power class, application and energy capturing configuration, and these are summarised in Table 1.

Pico-hydropower is the smallest variety being less than 5 kW [20]. Note that in this study SHP is a generic term capturing all the smaller types of hydropower but primarily mini, micro and pico-hydropower. Some of the common turbines are shown in Tables 1 and 2 are described by Okot (2013) [21] and Williamson et al. (2014) [22].

A turbine converts the energy from falling water into rotating shaft power and power output depends on the water head pressure and can be classified as impulse, reaction or action (kinetic) [25]. The impulse type often operates in tailraces where kinetic energy from jets of water is converted into mechanical rotation energy in the turbine [25]. Reaction turbines change the direction of the momentum of water, converting pressure and kinetic energy into mechanical energy [26] and are efficient at relatively low heads as shown in Table 2. Action turbines can operate in zero water head pressure where energy is fully kinetic as opposed to gravitational kinetic [27].

Cumbajín et al. (2020) [28] provide a thorough theoretical overview of hydropower turbines and generators which they describe as a machine that converts hydraulic energy into mechanical energy, transferred to an electrical generator to produce electricity. Numerous authors have reviewed available suppliers [29,30] and give reviews of the technical aspects of pump-as-turbine (PAT)

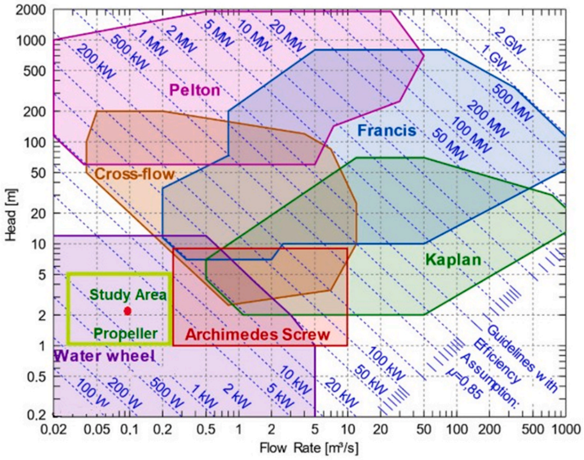


Fig. 1. Classification of hydropower based on design and performance features. Adapted from YoosefDoost (2020) [19].

Table 1
Classification of hydropower systems (adapted from Refs. [20,23], and [24]). Classification by power size class, operating system (application) and turbine type, operating pressure range. PAT denotes pump as a turbine.

Name	Capacity	Operating System	Description
Large	>100 MW	Run of River	Energy captured from the flow of water
Small	1–10 MW	Reservoir (Dam)	Storage of seasonal wastewater released through hydro-turbines
Mini	100 kW to 1 MW	Pumped Storage	Water pumped through a high reservoir with renewable or off-peak electricity
Micro	5–100 kW	Energy recovery	Captures excess energy in water distribution or treatment systems
Pico	Up to 5 kW		
Turbine Type	**Head Height Range**		
	Low head (<10 m)	Medium head (10–50 m)	
Impulse	Cross Flow	Crossflow, Pelton, Turgo	
Reaction	Francis (radial flow), Kaplan, axial flow, propeller	Francis (radial flow)	
Waterwheel	Overshot, Breastshot, Undershot		
Other	Archimedes, PAT, hydrostatic, split pipe, vortex	PAT, cross pipe	

systems where a pump is run in reverse to generate energy rather than using energy for pumping [13,31]. A database (Reduction Energy Dependency in Atlantic area Water Networks or REDAWN) has been made available to aid in pump selection [32]. PATs have been widely used as they are readily available, simple and cost effective [33,34]. However, there are challenges for PATs when the flow rate is not stable [35]. The peak performance of a PAT is typically less than conventional turbines, however the cost can be less, with payback of 2–6 years compared to 8–10 years for micro-hydropower [36]. Previous studies give reviews of existing and emerging technologies in the hydropower sector [37,38] and Niebuhr et al., 2019 [39] provide a review of hydrokinetic (zero head) turbines.

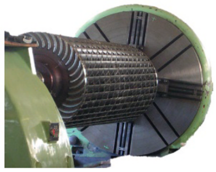
3. Literature review of small hydropower energy recovery in the water industries, agriculture, and buildings

A systematic literature search and review was undertaken using an adapted method by Kuriqi et al. (2021) [40] which follows the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guideline [41]. A database search for relevant global studies was undertaken, followed by an analysis of studies found. Web of Science, Scopus and Google Scholar were chosen as they are recognised as leading global platforms. The abstract, title, keyword criteria were used. The search terms used were "small hydropower" filtered by "energy recovery".

The timeframe for studies was set based on availability of studies and the scope excluded traditional hydropower (run-of-river, pumped hydro and dam or reservoir). The scope included non-traditional hydropower for energy recovery in the water industries (potable water treatment, distribution, and reverse osmosis), wastewater treatment plants (WWTP), agriculture and industry outflows and buildings. Studies were grouped into multi-country and national scale as shown in Table 3, and individual case studies are shown in Tables 4 and 5.

To aid the selection of an appropriate turbine for the case study, a targeted search was undertaken for pico-hydropower in buildings beyond the water industries. The three databases were searched using "pico-hydropower" filtered by "energy recovery" and

Table 2
Categorisation of hydropower generators by design features (adapted from Ref. [28]).

		
Pelton (large head and low flow, high efficiency 70–90%) Credit: used with permission from EcoInnovation NZ	Turgo (one or multiple jets, high efficiency 87–91%) Credit: used with permission from EcoInnovation NZ	Crossflow (higher flow than Pelton and Turgo – 80% efficiency) Credit: Teratornis via Creative Commons
		
Francis (70–74% efficient) Credit: Rama, CC BY-SA 2.0 FR via Wikimedia Commons	Kaplan-Propeller (more efficient for lower head sites – 70% efficient) Credit: GT1976, CC BY-SA 4.0 via Wikimedia Commons	Archimedes Screw (low head sites – 86% efficient) Credit: Pesymista, CC BY-SA 3.0 via Wikimedia Commons

"buildings", and "high rise hydro". Snowballing was used to find further relevant studies. Studies from applications such as public aquaria, aquaculture pumping systems, community swimming pools or water parks, building water reticulation systems, cooling systems and towers, reverse osmosis systems were included. Individual case studies for pico-hydropower in buildings are shown in Table 6.

There were limitations to the review. Some studies may have been overlooked, due to the range of technical key terms used. Only English language studies were included however studies in other languages may be relevant. The screening process also involved some

Table 3
Studies on small hydropower (SHP) at a multi-national, national and case study level since 2012.

Author/s (Year)	Countries	Potential or actual sites	No. studies included	WTP	WWTP	Farm Industry Irrigation Building	power generation MWh/yr	annual CO2 emissions avoided (t)
Multi-country Assessment of SHP for energy recovery								
[44]	8	Actual	8	✓		✓	np	np
[17]	11	Actual	36		✓		np	np
	14	Actual	49		✓		22	np
[45]	9	Actual	1	✓	✓		np	np
		Potential	8	✓				
		Potential	6					
[46]	27 (EU)	Potential		✓	✓		2025–3662	0.54–1.01 million
[42]	6 (EU)	Potential	8828 (sites)	✓	✓	✓	482–822	np
[47]	16 cities	Potential	1			✓	5.11–80.7	np
National (whole country) level assessment of SHP for energy recovery								
[48]	Switzerland	Potential	13		✓		9.3	np
		Actual	6		✓		3.5	np
[49]	Spain	Actual	177			✓	21	np
[50]	Spain	Potential	471		✓	✓	29	np
[51]	USA	Potential	np	✓	✓	✓	1–2	np
[18]	USA	Actual	np	✓	✓	✓	0.53	np
		Potential	1415	✓	✓	✓	1.41	np
[42]	Ireland	Potential	579	✓	✓		15.5–32.2	np
	Northern Ireland	Potential	2154	✓	✓		5.9–8.2	np
	Scotland	Potential	5351	✓	✓		17.8–139.7	np
	Wales	Potential	179	✓	✓	✓	8.1–10.2	np
	Spain	Potential	550	✓	✓	✓	375–539.9	np
	Portugal	Potential	15	✓	✓	✓	57.7–93.4	np
[52]	Ireland	Potential	14	✓			1.75	np
[16]	Australia	Actual	25	✓	✓		84	np

Note: "np" indicates not provided. ✓ indicates true for the criteria. WTP denotes water treatment plant. WWTP denotes wastewater treatment plant.

Table 4
Case studies for small hydropower for energy recover at potential sites from 2012.

Individual Case Studies of SHP for energy recovery in potential sites (studies in buildings shown in Table 6)								
Authors/s (year)	Country	Potential sites	No. studies	WTP	WWTP	Farm, Industry, Irrigation, Building	Power generation MWh/yr	annual CO2 emmissions avoided (t)
[53]	USA	1	270	✓			1564	np
[54]	Italy	114			✓	✓	856	8800
[30]	South Africa	10	130–884		✓		1123–7638	np
[55]	Spain	5	25.1			✓	93.9	np
[56]	Korea	1	10			✓	57	np
[57]	UK	1	np			✓	1	np
[58]	Ireland	1 network	up to 100	✓			3309	np
[59]	South Africa	2	7–9.8	✓	✓		np	np
[60]	Switzerland	2	380		✓		851	np
			170				460	
[61]	Ireland	8 networks		✓				np
[62]	Spain	2 networks				✓	43, 92	np
[63].	UK(Ireland)	80	4.8–22	✓	✓		17,900	np
	UK(Wales)	1	15–140	✓			18,000	np
	UK	5	50–650	✓			4600	np
[64]	Ireland	7		✓			0.63–84.5	np
[65]	Iran	1 network	168	✓			np	np
[66]	Saudi Arabia	1 network	5571	✓	✓	✓	np	35,395
[67]	Iran	1	16	✓	✓		68–69	np
[68]	Pakistan	1	6	✓	✓	✓	np	np
[69]	South Korea	1	np	✓	✓		30	np
[70]	South Africa	10	550	✓	✓		10,000	np
[71]	Spain	4	198	✓	✓		270.5	108t
[72]	Spain	1	6	✓	✓		49.9	np
[73]	Portugal	1	np	✓	✓		485	np
[74]	South Africa	5	166	✓	✓		55.7	np
[75]	Portugal	1	np	✓	✓		23	12
[76]	Italy	2	1.15–3.18	✓	✓		39.8–54.9	np
[77]	Switzerland	1	8–18.5	✓	✓		60–136	np
[78]	China	1	187	✓	✓		np	np
[79]	Spain	1		✓	✓		280	np
[80]	Spain	2	0.75–2	✓	✓		6.75–17.52	np
[81]	Korea	1	98	✓	✓		np	np
[82]	Italy	1	1.1	✓	✓	✓	7.55	np
[83]	Italy	1		✓	✓		818,028	327
[84]	USA	65	NA	✓	✓	✓	280	np
[85]	China	1	91 kW	✓	✓		np	np

Note: "np" indicates not provided. ✓ indicates true for the criteria. WTP denotes water treatment plant. WWTP denotes wastewater treatment plant.

Table 5
Case studies for small hydropower for energy recover at actual sites from 2012.

Individual Case Studies of SHP for energy recovery in actual sites (studies in buildings shown in Table 6)								
Author/s (Year)	Countries	Actual sites	electrical output (kW)	WTP	WWTP	Farm Industry Irrigation Building	power generation MWh/yr	Annual CO2 emissions avoided (t)
[87]	Chile	1*	np			✓	168,593	np
[60]	Switzerland	2	380		✓		851	np
			170				460	
[55]	Spain	1	3.6			✓	222	9.1
[88]	Korea	1	8.48		✓		68	39
[89]	Venezuela	1	np				np	np
[61]	Ireland	6*	4			✓	8.7	np
[43]	USA	5	12–820	✓	✓		np	np
[13]	Germany	2*	15	✓		✓	106.5	no
[90]	Ireland	1*	3	✓			16	np
[45]	Ireland	1	90	✓			np	np
[91]	Portugal	1	5.5	✓			np	np
[92]	USA	1*	220	✓			225	np
		1*	200	✓			900	np
	Canada	1	34	✓			np	np
[93]	Kenya	1	0.5		✓		0.003	np

Note: "np" indicates not provided. ✓ indicates true for the criteria. WTP denotes water treatment plant. WWTP denotes wastewater treatment plant.

subjective decisions. Some grey literature sources were included, but only a few major reports from government organisations or universities were used. Some experiments were included but not if there was a high focus on technical details or lacking enough data to be meaningful to this study. Some studies had cryptic titles containing only one or none of the search terms.

3.1. Multi-country and national level studies

Table 3 shows the multi-country studies found. Despite the limited number of comprehensive studies, the potential for SHP for energy recovery in the water industries appears significant on a global scale. It is also notable that of the studies spanning multiple countries only three assessed hydropower for energy recovery in existing systems (WWPTs and WTPs).

The potential for energy recovery in the water industries for 6 countries in the European Union (EU) had a total annual generation between 482 and 822 GWh. Sites with energy recovery potential of less than 2 kW were excluded on the assumption that they weren't economically viable [42]. The potential energy savings in these studies ranged between 1.7 and 13% (depending on the assumptions), with an abundance of potential sites located. All of the studies in Table 3 recognised the significant potential for SHP for energy recovery and one indicated that the potential for SHP may be underestimated [43].

Estimation of annual CO_2 emissions avoided by the installation of the SHP was reported as a challenge, as emissions factors differ for each country. Numerous authors [16,42] assessed the potential impact of SHP in water pipe networks across a large geographical area. They observed the difficulty in obtaining the water network data from water authorities, which is often missing or unavailable. Hence, the full potential impact of this technological intervention on energy consumption and CO_2 emissions in the sector is unknown [42].

Llacer-Iglesias et al. (2021) [17] assessed available case studies in the wastewater treatment sector using energy self-sufficiency and sustainability as a performance criterion in decision-making in addition to cost. Results show that it was possible for a WWTP to be 100% self-sufficient using hydropower.

3.2. National assessments

Analysis of the whole of country studies in Table 3 shows that nine studies have estimated the total potential annual power generation for the sites studied. Similar to the multi-country studies, few existing national SHP sites report on the estimated total CO_2 emissions reduction. Five studies look broadly at SHP across the water industries, farm, irrigation and industry outfalls. None of the studies included buildings outside of those industries. The results show significant potential exists in the sectors examined, and significant existing renewable energy production is occurring across these sectors in many countries.

Strazzabosco et al. (2020) [16] provided a comprehensive assessment of Australian water utilities and found that hydropower was the second highest source of renewable electricity (supplying 5.4% of the sector's electricity demand) with a high potential for growth. An existing water utility was able to fully offset its electricity demand using hydropower. They suggested the study could be used by policy makers to design targeted policies to resolve data gaps and grow renewable energy generation in the sector to meet the renewable energy targets.

Table 6
Case studies for energy recovery using pico-hydropower and small hydro in the water industries.

Author/s	Type of study	Application	Turbine type	Head (m)	Flow (L/s)	Electric Output (kW)
[95]	Experiment	Building	Inline Cross flow	–	0.1	0.015
[96]	Feasibility	Building	Telsa	5	np	np
[97]	Case study	Building	Spherical helical	4	209	0.168
[44]	Review	Buildings	Various	NA	NA	NA
[98]	Review	Building	Various	NA	NA	NA
[7]	Feasibility study	Building	Pelton	15	9.81	0.0015
[27]	Case study	building	Francis	–	0.14	negligible
[28]	Case study	Irrigation	Banki	3	0.5	np
[99]	Case study	Building	PAT	35	2.7	0.11
[100]	Case study	Building	PAT	2–5	20	0.49
[101]	Case study	Building	np	157	499	733
[89]	Case study	Building	np	190	np	1.4
[102]	Case study	Building	Pelton	36	2	0.923
[25]	Experiment	Building	Turgo	1	–	0.322
[24]	Experiment	Building	Pelton	3	10	2
[103]	Case study	Building	Francis, Kaplan	np	np	0.830
[104]	Case study	Building	np	5	1.1	0.1
[105]	Experiment	Various	Inline propeller	7.5	4.43	0.328
[47]	Feasibility study	Building	np	28	np	6
[94]	Case study	Building	Pelton	20	np	1.5
[106]	Simulation	Building	Pelton	15	np	np
[107]	Case study	Building	Pelton	27	np	np

Note: "np" indicates not provided. NA indicates not applicable.

3.3. Individual case studies

Tables 4 and 5 show that of the few individual case studies from actual sites, most come from water treatment plants processing potable water (WTP). Results were highly variable and site specific. Some case studies showed that it was possible to supply the 100% of the energy demands of the site and export the surplus to the electricity grid [49]. Many the case studies used PAT systems as this was deemed an effective option for replacing pressure reduction valves (PRVs) and for cost considerations.

Few case studies estimated the total carbon emissions reductions expected from the system. Gallagher et al. (2015) [63,86] demonstrated studies from the water industry have a strongly positive environmental balance, with a carbon payback times between 0.16 and 0.31 of a year.

Most studies for potential sites were undertaken in potable water treatment plants and water distribution plants (WTP). The studies were very varied in their scope, with some being very comprehensive such as Algieri et al. (2020) [54] which explored individual 114 sites in Italy and showed an annual power generation of 856 MWh.

Studies have investigated SHP potential for cooling systems, desalination plants, the tailraces of power stations and for marine outfall effluents. WWTPs can be high contributors to greenhouse gas emissions but energy recovery has been demonstrated as a viable option to reduce emissions [30]. A review of sites in South Africa for energy recovery (irrigation systems, conduits, urban water services including a desalination plant) identified that minimisation of water leaks and energy efficiencies can help to reduce the cost of living for vulnerable populations [29].

3.4. Targeted review of pico-hydro for energy recovery in buildings

Table 6 shows that consistent with the previous sections, very few real-world case studies were found for pico-hydropower energy recovery in the water industries or buildings. Sarkar et al. (2014) [47] offered a specific review of pico-hydropower energy recovery in buildings, however the scope of this study was very limited, examining a protype for grey water and only theoretical application to other buildings. Most studies related to the potential energy stored in high-rise buildings, and most of these are captured in a review by Boroomandnia et al. (2022) [44]. A variety of turbines were used, indicating that numerous options were possible in a building setting. Although many of the studies were experiments, simulations, or isolated prototypes, most of the authors indicated that there is potential to recover potential energy in buildings.

Most studies did not provide the total annual generation data, however one study found 867 kWh and 600 kg CO_2 avoided annually [94]. Whilst these studies show it is technically feasible to install SHP in a high-rise building, some had concerns that it is cost prohibitive [95].

In summary, key findings from analysis of the literature review are that significant energy recovery is being demonstrated across the range of sectors, enormous potential remains untapped, and most authors report lack of knowledge as a primary factor. Much of the untapped potential exists in engineered water conduits where significant energy is being wasted in dissipated devices such as pressure reducing values and canal drops [81]. The literature review is discussed further in Section 7.

4. Case study for hydro energy recovery in a commercial building

ReefHQ Aquarium is located in the city of Townsville (19.2577° S, 146.8238° E), in the northern part of Australia. The entire useable building space including service and outdoor storage areas, is ca. 5400 m^2. Of this space, 775 m^2 was taken by the two main Aquarium tank systems shown in Fig. 2 (approximately 4 million litres of chilled seawater). In 2020, grid energy consumption was 1118 MWh per annum, solar power generation was 336 kWh per annum, with 270 kW peak demand used on typical equipment found

Fig. 2. 'The Aquarium' and specific site of the filtration system used for the study (circled in red) (photo credit: Queensland Fire and Rescue Service). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

in most commercial buildings. A significant energy user was pumping and filtration systems to support the animal life in the reef aquariums. Seawater filtration systems continuously pump water to maintain optimum water quality for the marine animals and plants used in educational displays to showcase key messages relating to the Great Barrier Reef.

During the life cycle of the building, major refurbishments have been infrequent and represented a rare but important opportunity to find efficiencies and integrate more sustainability and energy efficiency into the building system [108]. In 2020, the building included a 260 kW peak roof-top solar power system feeding directly into the building's electrical distribution network, a 20 kL thermal energy storage tank (6 °C water), a phase change material thermal storage system (20 tonnes of ice), and a 90 kWh electrical battery storage system.

Fig. 2 shows the specific site in the building for the study was a filtration system on a Coral Reef Exhibit, which was identified as requiring refurbishment. Energy is used in the pumping system to deliver seawater through a filtration system which returns by gravity to a source aquarium tank. Since water was returning via gravity to the system, the possibility of recovering surplus energy was identified.

A microgrid is an electrical system that accepts multiple loads, distributed energy sources and energy storage that can be operated in parallel with a centralized grid [109]. Using the definitions described by Martin-Martínez et al. (2016) the Aquarium's electrical architecture will be referred to as 'micro-grid' (as shown in Fig. 3) since at the time of the study, the site included its own network, was controlled by a single entity, and could be operated in island mode if necessary but was normally connected to the grid. The site had its own generation and storage, a single connection point to the grid, with a dynamic control system related to demand and supply. Using the definition used by Martin-Martinez et al. (2016) the Aquarium also utilised a 'pico-grid' connected to the microgrid which carried out load management to flatten the electrical use profile, to minimise electricity costs and to execute orders from the micro-grid as shown in Fig. 3. The micro-grid controlled the building generation, in this case photovoltaic (PV) panels, hydropower, emergency diesel generation, and possible future wind power as well as electrical battery storage and thermal storage (chilled water and ice). The pico-grid used a power management system to carry out peak-shaving, load-shifting and other energy management algorithms. The system was a tailored solution to optimise cost, reliability and continuity of power, energy security and sustainability. The system did not export any power from the 260 kW generation system to electricity grid and generated electricity was all used at the site.

5. Methods

5.1. Overall design and pico-hydro unit selection

The detailed mechanical design of the filtration system was out of scope of this study. However, the choice of pico-hydro unit was constrained by the existing conditions at the site, and thus the overall system configuration relevant to the pico-hydro unit was considered and presented. The methods include identifying key constraints, requirements and parameters directly linked to a proposed pico-hydro unit for the filtration system.

The original filtration system was designed to process seawater from a Coral Reef Exhibit, pass it through a protein skimmer filtration device, which injects ozone gas via a venturi into a chamber to aid the removal of unwanted particles from the system (primarily fish waste and their by-products). A deficiency with the existing system was the absence of a returning chamber to de-gas ozone. Ozone can be harmful to animals in the system and may have been present in the returning water. To address this deficiency, a reservoir was proposed in the new filtration system design and was considered a possible location for a pico-hydro turbine. The shape and configuration of the reservoir was limited by the available space, carrying capacity of the supporting concrete slab, pipe pathways and the seawater pathway to the source tank. Another key requirement was that a suitable turbine must be readily commercially available.

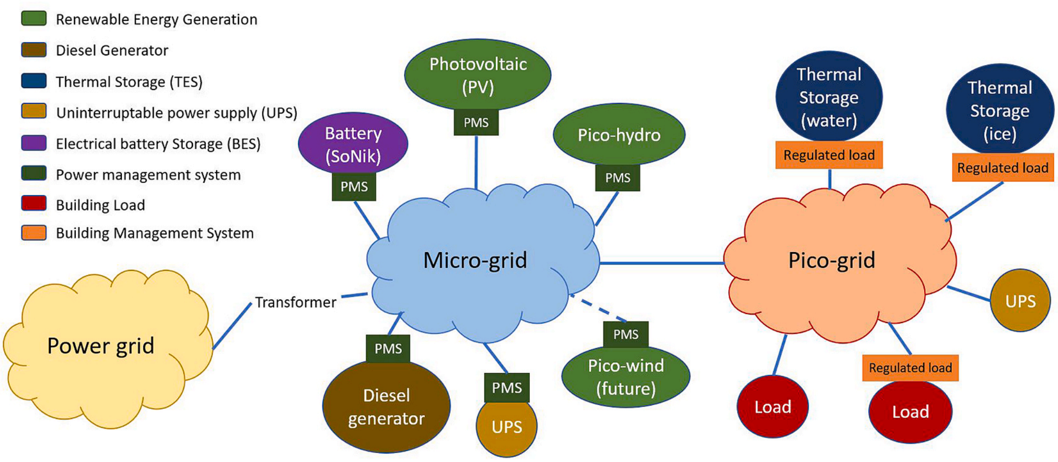


Fig. 3. Electrical and energy control systems at the study site (adapted from [110]).

The methods for the study had four main steps including a literature review, market search, multivariate analysis to find the preferred option and methods to analyse the performance.

5.2. Step 1 – pico-hydropower literature review

Step 1 of the selection process included a targeted literature review as described in Section 3 to identify relevant previous studies and draw upon the results and conclusions to narrow the field of pico-hydropower turbine candidates to a smaller group and guide the design.

5.3. Step 2 – search for a locally availability and suitable generator

Following the selection of suitable generator types based on the literature review, a 'Google Search' was then undertaken to identify potential suppliers of commercially available products (locally available products being preferred) that supplied products for the available head and flow. The literature review also revealed lists of suppliers and manufacturers.

5.4. Step 3 - multivariate analysis

A multivariate analysis based on Williamson et al. (2014) [22] was chosen to identify the most suitable generator to align with site specific conditions, user requirements and energy efficiency (Table 7). Key site-specific requirements and restraints were identified and incorporated into the multivariate analysis. In addition, since the system was a critical animal life support system, for risk mitigation, the design had to include a mechanism to easily de-couple the hydro-generators from the system, without compromising the performance of the system. Easy access and maintenance of the generators with appropriate safety features were also key requirements.

Since the overall system design was based on the relocation of an existing system yet to be designed and installed, some flexibility in the design was possible to allow incorporation of a pico-hydropower generating device. As candidates were identified they were eliminated if location into the new system was not considered feasible due to excessive space requirements or factors negatively affecting system operation.

5.5. Step 4 – design, performance and data analysis

The power available is proportional to the product of head and volume flow rate according to the following energy principles that apply to hydropower turbines in the following equation [111]:

$$P = \eta \, \rho_w \, g \, Q \, h \tag{1}$$

where P is the mechanical power produced at the turbine shaft (watts), η is the efficiency of the turbine (%), ρ_w is the density of water (kg/m3) and in this case seawater (1.02 kg/m^3), g is the acceleration due to gravity ($g = 9.81$ m/s^2), Q is the volume flow rate passing through the turbine (m3/s), and h is the pressure head of water across the turbine (metres).

Raja Singh et al. (2014) [109] give a review and in-depth discussion of the electrical aspects of the pico-hydropower and micro grid arrangements which are not covered in this study.

The power output from the generator was measured using a Fluke Power Quality Meter. The data was compared to the theoretical calculations that were also plotted using Matlab R2022a software.

The concept design was reviewed to assess the feasibility or suitability of the shortlisted available generators. The element that most affected the system design was the location and mounting feasibility, accessibility for maintenance and safety features. Theoretical performance was calculated prior to installation and compared to measured performance. The hydropower system had to be designed to comply with the AS3000 – Electrical Wiring Standard [112].

Table 7
Multivariate analysis criteria (adapted from Ref. [22]).

Quantitative Criteria	Required	Qualitative	Importance
Flow (available)	100 L/s	Maintainability/serviceability	high
Head (available)	2.3 m	Design modularity	med
Output frequency (required)	50 Hz	Availability	high
Physical size (required)	<20 kg	Electrical compatibility	high
Corrosion resistance of materials	seawater	Durability and safety features	high
Temperature	23–28°C	Operational and strategic benefits	med
Grid connectability	Yes/No	Physical location feasibility	high
Power generated	watts	Cost benefit	med
Generator efficiency	%	Recycled content %	med
Other electrical	AS3000*	Life cycle and end of life options	med

*Australia wiring rules [120].

6. Results

6.1. Stage 1 - the pico-hydropower for energy recovery literature review

Considering the objective to use the literature review from Section 3 to aid selection of a suitable pico-hydropower unit for the study site, the case studies found had limited applicability to the chosen site. However, the studies verified that energy recovery using pico-hydropower was feasible if water flow and head were adequate for the type of turbine selected. Data collected from over 100 plants in the UK found that low head pico-hydro was viable for some cases with payback times less than 10 years [52]. Thus, the selection of turbine type was made based on the classification and theory section and the site conditions (head, flow and available space). Based on hydropower theory and classification [18] some turbines would not be suitable for the site, and hence these were ruled out, in the first stage of selection. These included the Pelton, Cross Flow, Francis and Kaplan types, because their operation sits outside the available head and flow at the site. The Archimedes screw type, although it may have been feasible based on available flow and head, was ruled out due to its physical size and configuration being impractical in the filtration system design. The most suitable pico-hydro turbine was deemed to be the propeller type, which would normally be used in a run of river application for rural electrification.

6.2. Step 2 – search for a locally availability and suitable generator

The Google engine search revealed many available hydro turbines from around the world. The Wiki platform Energypedia [113, 114] refers to a list of SHP suppliers. These references indicated that low head generators are widely used, particularly in developing countries. However, only a very small number (two) small hydro turbines that met the core criteria for the site and were found to be available for sale in Australia.

6.3. Stage 3 selection: the multivariate analysis

The multivariate analysis was undertaken using the available information for the two options found. The two options were similar, and Option 1 was chosen, primarily because of the non-corrosive materials used in the design and rated power output. The summary of the multivariate analysis is shown in Table 8.

6.4. Step 4 – design, performance, and data analysis

The selected pico-hydro turbine, the PowerSpout® LH, is a propeller-type turbine designed to be completed submerged in water [115]. Fig. 4 shows the configuration of the system. Fig. 5 shows the drive shaft connects the propeller to an alternator above the water level, which produces electricity, and current is rectified within the unit to DC which then is connected to an inverter [115]. The design of the filtration system was adjusted to suit the installation of the pico-hydropower unit, to maximise the available head, support the generators, protect from the harsh tropical environment, and enable safe operation of the equipment. Fig. 6 shows the physical arrangement of the pico-hydropower turbine in the reservoir and available water height.

Table 8
Multivariate analysis for the pico-hydro unit options.

Quantitative Criteria	Required	Option 1	Option 2
Generator Type	Not specified	Reaction, propeller	Reaction, propeller
Flow (available)	90 L/s	25–55 L/s (each)	35 L/s (each)
Site head (available)	2.3 m	1–5 m	1.5–5 m
Output frequency (required)	50 Hz	50 Hz	50 Hz
Physical size (required)	<20 kg	3300 dia × 1.05 m, 29 kg	No information
Corrosion resistance	Seawater	SS316, plastic housing	Coated steel
Temperature	23 °C–28 °C	Yes	Yes
Grid connectability	Yes	Yes	Yes
Power output	–	Up to 0.400 kW each	up to 0.200 kW each
Turbine efficiency	–	50–60%	no information
Max cable length	–	1000 m	no information
Qualitative			
Maintainability/serviceability	High	High	No information
Design modularity	Yes	Yes	Yes
Availability in Australia	Yes	Yes	Yes
Electrical compatibility	Yes	Yes	Yes
Durability and safety features	Yes	Yes	No information
Recycled content	Yes	Yes	No information
Physical location feasibility	Yes	Feasible	Yes
Available information	Yes	Yes	Yes
Availability of unit/spare parts	Yes	Yes	Yes

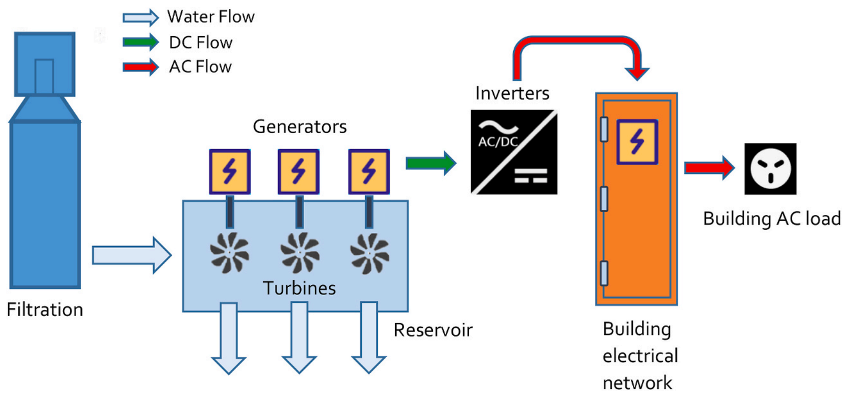


Fig. 4. Design of the installed pico-hydropower PowerSpout LH turbine units in the filtration system and connected to inverters feeding the building electrical network.

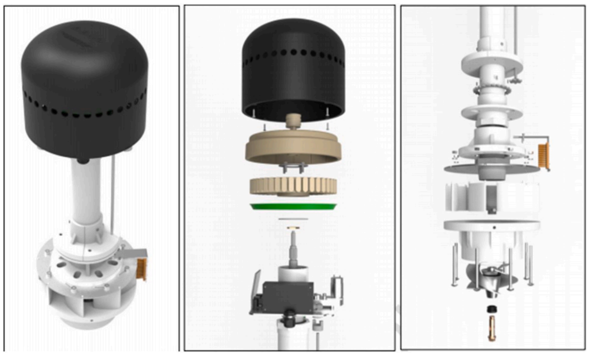


Fig. 5. PowerSpout LH pico-hydropower turbine: pico-hydropower turbine assembly (left), stator and rotor assembly (middle), and shaft and propeller assembly (right). Used with permission from EcoInnovation NZ.

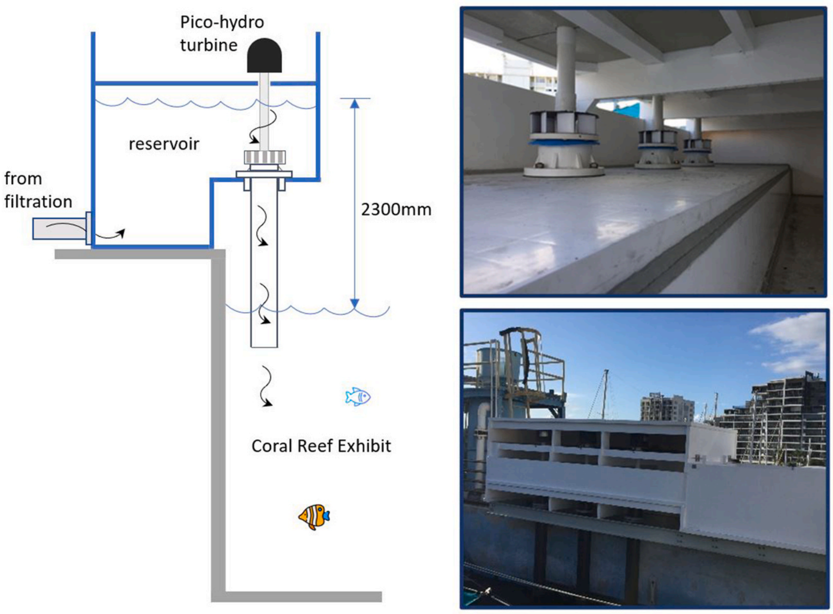


Fig. 6. Schematic configuration of the installed pico-hydro unit (left), pico-hydropower turbines installed into the reservoir (top right) and filtration reservoir with pico-hydropower turbines inside (bottom right). Photos: with permission from Tony White (top right) and Don Booth (bottom right).

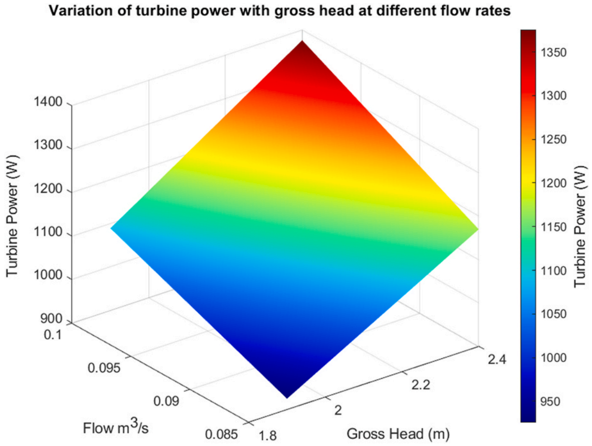


Fig. 7. Variation of turbine power with varying flow and water head, plotted in MATLAB R2022a (Mathworks 2022) [116].

Fig. 7 shows a graph produced with MATLAB® using Equation (1) for flow and water head between 85 L/s–100 L/s and 1.9 m–2.4 m head respectively. The colourmap shows (red representing the highest values) that there is a direct relationship between power output and the available water head and flow, where power output will be the highest when flow and head are highest. The actual head available was 2.3 m with the coral reef exhibit wave machine turned off (no wave) and total flow measured at 90 L/s. Some late pipe design changes resulted in a slightly lower flow than originally anticipated (details shown in Table 8). The calculated performance was determined in consultation with the supplier and later compared with measured results and summarised in Table 8. It was assumed some head loss due to friction in the pipework up to 0.1 m, and total efficiency assumed to be 54%. The PowerSpout LH supplier calculated the power output at 1086 W, the theoretical output using equation (1) and based on the assumptions was calculated at 1070 W. Following installation, the power output was measured to be between 1042 W and 1124 W with fluctuations discussed below.

Table 9 shows that when comparing the calculated output with the actual power output there is a variation between −2.7% and +4.9%. Several factors may have contributed to fluctuation and variation in the power output:

a) The CRE includes a 'wave machine' which causes fluctuating water motion in the main exhibit tank (to simulate natural ocean waves). Fluctuation in water level in the draft tube may have caused the power output to fluctuate.
b) There was a difference in output between the three turbines installed. One of the turbine blades took more 'encouragement' than the others to move smoothly and this improved over time, but the middle turbine (even if the positions were swapped) continued to produce less power.
c) The velocity and turbulence in the reservoir were high, and this may have resulted in differences in the turbulence in each of the turbines.

Particular attention was paid to appropriate safety features for people working around electrical equipment and compliance with the Australian Standard for electrical installations, AS3000 [112]. Protection from saltwater ingress was given special attention and a special lid was designed for the reservoir to prevent water ingress into the generator section of the turbine.

Table 9
Calculated versus measured results for three PowerSpout LH turbines.

Criteria	PowerSpout rated/calculated Totals for 3 PowerSpout units	Measured values
Flow (available)	100 L/s	90 L/s
Head (available)	2.3 m	2.3 m
Draft tube diameter	0.19 m	0.19 m
Power output (total)	1.086 kW (supplier estimate)	1.042 kW–1.124 kW
Turbine efficiency	57%	–
Cable efficiency	97%	–
Max cable length	50 m	50 m
Output voltage	135 V	123–148 V
"No Load" Voltage	312 V	180–243 V
System main pumping power demand	–	10.5 kW max
Qualitative		
Maintainability/serviceability	High	High
Durability and safety features	Complies with AS3000[1]	Complies with AS3000

[1] Australian Standard.

7. Discussion

7.1. Small hydropower energy recovery status and potential

This study provides a unique snapshot of SHP for energy recovery at the global, national and local level, to gain some understanding of trends and gaps in literature. Opportunities exist to reduce energy consumption by the water industries, and in other sectors. Studies have shown that 30–60% of local government expenditure at a city level and in agriculture can be associated with water pumping, and energy prices are likely to increase [46,117]. Energy recovery using SHP turbines may represent an important tool for minimising GHG emissions when making fresh water for future drinking water needs [118]. However, more performance and case studies may be required to give organisations the knowledge and confidence to invest in SHP including pico-hydropower.

This study supports other studies that highlight potential contribution of SHP to renewable energy targets set by governments to reduce climate change [16]. A lack of studies assessing renewable electricity generation in the water industries and other sectors make it difficult to compare the performance of countries. More comprehensive national level assessments are needed, particularly for the existing stock of SHP for energy recovery in the water services, agriculture and other water intensive industries. Numerous authors have highlighted the difficulty in undertaking broad geographic studies, due to a lack of accessible data [16].

Many studies reported SHP for energy recovery as 'low hanging fruit' with significant untapped potential in the water industries and pico-hydropower in buildings. Water supply and distribution networks represent 4% global energy consumption [15], and some facilities can recover close to 100% of their energy consumption using SHP with other renewables [119]. Pico-hydropower has been sometimes overlooked or disregarded based on assumptions it is not economically viable. Recent developments in small scale hydropower may make generators as small as 100 W technical feasible [119] and some cases show payback times less than 10 years [52]. This study shows that assumptions about pico-hydropower may be incorrect and need to be tested more broadly. Larger facilities maybe in a better position to embrace risk that comes with innovation or there may be a lack of knowledge in smaller plants. Using a sustainability index rating system, Mainali and Silveira (2015) [120] found pico-hydropower to be one of the highest sustainability performers. The average levelized cost of energy (LCOE) of SHP has been reported at 0.04 US$/kWh with a payback time of 6 years [4].

SHP installed in pipelines for water conveyancing can provide consistent and predictable energy, require minimal licensing and reduce or eliminate the need for pressure reducing valves (PRVs) [81]. It can have little to no environmental impacts and has been demonstrated to have payback times of less than a year in some cases [81]. Many studies including those detailed in the World Small Hydropower Development Report (2019) [4] demonstrate the benefits of SHP including the installation into existing infrastructure, low cost, ease of maintenance, scalability, low environmental impact and many suitability for low head conditions [4].

There was a surprising lack of reporting on carbon emissions relating to energy generated by SHP cases studies. This information would be useful to understand broader benefits of this renewable technology, where the carbon footprint can be less than 0.1 kg CO_2e/kWh for hydropower compared 0.9 kg $C0_2$e/kWh for coal generated electricity [46].

7.2. Buildings and case study

The operation of buildings represents 28% of total global energy-related CO_2 emissions [29]. Energy efficiency can support decarbonisation of buildings where demand per square metre needs to drop 45% by 2030 to reach the Paris Agreement net zero goal by 2050 [29]. As the world transitions away from non-renewable energy sources, it magnifies the importance of alternative renewable energy to optimise mechanical and electrical services. More case studies that include details on design and performance may give others the knowledge and confidence to explore the use of SHP for energy recovery. This study agrees with others that there are few case studies from buildings beyond the water services (water distribution and wastewater).

This study demonstrates a novel, industry specific solution for SHP energy recovery in a public aquarium building. It helps to address a gap in the literature for SHP for energy recovery case studies in buildings. An aim of this study was to determine the feasibility and viability of hydropower for energy recovery to reduce the grid energy demand for the building. A propeller type, low head pico-hydro turbine was installed into a filtration system in the commercial building and recovered approximately 10% of the energy used for pumping seawater through the system. The continuous power output was 1.04 kW–1.124 kW (excluding any downtime for maintenance) and predicted to annually recover 9846 kWh. This equates to 7.88 tonnes CO_2-e annually, which is approximately 0.9% of the total CO_2-e for the facility from purchased electricity. This is a modest amount of energy, but equivalent to the use of an average Australian household, and an important measure in a suite of measures to reduce energy use of the building overall. Additional energy recovery opportunities were likely to exist in the same building. Taking into account buildings represent 28% of global CO_2 emissions, even modest reductions can represent important steps to support SDG13 where no single technology found to be the panacea [56]. Where some authors have reported limited feasible sites for SHP due to long payback times [52], other studies are pointing to more important drivers for decision making such as sustainability [119,121]. In this case study, the building had already undergone significant cost focused initiatives to reduced energy consumption [108], and cost was not the primary decision criteria. Other benefits, such as emissions reductions and education were also considered. Several authors have pointed out that even in cases where there are marginal economic benefits, significant capability to reduce CO_2 emissions may exist, making it valuable from an environmental perspective [122].

The system was installed in the education facility of the Reef Authority, the government agency that manages the Great Barrier Reef. An important benefit for the system was as an education tool to showcase key messages relating to climate change, energy efficiency and renewable energy and SDGs. When social value and benefits of hydropower are taken into account, others report a return on investment between 2.6 and 5.8 dollar for every dollar invested [123]. Considering only electricity cost, the payback time is estimated 8–10 years for this case. Considering indirect financial and non-financial benefits the payback time is likely to be significantly less. Raising awareness to a broader audience may improve understanding and uptake of the technologies, particularly among water system owners, designers and operators who may be unaware of the opportunity to lower operational costs and carbon emissions.

7.3. Global relevance

Although the building is this case study is highly specialised, there are over 200 public aquariums in at least 38 countries, and significant volumes of water is circulated in the aquarium systems. Other high water-use industries and public facilities such as water parks and swimming pools may also benefit from these findings to help lower the energy consumption and carbon emissions. Thus, the case study is relevant to a variety of applications where water is being pumped through treatment systems or being reticulated and flowing by gravity to another part of the system.

Where there is universal access to electricity and water, a primary driver for energy recovery hydropower is the opportunity to lower operational costs with on-site hydropower generation and these savings can be passed on to consumers [90]. The results of this case study showed that the energy recovery measure had a direct financial payback time of 8–10 years. When comparing to previous emissions reduction initiatives in the same building, the case study by Thyer et al. (2018) [108] reported payback times between 0.3, 2, 2.5 and 3 years for operational changes, energy efficient lighting, cooling related systems changes, and energy efficiency pumps respectively. It is evident from this study that the right mix of energy efficiency or energy recovery systems is very site specific. Future investigations for energy recovery using hydropower could include a marginal abatement cost analysis for each scenario considered to aid decision-making for feasibility and viability. Regulation instruments with specific emission reduction targets for the water industries can help incentivitise energy recovery using hydropower [124]. These actions could provide a valuable mechanism in achieving the desired CO_2 emissions reductions targets in this sector and drive deep energy efficiency actions [125].

Where there is water moving throughout a building, aquaculture, agriculture, water treatment or municipal water facilities such as swimming pools and water parks, there is the possibility of excess energy that could be recovered and re-used. Demonstration sites such as this case study may help to broadly communicate the benefits and challenges.

8. Conclusions

SHP has the potential to further contribute to SDG7 and SDG13 beyond dam and run-of-river systems, but a complete view of the magnitude of the global potential is unknown. This work directly contributes to filling those knowledge gaps and adds a new perspective by discussing the novel demonstration of pico-hydropower in an education facility.

It is concluded from the literature review on SHP for energy recovery there is no global view and only a small number of national or multi-national assessments for the water industries. A global focus is needed to create greater investment in the technologies and their implementation. Consolidating and addressing gaps in knowledge may act as catalyst for improvements and provide tools for policy makers and facility operators.

A lack of knowledge is a primary obstacle to the uptake of SHP and perhaps current knowledge is not reaching those who can drive change. Publicly available demonstration systems and technical information may help reach the target audience. SHP hydropower for energy recovery has many benefits and it can also reduce operating costs which can be passed on to consumers to reduce basic cost of living, and reduced demand for grid power.

This case study is novel, and it adds to the small collection of real-world studies for energy recovery in buildings. Key findings were that a propeller pico-hydropower turbine could be used in a commercial aquarium filtration system to recover energy used for pumping water through the system. At 2.3 m head and 90 L/s flow, up to 1.124 kW power output was achieved. This represented approximately 10% of the energy used for pumping water through the system and 0.9% of the building grid electricity use. The power was fed back to the building's electricity network. The project was economically viable with financial and non-financial benefits for the life cycle of the product. Future work could involve adjustments and more detailed investigations on performance.

A publicly available demonstration of hydropower for energy recovery can shine a light on opportunities to find value from waste using a novel application in a building and the water industry. This education tool may lift the profile of SHP for energy recovery to a wider target audience including students, engineers, technologists, facility operators and policy makers to promote advances in clean renewable energy technologies that support SDG7 and SDG13. Increasing the research, attention and uptake of pico-hydropower may lead to improvements in technologies that could increase access to simple, clean, and affordable energy in vulnerable communities.

Declarations

The Great Barrier Reef Marine Park Authority funded the pico-hydropower installation. The case study did not receive any specific funding. The authors have no competing interests to declare that are relevant to the content of this article.

Author contribution statement

Sascha Thyer: conceived and designed the experiment; performed the experiments; analysed and interpreted the data; contributed materials, analysis tools and data; wrote the paper.

Tony White: conceived and designed the experiment; performed the experiments; contributed materials, analysis tools and data;

wrote the paper.

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The corresponding author, Sascha Thyer is Director – Business Operations (Sustainability, Property) at the Great Barrier Reef Marine Park Authority. The installation of the case study system described in this paper was funded by the Great Barrier Reef Marine Park Authority. The case study did not receive any specific funding.

Tony White is a senior electrical engineer for Stowe Australia Pty Ltd, who was engaged by the Great Barrier Reef Marine Park Authority to undertake the electrical design and installation of the paper subject (a pico-hydro generator).

Data availability statement

Data included in article/supplementary material/referenced in article.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Abbreviations

GBR	Great Barrier Reef
PAT	Pump-as -Turbine
PHP	Pico-hydropower
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
HP	Hydropower
SDGs	Sustainable Development Goals
SGD6	Sustainable Development Goal 6, Clean Water and Sanitation
SDG7	Sustainable Development Goal 7, Clean Affordable Renewable Energy
SDG13	Sustainable Development Goal 13, Climate Action
SHP	Small Hydropower
WTP	Water treatment plant (potable water)
WWTP	Wastewater treatment plant

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