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Research Article

Integrating algae building technology in the built environment: A cost and benefit perspective

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Abstract Energy consumption rates have been rising globally at an escalating pace since the last three decades. The exploration of new renewable and clean sources of energy globally is thus gaining prime importance. In Australia, coal is still the primary source of energy, which, during the process of energy production, generates greenhouse gases, subsequently resulting in environmental degradation. Within this context, the paper compares the economic and environmental benefits of utilizing two renewable energy production sources: algae building technology (ABT) and solar PV panels. A case study site for retrofitting a specified area on the front façade of a multi-storied building at the University of Technology Sydney, City Campus, Australia was thus chosen for the study. A cost and benefit analysis model using the following performance indicators; return on investment, payback period as well as net present value of the two systems, was thus initiated. Annual revenue generation of both systems which included tangible and intangible benefits of both systems were simultaneously calculated. The investment and operation and maintenance costs of both systems were calculated based on market research as well as quantitative data adapted from our literature review. Our conclusions show that closed tubular photobioreactor systems have more benefit than solar panel system from an environmental impact perspective considering Australia's current struggle with water scarcity, drought, air pollution and carbon emission reduction goals.

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1. Introduction

1.1. Microalgae: an overview

Algae are a diverse group of aquatic organisms that range from single microscopic cells to macroscopic and multicellular organisms which can either live in colonies or in the form of large span ocean growing ecologies with a leafy appearance. More importantly, they are able to produce oxygen via photosynthesis though they differ from plants (in terms of lacking roots, stems, leaves and vascular systems for nutrient circulation). The size variations in algae species is thus truly astounding, with fronds of Giant Kelp (Sea weeds) growing as large as 60 m in length while Picoplankton growing to a maximum size of 0.2—2 μm in diameter. Different species of algae can thrive in freshwater or saltwater and depending on the species, are able to endure a range of temperature, O_2 and CO_2 concentration, acidity and turbidity. In the case of this research, we focus on 'microalgae': microscopic, unicellular species of algae which can be found in freshwater and marine streams and can live in both water column and sediment. Microalgae incorporate both cyanobacteria, commonly known as blue-green algae as well as green, dark colored and red algae. There are multiple assortments of microalgae which can be categorized in seven major types (Bailey, 2019). Some of these species such as Euglenophyta (Euglenoids), Cryophyte (Golden-brown algae and Diatoms), Pyrrophyta (Fire algae), Chlorophyta (Green algae), Rhodophyta (Red algae), Paeophyta (Brown algae), Xanthophyte (Yellow-green algae) can be nurtured utilizing various forms of water assets. For instance, harsh water, ocean water, and residual water, which are unacceptable for developing horticultural products can easily be used for growing algae. Besides this, algae play an essential job in numerous biological communities, including establishment of amphibian evolved ways of life, supporting all fisheries in the seas and inland, and also deliver around 70 percent of the air we breathe (Hall, 2011).

Microalgae cultivation involves utilizing daylight, carbon dioxide, and organic carbon simultaneously as a source of energy in order to produce Biomass. Besides this, they can produce 3000—15,000 gallons of oil/acre/year (Goldenberg, 2010). According to the U.S. Department of Energy (2010), this oil production rate exceeds production rates achieved using soyabeans (by 60 times), Jatropha (by 15 times) and oil palm (by 5 times). Furthermore, with 18.5—35 MJ/kg of energy content, algae easily outperform coal (24 MJ/kg), the energy density of wood, wastewater sludge, and agricultural by-product (IME, 2009). These factors not only profess considering microalgae as a promising source of biofuel based sustainable energy production source but have also resulted in focusing attention on nature and the potential of harvesting natural modes clean energy production. This is particularly important in today's context wherein fossil fuels are depleting at a fast pace and a global impetus on generating energy out of renewable and inexhaustible energy sources. Besides this, the potential hazards of using fossil fuels as our main energy source in the form of greenhouse gas emissions, food safety and urban heat island has been well documented (Brennan and Owende, 2012). However, gauging the advantages of harnessing microalgae only from the perspective of production of biofuels does not do justice to the bigger environmental benefits it brings about such as the interrelationship between energy transformation and ecological recycling (Hall, 2011). This recycling in the form of sequestration of carbon dioxide, wastewater treatment and the production of oxygen, have multiple environmental as well as health and wellbeing benefits.

1.1.1. Microalgae cultivation conditions

Microalgae cultivation conditions are usually categorized in four major types: Photoautotrophic, Heterotrophic, Mixotrophic and Photoheterotrophic. Photoautotrophic cultivation relies on photosynthetically active radiation (using sunlight and LED based artificial lights (Saha et al., 2013; Wang et al., 2007), and inorganic carbon in the form of CO_2 from the air as the carbon source). It is preferred to have the CO_2 source nearer to the cultivation facility while using this cultivation method in order to reduce costs and recycle CO_2 in an optimal manner. The Heterotrophic method is usually used for cultivating microalgae which lack photosynthetic mechanisms (Minhas et al., 2016). This method predominantly requires organic carbon (preferably Glucose) as the primary energy and the carbon source to produce neutral lipids. Fermentation method wherein microalgae are grown in the dark using LED lighting as the light source primarily use the Heterotrophic mode of cultivation. Avoidance of natural light is thus considered a big advantage in this mode of cultivation (Huang et al., 2007). Mixotrophic process of cultivation on the other hand is used for certain microalgae which can use both organic carbon compounds and inorganic carbon (carbon dioxide), as a source of energy for their growth. Photoheterotrophic cultivation involves the usage of light as the primary source of energy and organic carbon compounds as the carbon source. Water used for algae production can also be of low quality, including industrial waste water, the effluent of biological water treatment or other wastewater streams. The optimized growth of algae besides dependent on using cultivation methods best suited for different strains of algae is also dependent on the following interrelated factors:

- Light - Light is required for photosynthesis and thus the amount of exposure to light is a major contributing factor to the growth rate of Algae. Most algae species require indirect, middle intensity light levels (1000—10,000 lux) as direct sunlight can result in lower efficiencies, photo-bleaching and photo-inhibition (Schenk et al., 2008).
- Temperature - An ideal temperature range (depending on the algae strain) is required for algae to bloom, with typical temperature range for algae production being 16 to 27-degree Celsius.
- Medium/Nutrients - Level of salinity, carbon dioxide, ammonia, phosphate and oxygen content present in the water also directly affect the cultivation of Algae.
- pH - pH level ranging between 7 and 9 is considered as ideal for the sustained growth of Algae.

- Algae Type - Different types of algae have distinctive growth rate, for example heterotrophic microalgae are larger in size and have a faster growth rate. Selecting the species of algae in relation to all other variables is thus vital.
- Air circulation - Algae need appropriate contact with air, in order to harvest CO_2 from the atmosphere.
- Blending — Mixing of algae in reactors or ponds avoids sedimentation of green growth and ensures all cells are similarly exposed to light.
- Photoperiod: As with all plants, microalgae photosynthesize. Light intensity, spectral quality and photoperiod plays an important role, but the requirements vary greatly with the culture depth and the density of the algal culture: at higher depths and cell concentrations the light intensity must be increased to penetrate through the culture

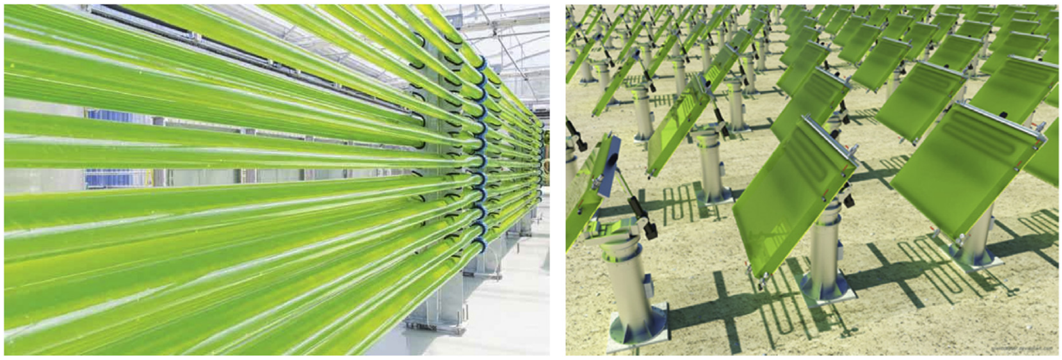
Microalgae grow rapidly given appropriate conditions, with some strains having the capacity to double in mass within a day and have the potential to generate a volume of biomass and biofuel many times higher than that of our most productive crops. This high rate of growth directly results in quicker harvesting cycles, thus ensuring a constant supply rate for batch wise harvesting purposes (Schenk et al., 2008). Microalgae cultivation is also beneficial from the perspective of reusing abandoned natural resources such as land, that in many cases, is deemed unsuitable for agriculture, as well as water sources that are not feasible for other crops, such as the sea, brackish and wastewater. Microalgae can also be produced to have a high protein and oil content and can be used to produce biofuels and animal feeds. Moreover, microalgal biomass, which is rich in nutrients, can also be used for dietary supplements to advance human health. Macroalgae (seaweeds) are cultivated in the ocean, or even on land with salty water, and their lipids can be converted into biofuels and chemicals. Algae grow in nutrient-rich waters like municipal sewage, animal wastes and some industrial waste, and at the same time, it purifies these waste streams. Even the residue of biomass after oil extraction can be used as fuel. The residue of algal biomass can be converted to "pellet" and can be used as a fuel that can be burned to generate power or electricity, besides being used to produce bioplastics, chemical feedstocks, lubricants, fertilizers, and cosmetics. Algae in small concentrations can be used to "scrub" gas emissions from power plants, absorbing as much as 85% of CO_2 content ((Phys.Org, 2010), Gundula, 2013).

1.1.2. Microalgae cultivation methods

A variety of microalgae cultivation methods such as the Open Pond method (Schenk et al., 2008; Pulz, 2001), The Fermentation method (Saha and Murray, 2018; Minhas et al., 2016), Hybrid method (Idaho Sustainable Energy LLC, 2013) and the Closed Photobioreactor method (Schott, 2015) have been in operation globally. However, for the case of this research, a method best suited for retrofitting existing buildings within dense urban contexts was a prime criteria. The Open Pond method, with its inherent requirement of open tract of land, the need for constant supervision to identify and prevent contamination resulting in growth of unwanted species, reduced sunlight utilization by cells, diffusion of carbon dioxide, evaporative losses as they are open to the atmosphere etc. does not qualify for the purpose of this study. The Fermentation method, though utilizes a relatively low cost PBR which is ideally suited for seed culture generation and biomass production at a more manageable scale, requires a laboratory condition and a heavy vessel reactor which is not possible to be hosted within conventional buildings at all times besides being profitable via aiming at efficiency of scale. The Hybrid method is deemed best for cultivating algae in the commercial sector at large scales and is thus impractical for situating within the already dense urban settings of contemporary cities.

Closed Photobioreactor (PBRs) method was made to mitigate the ill effects of other methods of cultivations such as tainting, uncontrollable environmental conditions, constrained species appropriateness, low volumetric profitability and utilization of large land zones. In this method of cultivation, algae are typically grown in glass tubes through which water is continuously pumped. This allows for optimal mixing of the algae, which is necessary to prevent settling of the algae cells and to support even distribution of CO_2 and O_2. This cultivation method can be initiated inside a building or in open air using both artificial light and daylight. More microalgae species can be developed in photobioreactors than in an open pond framework because of their ability to retain warmth. Since the temperature is better controlled in this system, microalgae can be grown for extended periods in a controlled atmosphere. However, overheating can rapidly happen in photobioreactors during mid-day, with severe blending and pumping of air and water required to cool the photobioreactor to a temperature in which the microalgae cultivation is most effective. This method also differs from an open pond method since algae cultivation in this case is conducted in enclosed transparent vessel, which, apart from tubular reactors (Schott, 2015), can range from plate reactors (Fig. 1a and b) and bubble column reactors (Pulz, 2001; Weissman et al., 1988), which can be oriented horizontally or vertically (closed vertical growth systems). In some cases, additional artificial LED lighting is used to boost production. Moreover, in order to increase the efficiency of the photobioreactor, their design needs to distribute light over a large surface area in order to cater for light dilution. The surface area of such bio-reactors is thus much larger than the footprint they occupy. A newer development in the design of the photobioreactor system is the 3D Matrix Algae Growth Engineering Scale Unit Reactor (Fig. 2), which is triangular in form, and combines the principles of a bubble column with in-built static mixers. Its productivity rate of 98 g dry weight m^{-2} day^{-1} over a period of 19 days even when under sub-optimal lighting conditions (Schenk et al., 2008), makes it one of the most efficient cultivation systems till date (Pulz, 2007).

Even though PBR installations cost significantly more than open pond systems, they can produce 5 to 10 times higher yields per aerial footprint (Barbosa et al., 2003), thus compensating for the initial costs of investment (Chisti, 2007). The cultivation process results in no waste production and uses a small culture volume and less energy for mixing (Schenk et al., 2008). Owing to its closed and



(a) (b)

Fig. 1 (a) Tubular PBR system. (b) Plate Photobioreactor (Image source: Schott, 2015).

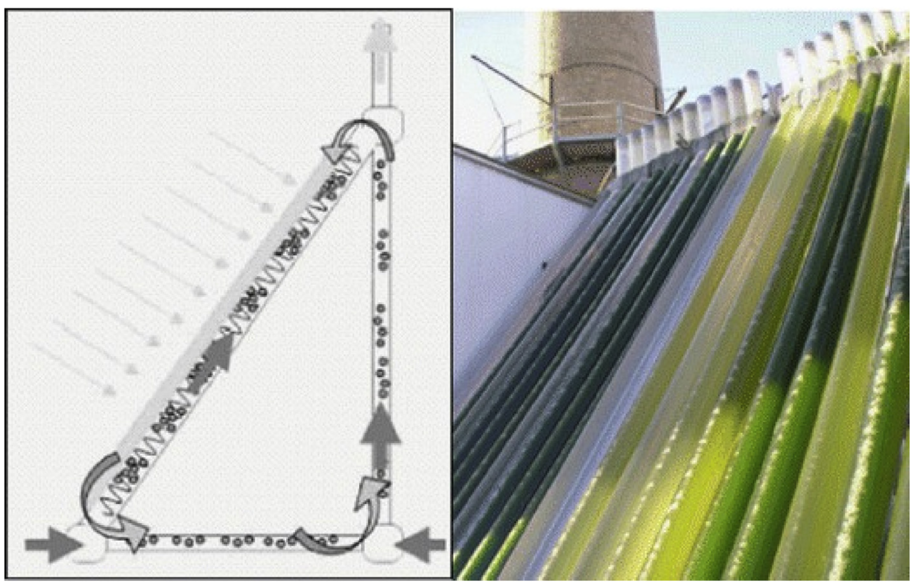


Fig. 2 GreenFuel's 3D Matrix Algae Growth Engineering Scale Unit: "triangle airlift reactor". Left: Patented Drawing (patent US 20050260553), Right: Demonstration plant at the Red Hawk Power Plant, Arizona, USA (Schenk et al., 2008).

controlled nature of cultivation, all types of pollutants and resulting contamination is avoided during the growth process while it is efficient in processing/ingestion of a high amount of CO_2. Its high yield rate per aerial footprint, possibility of installing the system on roof tops as well as vertical facades, no waste production, ability to avoid external pollutants owing to its closed and controlled nature of cultivation and its efficient CO_2 processing make it ideal for the urban built environment. Apart from this, the possibility of operating them horizontally as well as vertically and outdoors as well as indoors is further beneficial for adapting to various conditions in the Built Environment. The only negative which accompany these benefits is the cost associated with the system itself in the form of high-power consumption and the use of artificial light sources if needed. LED lighting, submersible lights for increasing lighting efficiency, light guides etc. can be used in combination with partial exposure to sunlight in order to enhance the performance of this method, hence reducing the associated costs with this method of cultivation.

The BIQ house, in Hamburg, Germany (Fig. 3), serves as an actual built case study which incorporates 200 m^2 of closed photobioreactors in 120 façade-mounted boards creating algal biomass and heat as a renewable energy asset in this low-energy multifamily private building.

The algae façade framework resulted in the creation of thermally controlled microclimate around the building (Miceli, 2013), resulted in noise reduction as well as provided dynamic shading. Microalgae in the Facades were developed in level board glass bioreactors, of 2,500 mm $\times$ 700 mm x 90 mm. The algal biomass and solar thermal heat energy created by the façade (Cervera Sardá and Vicente, 2016) is transported using a closed loop framework to the energy administration center situated in the basement. Here, the biomass is separated through a floatation method, while the heat gets isolated from the algae generated water using a heat exchanger. It is to be noted that the energy generated from BIQ Hamburg building was much lower than that of customary solar panel-based systems. The heat produced by the panels has 38%

(a) (b)

Fig. 3 (a) BIQ House, Hamburg and (b) the PBR panel used as the facade component Source: NordNordWest, Lizenz: Creative Commons by-sa-3.0 [CC BY-SA 3.0].

efficiency compared to 60%—65% in a conventional solar thermal source and the biomass has a 10% of efficiency compared to 12%—15% with a conventional PV (Build Up, 2015).

1.2. Solar panel technology and its environmental benefits

Solar energy is obtained from the sun's radiation. The energy Sun provides to the Earth in one hour could satisfy the global energy needs for one year (Harrington, 2015). According to the US Department of Energy, 430 quintillion Joules of energy per hour hits the earth from the sun. As compared to this, humans globally use 410 quintillion Joules of energy. However, we can harness only 0.001 percent of this energy provided by the sun. Currently, we use Solar energy harvested by solar panels in various ways, for instance to heat water, to provide AC power for powering devices. Converted solar energy can also be stored in large batteries used in off-the-grid solar systems, which can be charged during the day so that the energy stored in the batteries can be used effectively at night. However, 3—5% of this harvested energy is lost during transportation and distribution, depending upon the distance between the production site and the supply location. This tends to impact the efficiency of solar panel installations in locations such as an area with high population density. It is thus preferable to install solar panels on the roof or in the yard of properties to significantly reduce this distance, thereby increasing the efficiency of the installed system.

Solar Energy generation is completely based on exposure of the solar panels to sunlight, an infinite, renewable source of energy. Apart from this, as compared to other forms of energy production (coal, oil, gas), solar panel-based energy production is relatively safer and cleaner. Solar PV panel also occupy considerable space to be installed, often covering roofs and vertical facades of buildings. This, at times is not feasible owing to aesthetic and design-based limitations on building surfaces and often hampers the installation of the optimal number of solar panels for generating the amount of energy corresponding to the electricity consumption rates of the building. Apart from this, the manufacturing of photovoltaic cells includes some hazardous and toxic material, and this can indirectly affect the environment. Installation and transportation of solar panel system and its parts are also connected with the emission of greenhouse gases. However, as compared to other sources of energy, pollution generated by solar panels is far less. Furthermore, solar energy systems have relatively lesser maintenance costs as they involve no moving parts, maintenance usually involves cleaning the solar panels once or twice a year and replacing inverters between 5 and 10 years.

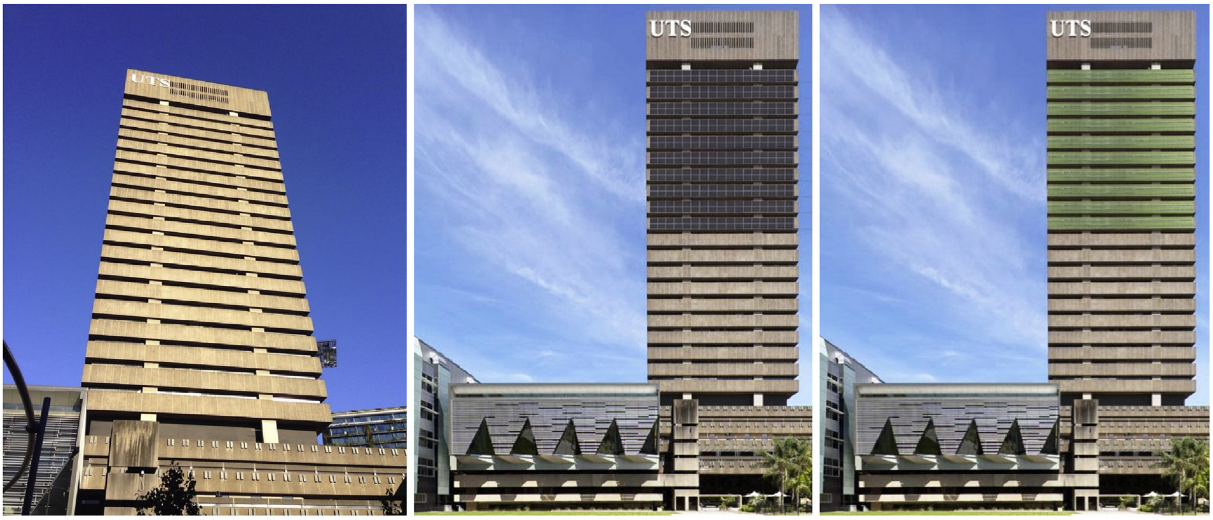
1.3. Research objective

Within this context of renewable energy technologies, the empirical study presented in this paper aims at deciphering environmental and economic benefits of deploying closed tubular photobioreactor systems over solar panels. The comparison goes beyond identifying benefits in terms of pure monetary gains and net present value calculations, but also assess the nested environmental benefits including the interrelationship between energy transformation and ecological recycling.

2. Methods and material

2.1. Site selection

In order to conduct a cost and benefit analysis for comparing the tangible and intangible benefits of both, Solar Panel system and PBR system, a case study building within the University of Technology Sydney: UTS Building 1: Tower Building was chosen. The building exhibits a Brutalist style of Architecture (Fig. 4) and serves as a landmark on Broadway, Sydney, Australia, one of the prominent roads in the center of Sydney. A vertical footprint of 1500 sqm



(a) (b) (c)

Fig. 4 (a) UTS Tower Building, (b) Impression of the vertical area (150 sqm) selected for the deployment of solar panels and closed PBR's, (c) Impression of the vertical area (150 sqm) selected for the deployment of closed PBR system (Image Source: Author).

spanning 10 floors of the UTS Tower Building (Fig. 4b and c) with optimal exposure to solar radiation (insolation) throughout the day (Fig. 5) was decided upon as an area to be considered for the simulated deployment of both systems (with each floor comprising of a width of 30 m and a height of 5 m).

2.2. Cost and benefit calculations

A systematic cost and benefits study covering the following fixed and variable cost aspects for both solar panel systems and the closed PBR system to be deployed on a 150 sqm vertical surface area of the chosen building within the context of Sydney, Australia were considered:

Fixed Costs:

- Cost of procurement (material costs and installation costs)
- Microinverter costs (for solar panels)
- Anaerobic digestor cost (for closed PBR system)

Variable costs per annum:

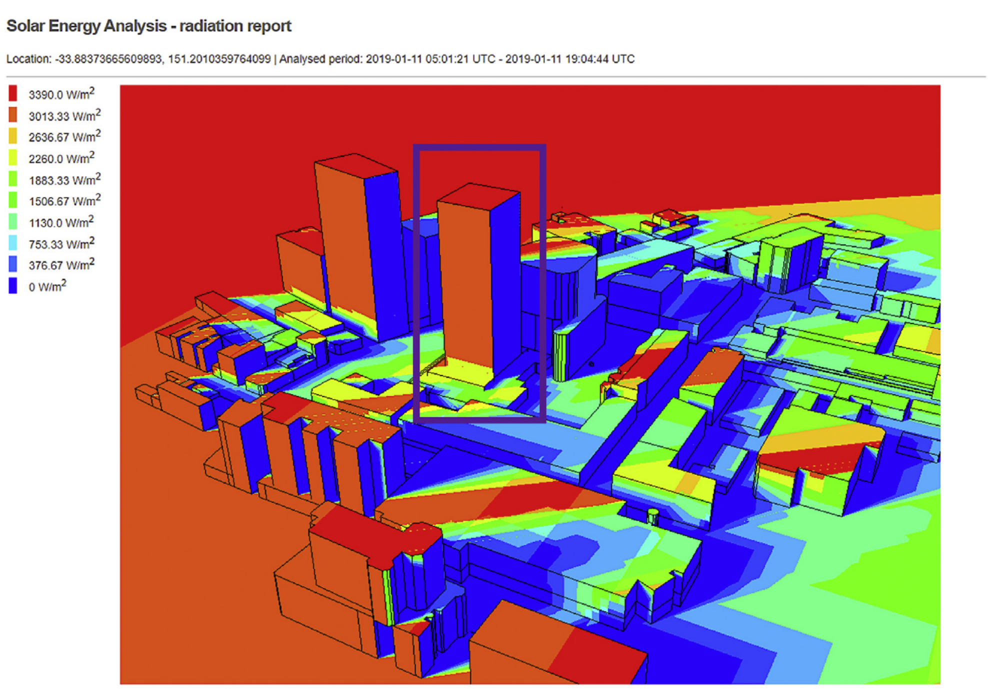


Fig. 5 Solar Insolation analysis on a typical summer day for the chosen building facade showcasing an average solar radiation value of 3013.33 W per sqm (Image Source: Author).

- Electricity costs
- Operation and maintenance cost
- Cleaning costs (for solar panels)
- Insurance costs
- Labor costs (for PBR systems considering the hourly rates for technicians in Australia)

This phase is followed by the calculation of revenue generation and the identification of benefits for both systems. To calculate the revenue generation potential of the solar panel system we use a payback estimator calculator developed by one of the reputed solar energy providers based in Sydney: Solar Choice. The revenue generation of the closed PBR system is subsequently calculated based on its energy generation, carbon sequestration and water recycling potential for the chosen case study. Data pertaining to energy generation potential of the PBR system as well as its carbon sequestering potential is extrapolated via literature review (De Vree et al., 2015; Norsker et al., 2011). Water recycling potential for the closed PBR system by firstly mapping the overall water consumption rate as well as usage distribution (toilets, food outlets, cooling towers, gardening, mechanical plants, labs and others) of the chosen building using the UTS facility management's energy monitoring tool. The Anaerobic digestor's capacity and ability to purify water is ultimately interfaced with the acquired consumption rates. For the case of this research, we specifically cater to the consumption of water for toilets and gardening purposes.

After calculating the annual savings and identifying that this amount is only based on fixed costs, we stipulated that the interest rate paid on fixed costs and associated variable costs will play a major role in calculating the return on investment. The Net Present Value (NPV) and Return on Investment (ROI) is thus subsequently calculated using the following formula:

$$NPV = \sum_{t=1}^{T} \frac{B-C}{(1+i)^t} - C_o$$

This formula also considers both variable costs and interest costs. *NPV* is calculated by subtracting cash flows (Benefit and Cost) for a period (t) within the holding period (T), discounted at an expected rate of return on the cash flow (i, interest rate) while C_o is considered as the investment cost. ROI is calculated using the following formula: *(Gain from Investment − Cost of Investment) Cost of Investment*. A Fixed interest rate of 4% per annum has been considered for both solar panel and closed PBR systems.

Note: Currency conversion rates applicable on the 14th November 2019 have been used in the article in order to reflect corresponding USD value.

3. Analysis and results

3.1. Solar panel system design for the case study

The basic cost of procuring a solar system involves paying for solar panels, batteries, inverters, associated wiring, and installation. The price of a solar panel system depends on the size of the installation and the number of Kilowatts (kW) of energy required to be generated from it.

The costs presented in this paper are based on the current Installation, Micro-inverter, Operation and Maintenance and Cleaning costs in New South Wales (NSW), Australia:

- Installation cost: The cost in NSW in 2019 for a PV system is heavily subsidized by the Australian government-run solar rebate scheme. The costs for a typical 3 kW system, including installation can be broken down as follows:
  - The basic cost for a 3 kW solar system: AUD 5950 (USD 4044.48)
  - Government Rebate: AUD 1950 (USD 1325.50)
  - Cost for 3 kW of solar power after rebate: AUD 4000 (USD 2718.98)
  - In our case, we have a 1500 sqm area to be fitted with solar panels. The standard size of each solar panel is 1.6 m × 1.0 m. Typically a 10 kW solar system will consist of 31–40 such panels and will require 60 sqm area. In the available 1500 sqm, we can typically install 1000 solar panels, capable of producing 250 KkW.
  - Total cost for solar panels, wiring, batteries and installation would thus be approximately AUD 250,000 (USD 169,936.25)
- Micro-inverter Costs: micro-inverters allow for the energy produced by the solar system to be directly harvested as alternating current instead of direct current. Using micro-inverters over singular large inverters is also beneficial because it reduces the probability of short circuits and fire since it distributes the total amount of DC energy produced into smaller and more manageable units. However, using high quality micro-inverter systems adds 20% to the aforementioned price range. Considering the safety component within our Institutional Building case study, we shall nevertheless deploy the Micro-inverters with an additional cost of AUD 50,000 (USD 33,987.25)
- Operational and Maintenance Cost: The economic viability of a solar panel system, not only depends on the procurement and installation costs but also the operational costs during a time period of 20–25 years. The operating costs are typically between 1 and 1.5 percent of the procurement cost of the solar panel system on an annual basis. The maintenance cost for the solar system is integrated in the above-mentioned 1.5 percent operational costs. The average costs for such contracts in Sydney are AUD 200 (USD 135.95) annually. The operational and maintenance cost per annum for our case study is calculated as AUD 2000 (USD 1359.49)
- Solar Panel Cleaning costs: Solar panels produce energy based on the amount of exposure to solar radiation. Leaves, flower pollen, dust and other debris, can cause dirt to accumulate on solar PV modules. This reduces the exposed area of the panels, thus reducing the energy generation capacity of the panels. In Sydney, most of the solar specialist company cleaning charges range from AUD 5 to 6 per solar module. Our case study comprises of 1000 solar panels with an estimated cleaning cost of AUD 5000 (USD 3398.73) per cleaning session. In our case,

considering the inward facing character of the facade chosen for the application of the panels, we estimate one cleaning session would be required every 4 years with an annual cost of AUD 1250 (USD 849.68) per annum.

Total Fixed and Variable costs are shown in Table 1.

3.2. Revenue and benefits

Besides the energy generation potential of solar panel systems, the most crucial aspect to consider is that solar energy is a fully renewable and a perennial energy source. Electricity can be generated using the solar panels, and this energy eventually result in saving on energy bills as well as help in feeding the grid resulting in the development of innovative participatory business models. Furthermore, technology in the solar power industry is continually advancing with Innovations in nanotechnology and quantum physics (Asano et al., 2016; Chandler, 2015) which can probably increase the efficiency of solar panels and double, or even triple, the electrical output of new solar power systems.

In New South Wales, currently, there is no government-backed solar feed-in tariff in place. Thus, a solar power system can provide direct savings on electricity bills to its owner by reducing the power consumption from external electricity suppliers. Moreover, if the generation of energy is higher than that which is required, additional credits can be earned by selling the extra generated energy into the grid. The rate offered for this energy trading depends on the local energy retailer. Hence, investing in a solar power system would be particularly beneficial for buildings which consume energy in bulk during daylight hours. However, it is also deemed economical for buildings which can consume at least 30% of the energy that the solar system generates.

In our case, we use a payback estimator calculator developed by one of the reputed solar companies based in Sydney: Solar Choice (Fig. 6). The table shows the return on investment plan of the proposed solar system; however, it is to be noted that this calculator only considers fixed cost of the solar system, thus providing us with an annual savings figure of AUD 29,939 (USD 20,350.89) for the 250-kW system.

Table 1 Fixed and Variable cost calculation for a Solar Panel System for the chosen case study.

Solar Panel (Material + Installation costs)	AUD 200,000
Microinverter costs	AUD 50,000
Total fixed cost	**AUD 250,000** (USD 169,936.25)
Electricity per annum	AUD 2500
Operational Cost + Maintenance Cost (per annum)	AUD 2000
Solar Panel Cleaning per annum	AUD 1250
Insurance per annum	AUD 2500
Total variable cost per annum	**AUD 8250** (USD 5607.90)

After calculating the annual savings and identifying that this amount is only based on fixed costs, we stipulated that the interest rate paid on fixed costs and associated variable costs will play a major role in calculating the return on investment. The Net Present Value (NPV) and Return on Investment (ROI) is thus subsequently calculated using the following formula:

$$NPV = \sum_{t=1}^{T} \frac{B-C}{(1+i)^t} - C_o$$

This formula also considers both variable costs and interest costs. *NPV* is calculated by subtracting cash flows (Benefit and Cost) for a period (t) within the holding period (T), discounted at an expected rate of return on the cash flow (i, interest rate) while C_o is considered as the investment cost. ROI is calculated using the following formula: *(Gain from Investment − Cost of Investment) Cost of Investment*. We consider the following fixed and variable costs which were calculated for the solar systems installation, maintenance with a fixed interest rate of 4% (Table 2):

These costs are used for the calculation of ROI and NPV in the table below (Table 3). The total duration to attain return on investment for a 250 KW solar system for the chosen case study is thus calculated as 16 years (Table 3 and Fig. 7).

3.3. Photobioreactor design for the case study

For the closed PBR system, we divided the same 150 sqm area on the vertical surface of the tower into 5 equal parts of 300 sqm area. This way every unit has two floors of vertical surface area (150 sqm x 2) containing photobioreactor tubes, with a reactor system for regulating flow of water and oxygen installed in between two floors. Fig. 8 refers to a photobioreactor system architecture for the available elevation area developed in a previous research at UTS (Bender, 2017). Tubes of 0.1 m diameter, with a vertical distance between the tubes of 0.05 m is opted for. Each reactor consists of 10 similar loops, and a maximum tube length of 80 m (with each tube being 8 m). The total height of the system is 5 m and it will be placed 0.5 m away from the wall to prevent adverse effects of rainfall on the tubes. No overlapping is proposed since it can decrease the productivity level due to the decrease in light intensity on the surface area of the tubes.

The biomass produced by the system will be transferred to an underground anaerobic digester to produce biofuel. Wastewater of the case study building will also be transferred to this digester for purification purposes.

3.4. Cost estimation for the proposed closed PBR system

The costs are broken down into Capital costs, Anaerobic Digester costs, Operational and Maintenance costs and insurance costs:

Capital Cost: The main assumptions of the capital cost estimation are determined using literature review: De Vree et al., 2015 have tested the photosynthetic efficiency of Nannochloropsis sp. algae species by cultivating four

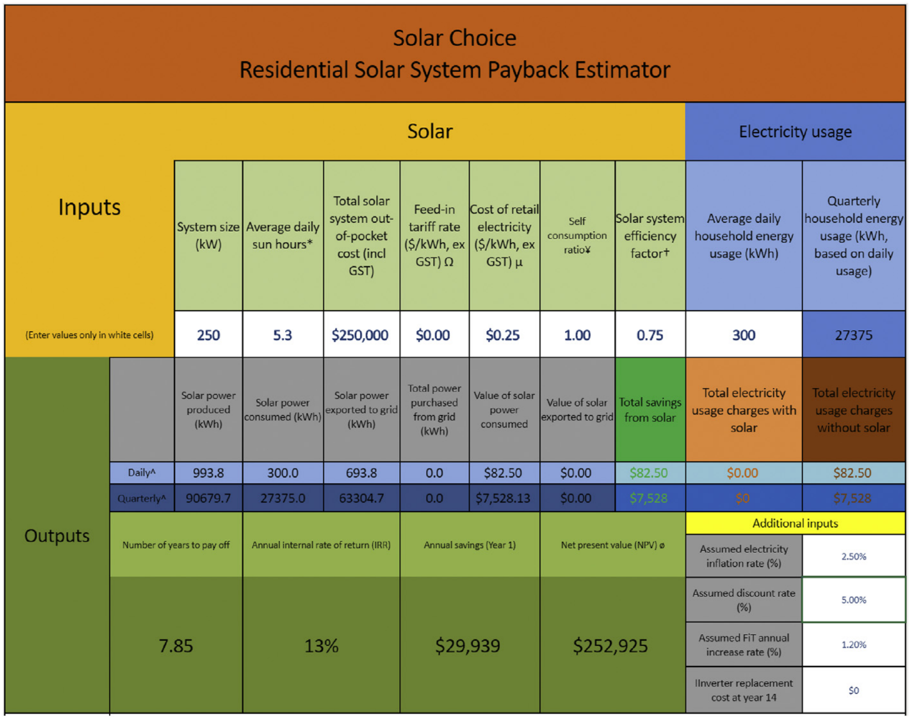


Fig. 6 Solar Calculator, source: https://www.solarchoice.net.au.

different pilot-scale systems in The Netherlands; Norsker et al. estimated investment cost of 0.51 M€/ha for a photobioreactor algae cultivation system (Norsker et al., 2011). We converted the currency value to Australian dollar, and the associated inflation rate has been considered at 13.5% over nine years in accordance with the Australian context. Thus, the investment cost of the vertical tubular system for the 1500 sqm area is calculated as AUD 139,792:

Investment Cost per sqm (in Euros) $= 0.51 \times 10^6/10^4 = 51$

Investment Cost for 1500 sqm $= 51 \times 1500 = 76{,}500$ Euros

Converted AUD Value (considering 1 Euro = AUD 1.61) $= 76500 \times 1.61 =$ AUD 123,165 (USD 83,720.79)

Considering 13.5% Inflation rate = AUD 138,465 $\times$ 1.135 = AUD 139,792 (USD 95022.91)

Anaerobic digester cost: Anaerobic digestion (AD) process converts wet biomass biochemically in its entirety. The emissions and outflow from this process can be stored for reuse of resulting components like carbon dioxide, ammonia, and phosphorus. It therefore has both economic and environmental benefits. The cost and size of anaerobic digester mainly depend upon retention time and daily input. More retention time suggests a higher volume of the digester. Photobioreactor can typically produce 19.4 g m^{-2} day^{-1} of algae. Algae production from our 1500 sqm area, is estimated as 28.5 kg of algae per day. In addition, we estimate 11.5 kg of solid organic waste to be produced from the chosen case study building. For a total of 40 Kg of organic waste, we thus require an anaerobic digester of 115 cubic meter size which costs AUD 389,000 (USD 264,420.80). Considering Installation and full setup with the proposed Photobioreactor system, the approximate cost is thus estimated as AUD 400,000 (USD 271,898.00). The electricity demand for the proposed system is 2.4 kWh/m^3/day. Thus, annually, it costs AUD 9936 (USD 6753.95). The labor costs involved in setting up the anaerobic digester system is AUD 26,000 (USD 17,673.37), and the maintenance cost, including insurance, is calculated as AUD 6500 (USD 4418.34) annually. Hence, the fixed and total variable cost for the proposed Anaerobic digester are calculated as follows (Table 4):

Table 2 Fixed and variable costs, interest rate and average annual savings for the Solar Panel System.

Fixed cost	AUD -250000 (USD 169936.25)
Interest rate	4% per annum
Other maintenance and processing cost personal annum	AUD 8250 (USD 5607.90)
Average annual saving	AUD 29939 (USD 20350.89)

Operating Costs: The operating cost of the photobioreactor is dependent on the size of the photobioreactor. According to Bender (2017), the operating costs for cultivating 1 kg dry weight algae biomass was estimated as 5.55 €/ha. Extrapolating this value for our 1500 sqm area and 8730 Kg of algae production, annual operating costs have been determined as AUD 13,281 (USD 9027.69);

Annual operating cost AUD $= 5.55 \times 1500/10000 \times 8730$ x 1.61

Considering (1 Euro = 1.61 AUD) = 11,701.04

13.5% Inflation Rate = 13,280.70

Table 3 ROI and NPV considering an annual Interest of 4% and variable costs for the Solar Panel system.

Calculation of ROI and NPV while considering Annual Interest of 4% and Variable Costs							
A	B	C	D	E	F	G	H
Years	Beginning principal amount	Annual ROI	Annual interest paid [B*0.04]	Annual other cost paid	Principal amount paid [C-(D + E)]	NPV/ending balance [B + F]	NPV/ending balance in USD
1	AUD −250000.00	AUD 29939.00	AUD 10000.00	AUD 8250.00	AUD 11689.00	AUD −238311.00	USD −161990.71
2	AUD −238311.00	AUD 29939.00	AUD 9532.44	AUD 8250.00	AUD 12156.56	AUD −226154.44	USD −153727.35
….	…..	…..	…..	…..	…..	…..	….
15	AUD −36185.85	AUD 29939.00	AUD 1447.43	AUD 8250.00	AUD 20241.57	AUD −15944.28	USD −10838.04
16	AUD −15944.28	AUD 29939.00	AUD 637.77	AUD 8250.00	AUD 21051.23	AUD 5106.94	USD 3471.42

Insurance Costs: Algae production system and photobioreactors are still novel in NSW. There is thus no current insurance provider for such systems in NSW currently. As a general rule of thumb, we assume 1% of initial cost as the annual cost of insurance. This would be approximately AUD 1570 annually.

Total Cost: All the cost presented in Table 5 below are calculated for a 20 years period of the photobioreactor system.

3.5. Revenue and benefits

The revenue generation of the proposed PBR system have been calculated based on their energy generation, carbon sequestration and water recycling potential for the chosen case study as follows: Energy Generation: De Vree et al., 2015 (De Vree et al., 2015) estimated that Photobioreactor can produce 19.4 g m^{-2} day^{-1} of algae. Considering the climate of Sydney, NSW, we consider 300 days out of 365 days of adequate available solar exposure. Estimating the algae production for 300 days for 1500 sqm area, we calculated 8730 kg of algae production annually. Furthermore, we are also using the organic waste produced from the chosen building, hence a total of 12000 kg of biomass is estimated annually. This biomass will be transferred to an anaerobic digester to produce biomethane gas. From this waste, around 259,000 MJ biogas can be produced (Bender, A. 2017). If we use this gas to produce electricity, 40% of the gas will be lost in the process and with 60% efficiency, only 43,200 kWh energy can be produced annually (Bender, A. 2017). The current energy rate from the grid in NSW is AUD 0.25 per KWh. Hence AUD 10,800 (USD 7341.25) can be derived as our annual saving.

Carbon Sequestering: According to Norsker et al. (2011), of an algae farm of 1 acre, which produces 2000 to 5000 gallons of algae absorbs more than 2 million tons of carbon dioxide. In our case study, we produce 3200 gallons of biomass, which will not only help in negating the carbon emission of the building but will also impact the carbon emission rates of the surrounding buildings.

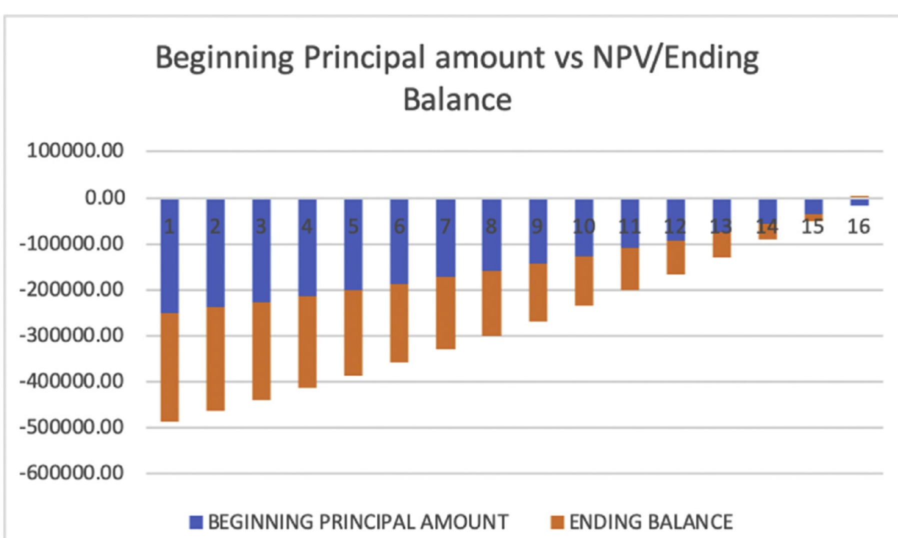


Fig. 7 NPV calculation showcasing a 16-year term to achieve return on investment for the solar panel system.

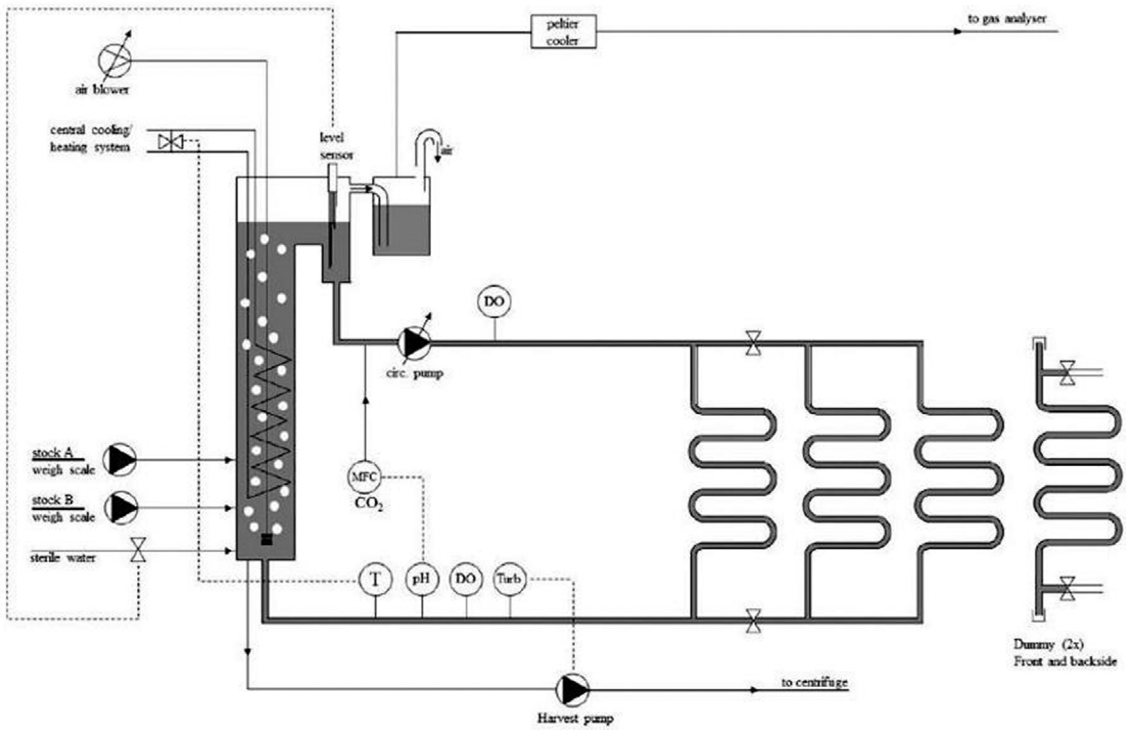


Fig. 8 Proposed system architecture for the PBR system (Bender, 2017).

Water Recycling: The annual consumption of water for the year 2018 for the chosen building is 54814.8 kL. From this total usage, 40% of the usage is by cooling towers and gardening of adjacent building, hence we can consider that annual consumption of our chosen building is 32889 kL. This usage can be further elaborated as below (Statistics from UTS facility management energy monitoring tool: Fig. 9):

The anaerobic digester also purifies the water by removing pathogens from it. Moreover, algae production from the wastewater will extract the chemical and biological waste from the water, and this water can be used for flushing toilets and for gardening purposes, which amounts to 25% of the total consumption. Hence by using this system, we can save around 13704 kL of water annually. In terms of money, around AUD 33,000 (USD 22,439.50) annually can thus be saved. Moreover, algae production in wastewater, oxidizes the water thus helping in purifying the water quickly. If this purification process is further

Table 4 Fixed and Variable costs for the proposed Anaerobic Digester.

Capital cost of anaerobic digester (Fixed Cost)	**AUD 400,000** (USD 271,898.00)
Electric cost per annum for digester	AUD 9936
Maintenance cost per annum for digester	AUD 6500
Labor cost per annum	AUD 26,000
Total variable cost of digester per annum is	**AUD 42,436** (USD 28,845.66)

Table 5 Fixed and Variable costs for the proposed PBR system.

Photobioreactor (Material + Installation)	AUD 139,792
Anaerobic Digester (Fixed cost)	AUD 400,000
Total Fixed cost	**AUD 539,792** (USD 366,920.91)
Operational Cost + Maintenance Cost per annum	AUD 13,281
Insurance per annum	AUD 1570
Variable cost of digester	AUD 42,436
Total variable cost	**AUD 57,287** (USD 38,940.55)

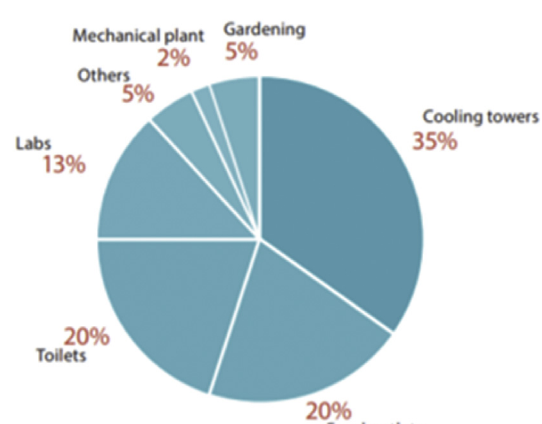


Fig. 9 UTS Campus water usage distribution (UTS Water Consumption data - 2015).

Table 6 Annual revenue generation from the proposed PBR system.

Electricity Production/ Gas production	AUD 10,800
Water Saving	AUD 76,960
Residue	AUD 5000
Total Annual Revenue	**AUD 92,760** (USD 63,053.15)

deployed than approximately 35% of cooling tower requirements can be satisfied with the recycled water resulting in a further saving of AUD 50,000 (USD 33,999.25) annually. Apart from revenue generation this will aid in easing the water crisis currently plaguing NSW.

Biomass Residue: After production of biogas from biomass, the residue can be further sold for revenue generation. This residue is a high source of nutrients and can be used as fertilizer in the agricultural industry. The leftover can also be used for healthy diet preparation for human consumption. Moreover, the cosmetic and medical industry also uses this residue as their raw material to produce their products. We thus consider AUD 5000 (USD 3398.73) approximately as annual revenue from the resultant biomass residue (considering that there are currently no official industry tie ups in NSW who would directly buy the residue on a fixed rate).

Table 7 Fixed and variable costs, interest rate and average annual savings for the proposed PBR System.

Fixed cost	AUD −539,792 (USD −366,920.91)
Interest rate	4% per annum
Other maintenance and processing cost per annum	AUD 57,287 (USD 38,940.55)
Average annual saving	AUD 92,760 (USD 63,053.15)

Total Annual Revenue: Considering all the benefits, the annual revenue is thus calculated as AUD 92,760 (USD 63,053.15) (Table 6):

After calculating the annual revenue, we identified that the interest rate paid on fixed cost and other variable costs play a major role in calculating the return on investment. The Net Present Value (NPV) and Return on Investment (ROI) is thus subsequently calculated using the following formula:

$$NPV = \sum_{t=1}^{T} \frac{B - C}{(1+i)^t} - C_o$$

This formula also considers both variable costs and interest costs. *NPV* is calculated by subtracting cash flows (Benefit and Cost) for a period (t) within the holding period (T), discounted at an expected rate of return on the cash flow (i, interest rate) while C_o is considered as the investment cost. ROI is calculated using the following formula: *(Gain from Investment − Cost of Investment) Cost of Investment*. We consider the following fixed and variable costs which were calculated for the photobioreactor systems installation, maintenance with a fixed interest rate of 4% (Table 7):

These costs are used for the calculation of ROI and NPV in Table 8 and Fig. 10 below. The total duration to attain return on investment of installing and operating the PBR system for the chosen case study is thus presented in the table below. The total duration to attain return on investment of the PBR system for the chosen case study is thus calculated as 24 years, 8 years longer than the proposed Solar Panel System.

4. Results

4.1. Cost and benefit analysis findings

A comparison between the proposed solar panel system and the closed tubular photobioreactor system is shown in Table

Table 8 Calculation of ROI and NPV while considering annual interest of 4% and variable costs for the proposed PBR system.

Calculation of ROI and NPV while considering Annual Interest of 4% and Variable Costs

A	B	C	D	E	F	G	H
Years	Beginning principal amount	Annual ROI	Annual interest paid [B*0.04]	Annual other cost paid	Principal amount paid [C-(D + E)]	NPV/Ending balance [B + F]	NPV/Ending balance in USD
1	AUD −539792.00	AUD 92760.00	AUD 21591.68	AUD 57287.00	AUD 13881.32	AUD −525910.68	USD −357485.16
2	AUD −525910.68	AUD 92760.00	AUD 21036.43	AUD 57287.00	AUD 14436.57	AUD −511474.11	USD −347671.97
3	AUD −511474.11	AUD 92760.00	AUD 20458.96	AUD 57287.00	AUD 15014.04	AUD −496460.07	USD −337466.25
....	.....	....	....	....	....	....	....
23	AUD −64384.97	AUD 92760.00	2575.40	AUD 57287.00	AUD 32897.60	AUD −31487.37	USD −21403.38
24	AUD −31487.37	AUD 92760.00	AUD 1259.49	AUD 57287.00	AUD 34213.51	AUD 2726.13	USD 1853.07

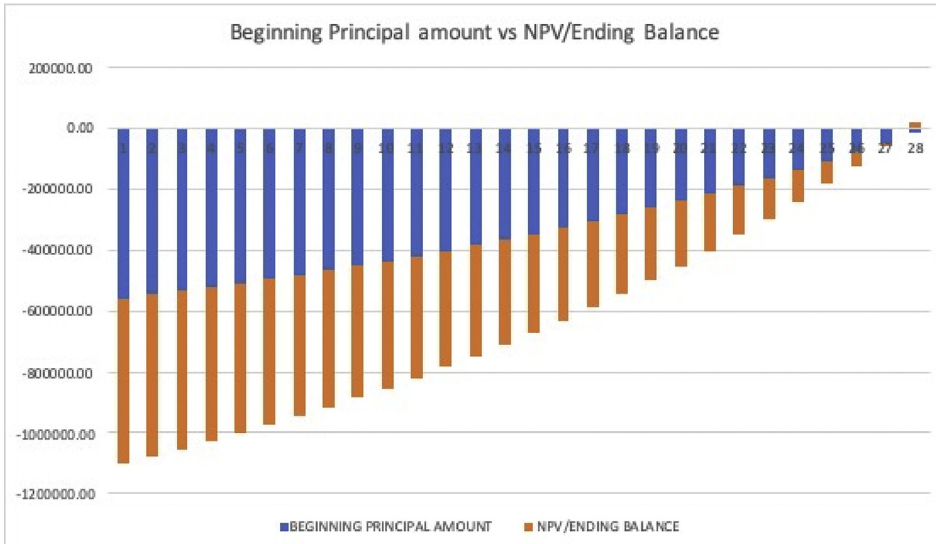


Fig. 10 NPV calculation showcasing a 28-year term to achieve return on investment for the closed PBR system.

Table 9 Cost and Benefit comparison between the proposed Solar Panel System and the PBR system.

Costs and returns	Solar panel	USD value	Photobioreactor	USD value
Initial cost	AUD 250,000	USD 169,936.25	AUD 539,792	USD 366,920.91
Total variable cost per annum	AUD 8250	USD 5607.90	AUD 57,287	USD 38,940.55
Tangible benefits				
Annual return	AUD 29,939	USD 20,350.89	AUD 92,760	USD 63,053.15
Return on investment	16 YEARS		24 YEARS	
Intangible benefits				
Carbon emission reduction	—		2 Million Tonne	
Water savings	—		32,888.88 kL	

9 below. We found that from a short-term monetary perspective, the solar panel system is much more feasible for the chosen case study as it can not only generate more energy but is also able to generate more revenue and faster return on investment (16 years as compared to 24 years). However, after the 24-year term, from a purely financial perspective (not considering any interest earned on net present value or any replacement or upgradation cost), the Closed Tubular PBR system becomes more profitable than the solar panel-based system after a term of 36 years. Furthermore, looking at the current Australian context, we are facing substantial water crisis as well as negative impacts of global warming, which presents an inevitable threat to both physical and environmental wellbeing. A recent article in the Guardian news (Spring 2019) stated that Sydney dam levels are at 53.5% across the 11 dams that it has, with levels falling down since April 2017 (with 96% combined capacity). As a result, the NSW government had to implement new water consumption rules with accompanying heavy fines for people who do not follow the stipulated rules (individuals and companies alike). This situation is even more crucial since NSW has been drought ridden since mid 2017 causing dam levels to fall 0.04% every week for the past two years. Environmental benefits in the form of reuse of treated water, carbon sequestration, production of oxygen and biomass to be used as a clean energy source etc. are deemed as far more beneficial as compared to solar panels.

Overall, looking at the long-term monetary benefits of deploying the closed tubular photobioreactor system, our research concluded with choosing the PBR system as a favored option over solar panel systems for retrofitting buildings within the urban built environment.

5. Conclusion

This paper presented an empirical study comparing the costs vs benefits of retrofitting the urban built environment using two sustainable energy generation means: Solar PV panels vs Closed PBR systems. We applied the two systems on a 150 sqm vertical footprint of a chosen case study building within the University of Technology, Sydney, Australia and conducted a thorough cost vs benefit analysis using the following performance indicators; return on investment, payback period as well as net present value of the two systems. Annual revenue generation of both systems which included tangible and intangible benefits of both systems were also simultaneously calculated. The investment and operation and maintenance costs of both systems were calculated based on market research as well as quantitative data adapted from our literature review. The analysis concluded that from a short term, purely monetary compensation perspective, the solar panel system requires 16 years as compared to the closed tubular PBR system which requires 24 years. However, from a long-term perspective, our calculations (not considering any interest earned on net present value and not considering any replacement or upgradation cost) suggest that the closed tubular PBR system, owing to its annual return value proves to be more beneficial from a monetary perspective. Besides this, the environmental benefits offered by the closed tubular PBR system (carbon sequestering, wastewater treatment and oxygen production) already outweigh the environmental benefits offered by the solar panel system. The research findings thus conclude that the integration of algae building technologies within the built environment offers a promising direction towards developing sustainable buildings. Furthermore, the potential for producing feedstock not only for biofuel production but also for the food, cosmetics and health sector (Saha, 2013; Saha et al., 2015) add to the list of benefits provided by the closed PBR system. Their ability to combine carbon neutral energy production and recycling of environmental pollutants offer a multi-performative solution within today's ecologically sensitive context.

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