Feasibility of solar-powered ultrafiltration membrane water treatment systems for rural water supply in Malaysia

Chun Ming Chew and K. M. David Ng

ABSTRACT

According to the World Bank's collection of development indicators, in 2017 approximately 25% of Malaysia's population were living in rural villages. Some of these villages are currently without electricity from the national grid and public piped water supply. In this study, a solar-powered ultrafiltration membrane water treatment system was installed at a rural village in Perak, Malaysia, to identify its feasibility. The ultrafiltration system was evaluated and compared with a conventional sand/media filtration water treatment system at the same location. Various aspects of both systems such as operational parameters, life-cycle cost and carbon emissions have been analyzed under this study. The distinct advantages of the ultrafiltration system include better filtrate turbidity quality (below 0.4 NTU), and lower operational cost and carbon emission. By utilizing a cross-flow filtration operation mode, the UF system does not require a daily intermittent backwash sequence, unlike the conventional system, to further simplify the daily operational routine. Accessibility of clean water supply for all has been heavily emphasized by the United Nations General Assembly (under sustainable development goal number 6) to ensure public health. This comprehensive study highlights the feasibilities of solar-powered ultrafiltration membrane water treatment systems for rural villages in Malaysia.

Key words | carbon emission, rural village, solar-powered, ultrafiltration, water treatment

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INTRODUCTION

In Malaysia, almost a quarter of the total population are living in rural villages with public facilities lagging far behind urban cities (Borhanazad *et al.* 2013). It is one of the government's National Key Results Areas (NKRA) to ensure basic facilities such as public piped water supply are available to these rural villagers. The government has intensified efforts to provide piped water supply at these villages with higher budget allocations for rural facility development. Due to the vast distance from some of these villages to the nearest urban public piped water supply networks, it has become very costly and time-consuming to lay ground pipes to these remote areas.

A feasible alternative would be to build small-scale water treatment systems complete with reticulation pipes near these rural villages to reduce the capital cost and construction period. Unfortunately, some of these villages are far away from the national electricity grid networks and these small-scale water treatment systems would require other resources for electricity (Izadyar *et al.* 2016). Portable generator sets are common means to generate electricity with fossil fuel which are costly to operate and release high carbon emissions in these rural areas. They also pose safety hazards as well as noticeable noise and air pollution in the villages.

Solar-powered water treatment systems have been identified as one of the possible sustainable solutions to provide potable water in such remote villages (Hernández-Escobedo *et al.* 2017). Electricity generated by solar photovoltaic

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panels could be utilized to power up motors to operate the pumps without any generator sets or electricity supply from the national grid networks. Solar energy has been considered a potential clean renewable energy resource available all year round in most continents of the world (Sansaniwal *et al.* 2018). Due to Malaysia's strategic location near the equator, it has an average solar irradiation of 400 to 600 MJ/m^2/month making it a promising place to harness solar energy (Mekhilef *et al.* 2012). There are currently lots of commercial solar farms utilizing solar photovoltaic panels to convert solar energy into electricity in Malaysia.

Ultrafiltration (UF) has been deemed as one of the most accepted advanced technologies in water treatment systems in recent years (Chew *et al.* 2017). Most UF membrane water treatment systems are pressure-driven processes which require electricity for pumps to overcome the membrane and solid cake layer resistance. This study intends to highlight the feasibility of solar-powered UF membrane water treatment systems for rural areas in Malaysia. Evaluations and comparisons between solar-powered UF and conventional sand/media filtration water treatment systems have been conducted and further elaborated in the subsequent sections.

METHODOLOGY

A solar-powered UF membrane water treatment system was designed and commissioned to evaluate various aspects of the study. This system was installed at a rural village located at Perak, Malaysia, to determine its feasibility. There are approximately 60 houses with over 200 people living in this village. Figure 1 shows the actual solar-powered UF membrane water treatment system installed at the village.

The system consists of a Dizzer P 4040–4.0 UF membrane module manufactured by Inge GmbH, Germany. It encompasses 4.0 m^2 of modified polyethersulfone (PES) hollow fibre UF membrane surface area with pore size of 0.02 μm. This system was designed for direct filtration without the need of any chemical coagulant and within the flux range of 60–90 L/m^2 hr. A solar photovoltaic panel with a maximum capacity of 50 W complete with a 40 Ah deep-cycle battery provides electricity to operate the feed pump. The UF system was operated under cross-flow filtration using feed water from a nearby river.

The UF system was placed inside the compound of a small-scale conventional sand/media filtration water treatment plant with 1.7 m^2 of filter surface area currently

Figure 1 | Solar-powered ultrafiltration membrane water treatment system.

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supplying 40 m^3/day of potable piped water to the village. This conventional water treatment plant is utilizing aluminium-based chemical coagulant and sand/media filters as final polishing. The conventional treatment plant acquires energy from the national electricity grid networks. Figure 2 shows the small-scale water treatment plant and the conventional sand/media filtration system inside.

RESULTS AND DISCUSSION

Both the solar-powered UF and conventional systems draw the same feed water from a nearby river located in the vicinity of the village. Operational parameters, life-cycle cost and carbon emissions from both systems were analyzed and compared. Data were collected for a period of 90 days to gather the necessary information for analysis as recommended in the literature (Kitanou *et al.* 2018).

Operational parameters

A total of six operational parameters of both systems have been evaluated under this study, which includes the system design (filtration flux, specific electricity required and filtration operation mode), output quality (filtrate turbidity) and operational aspects (filter cleaning frequency and required operator competency). Table 1 summarizes the various operational parameters of the systems evaluated under this study.

Figure 2 | Small-scale water treatment plant (left) and the conventional sand/media filtration system.

Table 1 | Operational parameters of the solar-powered UF and conventional sand/media filtration systems

Operational parameter	Solar-powered UF system	Conventional sand/media filtration system	Comments
Filtration flux	75 L/m^2 hr	2,940 L/m^2 hr	Based on low-turbidity feed water with average of 20–30 NTU and pH range of 6.5–8.5
Specific electricity required	0.18 Wh/L	0.15 Wh/L	Specific energy requirement of below 0.20 Wh/L is acceptable for both systems
Filtration operation mode	Cross-flow filtration	Dead-end filtration	Cross-flow filtration mode allows continuous operation without intermittent backwash
Filtrate turbidity	<0.4 NTU	1–2 NTU	Safe potable water should be less than 5 NTU
Filter cleaning frequency	Two weeks once	Everyday	Chemical cleaning of the UF membrane is required once every 2 weeks
Required operator competency	Basic training for 2 days	Basic training for 2 days	Both systems are operated under manual filter backwash/ cleaning

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Typically surface waters for different parts of rural areas will be different depending on the level of river pollution. Under this study the river water turbidity was observed to be below 50 NTU (average about 20–30 NTU), which is considered to be suitable for both conventional sand/media filtration and direct UF membrane filtration water treatment systems. Filtration fluxes for both systems would decline after a prolonged period of continuous operation. Initially the filtration flux of a cleaned UF membrane module was more than 85 L/m^2 hr but after 2 weeks of continuous operation it was reduced to 65 L/m^2 hr. The average filtration fluxes for both systems are shown in Table 1. It indicates that the filtration flux of the conventional system (2,940 L/m^2 hr) is 39 times higher than that of the UF system (75 L/m^2 hr) using the same low-turbidity feed water from the river. This might give a misconception that the conventional sand/media filtration systems could offer more savings on the actual footprint required for the water treatment plant. Hollow fibre UF membranes are usually bundled within housing modules to allow higher packing density (Lim *et al.* 2017). The 4-inch-diameter membrane module with 4.0 m^2 of membrane surface area utilized in this study occupied a footprint of less than 0.01 m^2 while the similar filtration surface area of the conventional sand/media filter housing required 4.0 m^2 of footprint. Under similar water treatment capacity, UF systems normally required much smaller footprints compared with conventional sand/media filtration. It has been reported in the literature that an industrial-scale UF membrane water treatment system only requires 30% of the conventional system's footprint with the same treatment capacity (Chew *et al.* 2016b).

The specific electricity required for the UF and conventional systems was 0.18 Wh/L and 0.15 Wh/L respectively. Power consumption of about 0.20 Wh/L is normally required to treat surface raw water for potable use in commercial-scale systems (Pearce 2008). Both systems evaluated under this study have exhibited reasonable power consumptions which comply with this general standard. Electricity supply to the conventional system originated from the national grid networks while the UF system was from the solar photovoltaic panels. The conventional system's operator is required to pay the amount of electricity consumed monthly based on the tariffs. Aluminium-based chemical coagulant is also required in the conventional system for the coagulation/flocculation process to enhance filtration.

One of the most common operational procedures for the conventional system is the need for sand/media filter backwash. Generally, sand/media filtration systems are operated under dead-end filtration mode with an intermittent backwash sequence to dislodge the particles from the filter media. In this study, the conventional system was operated under dead-end filtration while the UF system was under cross-flow filtration mode. Cross-flow filtration produces both the concentrate and filtrate streams at the same time.

The main advantage of cross-flow filtration is the omission of an intermittent backwash sequence required in the dead-end filtration mode. Under cross-flow filtration the UF membrane module continuously produces two streams, which are the concentrate and filtrate streams. Most of the solid contents in the feed water are discharged from the membrane module through the concentrate stream while small traces of it will attach on the membrane surface to form a cake layer. The UF system evaluated under this study was operated under cross-flow filtration for 2 weeks before a chemical cleaning of the membrane module was required. Chemical cleaning of the membrane is required to stabilize and maintain permeability by preventing foulant build-up (Porcelli & Judd 2010). A prolonged period (more than a month) of filtration without chemical cleaning will eventually promote the build-up of a fouling layer and decrease membrane permeability. This will cause a persistent increase of the specific electricity required due to the higher operating pressure to achieve the desired filtration flux. Furthermore the membrane will have a shorter service life-span as the specific electricity required to produce clean water is too high (or the permeability is too low) for an economically viable or sustainable system operation. Under this study the UF system was operated at low feed water pressure of below 1.0 bar, which is desirable to perform the solid–liquid separation process at low cost (Ng *et al.* 2018). The cross-flow filtration mode used in the UF system has significantly simplified the daily operation of the system without any backwash sequence required. The operator of the conventional system is required to manually perform the backwash sequence once a day on the sand/media filters. The water recovery rate of the conventional system during

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the study was 95% while that of the solar-powered UF system was 80%. Lower water recovery rate is an apparent disadvantage of cross-flow filtration compared with dead-end filtration. Nevertheless for small-scale systems such as those of 5 m^3/hr in rural areas, this does not pose a serious issue since there is a continuous higher flow of river water source available.

Turbidity of the filtrate provides a good indication of physical appearance or quality of the water for both systems (Chew *et al.* 2016a). Table 1 indicates that the filtrate quality from the UF system (<0.4 NTU) was much better than from the conventional system (1–2 NTU). Under similar raw water characteristics, membrane filtration normally produces much better filtrate quality than conventional sand/media filtration systems (Guastalli *et al.* 2013). Filtrate with lower turbidity or suspended solids reduce the chances of reticulation pipes scaling in the long term. Direct filtration for low-turbidity feed water (such as below 30 NTU) is a feasible practice to eliminate the use of coagulant to reduce the overall operational cost for the UF system (Chew *et al.* 2015). The conventional system requires careful operation and optimization of coagulant dosage to remain effective at all times (Rockey *et al.* 2018).

The conventional system operating under dead-end filtration mode requires a daily manual backwash sequence carried out manually by the operator. As for the UF system, a two-week-once membrane cleaning procedure is required to remove particles and solids attached on the membrane surface. A complete set of membrane-cleaning procedures involves hydraulic and chemical cleaning to remove reversible and irreversible membrane fouling respectively (Wang *et al.* 2016). The continuous concentrate flushing from the membrane provides the hydraulic cleaning in cross-flow filtration. The chemical cleaning procedure is proposed to be carried out by a competent technician tasked to remove the UF membrane modules at the village and transport them to the workshop where the actual cleaning takes place. Cleaned replacement membrane modules are installed back into the UF system each time during the technician's visit to ensure uninterrupted water supply. Both the conventional and UF systems require a trained operator appointed among the villagers to carry out simple daily operation.

Filtration flux of the solar-powered UF system remains at 75 L/m^2 hr if it is sized up to 5 m^3/hr to match the existing conventional system. The 4.0 m^2 membrane surface area shall be increased to 66.7 m^2 in order to produce the 5 m^3/hr of filtrate while maintaining the filtration flux of 75 L/m^2 hr. Frequencies of filter cleaning are expected to be similar (two-week-once for the UF system and every day for the conventional system) as in this study if the filtration flux and feed water characteristics remain the same. Small-scale water treatment systems in rural villages are normally designed for simplicity of operation to ensure the local villagers can handle the daily operation of the systems. Scheduled maintenance services are usually conducted by competent technicians travelling from the nearby cities once or twice a month to these villages. Both the UF and conventional systems were manually operated to avoid the use of sophisticated instrumentation. These systems were switched on manually in the morning and off in the evening for 8 hours of operation a day. The appointed operator among the villagers was able to adapt to the operation of both systems after 2 days of intensive training.

Estimated life-cycle cost and carbon emissions

In order to further evaluate the feasibility of the solar-powered UF membrane water treatment system, an estimated life-cycle cost and carbon emissions analysis has been conducted. Under this evaluation the actual cost of the conventional sand/media filtration water treatment system was compared with the estimated cost of a solar-powered UF membrane system of similar capacity (5 m^3/hr of treated water production with 8 hours daily operation). Carbon emissions are estimated based on the electricity consumed by both systems. More than 50% of electricity generated in Malaysia originates from natural gas power plants. These power plants release approximately 0.404 kg of carbon dioxide (CO_2) for each kWh of electricity generated (de Lira Quaresma *et al.* 2018). The conventional sand/media filtration system utilizes electricity from the national grid networks which originates from these power plants while the solar-powered UF system uses clean energy from the sun without any carbon emission. Table 2 summarizes the comparison analysis of the life-cycle cost and carbon emissions for both systems.

The conventional system was completed and commissioned in the year 2011. Yearly inflation was taken into

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Table 2 | Life-cycle cost analysis and carbon emissions for the solar-powered UF and conventional sand/media filtration systems

Cost descriptions	Solar-powered UF system (estimated)	Conventional sand/ media filtration system (actual)
Capital cost	USD 50,000	USD 40,000
Operational cost (electricity and chemical)	USD 0/month	USD 175/month
Maintenance cost		
a. Coagulant dosing pump cleaning and calibration	USD 0	USD 50/month
b. Membrane cleaning	USD 100/month	USD 0
c. Transportation to site	USD 200/month	USD 100/month
5-year system overhaul cost	USD 7,500	USD 3,500
Total cost of system for 20 years	**USD 144,500**	**USD 128,500**
Electricity consumption for 20 years	51,840 kWh	43,200 kWh
Carbon emissions for electricity consumed in 20 years	**0 tonne CO_2**	**17.5 tonnes of CO_2**

consideration to determine the actual capital cost of the system in 2018. Relevant vendor, supplier and sub-contractor inputs were obtained to estimate the capital cost of the solar-powered UF system in 2018. It is a generally accepted fact that the capital cost of a UF membrane system would be much higher than that of the conventional sand/media filtration water treatment system. Under this case study, the capital cost of the solar-powered UF system operated under cross-flow filtration mode was estimated to be 25% higher than the conventional system. It is highly probable that the capital cost of a UF system operated under dead-end filtration mode would be even higher due to the automation hardware involved to execute hourly periodical backwash sequences. The backwash sequences also require a backwash pump to deliver more than twice the filtration flux at a much higher pressure to provide the necessary hydraulic cleaning for the membrane.

The capital cost for the solar-powered UF system in Table 2 includes a one-time procurement cost for the solar photovoltaic panels, which are expected to perform satisfactorily for a 20-year operational period (Charles *et al.* 2019). Both the maintenance and 5-year system overhaul costs were estimated to be much higher for the UF system due to the requirement for membrane chemical cleaning and replacement of new membrane modules as well as the deep-cycle batteries in the solar photovoltaic system. The major saving of the UF system is in the operational cost compared with the conventional system which requires electricity from the national grid and chemicals for coagulation/flocculation every day. Since the UF system does not require any chemicals for coagulation/flocculation and electricity is generated by solar photovoltaic panels, there is no apparent operational cost except for the operator's salary. Under this study the costs for hiring operators are omitted since both systems require an operator, which evens out the cost.

It is assumed that both the systems are designed for a life-cycle of 20 years before they are de-commissioned, to correlate with literature reports (Dehesa-Carrasco *et al.* 2016). The total cost incurred for 20 years indicates that the UF system is only 12.5% higher than the conventional system. An important point worth taking note for the UF system is the zero carbon emission due to the utilization of electricity generated by solar photovoltaic panels compare with an estimated release of 17.5 tonnes of CO_2 within a 20-year operational period for the conventional system. Even though developed nations such as the United Kingdom, Switzerland and Japan have implemented a carbon tax to reduce greenhouse gas emission, such regulations are still under government consideration in Malaysia (Wong *et al.* 2018).

Feasibility of the solar-powered UF membrane water treatment system

Various aspects highlighted in Table 1 have indicated that in order to ensure the feasibility and sustainability of the UF system in rural villages, a few essential criteria are required to be fulfilled. Firstly the specific electricity required must be able to be met by the solar photovoltaic system with a reasonable design safety margin to reduce the initial capital cost (Sathyamurthy *et al.* 2017). The capacity of the deep-cycle batteries should be designed to cater for 24 hours of continuous operation or equivalently to 3 days of normal

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operations at 8 hours/day to cater for cloudy periods. The maximum electricity demand of the cross-flow membrane filtration system is lower than that of dead-end membrane filtration since there is no backwash pump that would necessitate much higher electricity demand than the feed pump. Capital cost for the cross-flow filtration system is also much lower since all of the automation hardware such as actuated valves required for intermittent backwash sequences in dead-end filtration mode can be omitted without affecting the operation. Cross-flow filtration is a much better operation mode for small-scale UF systems with significantly lower initial capital cost.

The data in Table 2 show that the solar-powered UF system has much lower operational cost compared with the conventional system due to the omission of coagulant and free electricity generated by the solar photovoltaic panels. The main drawback of UF operation is the requirement to replace the membrane module once every 2 weeks. After prolonged operation of the membrane module, chemical cleaning known as clean-in-place (CIP) is required to dislodge foulant from the membrane pores and surface (Lee *et al.* 2018). In order to overcome this issue, a competent technician visits the village once every 2 weeks to replace the UF membrane modules for CIP in the factory. After CIP, these membrane modules are taken back to the village for the next replacement and the same procedures are repeated until the membrane service life has reached 5 years. New UF membrane modules are replaced in the system after 5 years. So in a period of 20 years, membrane replacements are required three times before the system is decommissioned.

Another important aspect is the compliance of the filtrate quality of the UF system to the local authority requirements (Arnal *et al.* 2006). Filtrate quality from the UF system was much better in physical appearance with lower turbidity than the conventional system. Finally the system needs to be easy and simple for operation to suit the villagers' level of competency. Due to the vast distance of these rural villages from the nearest town, it is not economically viable to send technicians to operate and troubleshoot the system on a regular basis. Villagers have to be trained in basic operation and troubleshooting of the system while monthly periodical maintenance should be conducted by skilled technicians. The UF system has been designed with minimum moving parts (such as the feed pump) to ensure ease of operation and reduce the possibility of mechanical failures.

Low operational cost, high quality of filtrate, ease of daily operation and lower carbon emissions of the solar-powered UF membrane water treatment system have made the system highly feasible for implementation in rural villages. Due to mass production and economy of scale, the overall price of solar photovoltaic panels has declined significantly in recent years (O'Shaughnessy & Margolis 2018). It is shown in Table 2 that the 20-year life-cycle cost for the solar-powered UF system is slightly higher (12.5%) than the conventional system taking electricity directly from the national grid networks, but the higher quality filtrate and zero carbon emissions from the UF system would justify the selection. The right technology selection is important to ensure both economic and environmental sustainability (Eliamringi & Kazumba 2016).

CONCLUSIONS

This evaluation has highlighted the feasibility of the solar-powered UF membrane water treatment system for rural villages in Malaysia. Comparison of the UF and conventional sand/media filtration has been made to elucidate various aspects of operational, commercial and carbon emissions. The filtration flux of the UF system was much lower (75 L/m^2 hr) compared with the conventional system (2,940 L/m^2 hr) with low–turbidity feed water (average 20–30 NTU) from the nearby river. Filtrate turbidity from the UF system (<0.4 NTU) was much better even though both systems could produce treated water in compliance with regulatory requirements to ensure public health. Having lower turbidity or cleaner filtrate would definitely reduce the chances of reticulation pipes scaling in the long term. The UF system's full reliance on electricity generated from solar photovoltaic panels produces zero carbon emission. Reduction of carbon emission while ensuring public health is a sustainable solution worth consideration. The UF system has exhibited distinct advantages of lower operational cost, better quality of filtrate, ease of operation without the intermittent backwash and zero carbon emissions compared with the conventional system. All the

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aspects highlighted in the solar-powered UF membrane water treatment system in this study enable the relevant government authority to access comprehensive information to evaluate the feasibility of the UF system for rural villages in accordance with the United Nations General Assembly's sustainable development goal number 6 (clean water for all).

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