Theoretical study of a membrane filtration process for water treatment using low temperature solar energy

Corentin KONINCK[1], Vincent GOETZ[1], Driss STITOU[1]

Laboratoire CNRS-PROMES « PROcédés, Matériaux et Énergie Solaire », UPR CNRS 8521, Rambla de la Thermodynamique, 66100 Perpignan, France

Introduction:

Access to clean water for drinking will become a critical issue in the 21st century for humanity. Indeed, 26% of the world's population do not have access to safe drinking water managed by appropriate facilities (WHO/UNICEF, 2017). Population growth and subsequent rapid urbanisation combined with the effects of climate change, are affecting the availability of drinking water, both in terms of quantity and quality, and the forecasts are worse than the current state. These effects are particularly exacerbated when there are no facilities for treating wastewater and faeces, and/or when hygiene practices are poorly applied by the population. This results in the contamination of water with pathogenic micro-organisms, such as bacteria, viruses and protozoa, which are responsible for a long list of waterborne diseases such as cholera, typhoid fever, dysentery, protozoan infections, etc… (Pichel et al., 2019; WHO, 2022).

“Safe water” is defined as water whose consumption “does not pose a significant risk to health over a lifetime, including the different sensitivities that may arise between life stages” (WHO, 2011). A new human right has been defined by the UN General Assembly: everyone has the right to sufficient, safe, physically accessible, and affordable water for personal and domestic use, as well as sanitation. In 2015, the United Nations decided to follow a new sustainable development agenda which includes 17 Sustainable Developments Goals (SDG), among which the SDG 6 aims to ensure universal and equitable access to safe and affordable drinking water by 2030. Achieving this goal is particularly critical for a part of the population living in remote rural areas. Indeed, this is a crucial issue as four out of five inhabitants in the world who do not have access to safe drinking water sources live in rural areas. Today, one third of people living in the countryside still lack access to improved safe water sources and 40% live without sanitation facilities. These disparities are particularly concentrated in sub-Saharan Africa where almost half the population uses non-potable water, drawn directly from rivers, lakes, ponds, and irrigation canals. These types of water points can be easily contaminated by faecal matter since in emerging countries, 80% of wastewater resulting from human activities is directly discharged into surface waters without any treatment (Bijekar et al., 2022).

For highly remote areas, water treatments using chemical disinfectants, such as chlorination may not be suitable because of the difficulty of achieving in practice a constant and regular supply. In these cases, the design of water treatment processes without any consumables, based on solar energy, which is abundant in many regions where drinking water is lacking, is highly relevant. Emerging solar technologies based on membrane filtration or UV disinfection represent a pertinent alternative to chemical treatment and could address the lack of access to clean water and electricity in these remote areas (Blanco et al., 2009).

The objective of the study is to present an innovative process based on membrane filtration driven by thermal energy delivered at 60-70°C by standard solar thermal collectors. The key points of the process operating mode are described. The specific energy consumed SEC_{solar} (kWh/m^3), the amount of solar energy necessary to produce one cubic meter of safe water, is estimated for this new process. It is compared to the specific energy consumed by the UV disinfection and ultrafiltration process driven by photovoltaic energy delivered by PV panels, the other options currently studied.

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A new thermo-hydraulic membrane filtration process for drinking water production

Process driven by photovoltaic energy

UV disinfection is based on the photochemical effect induced by UV rays that creates lesions in the DNA of micro-organisms, blocking cell division and possibly leading to cell death (Kowalski, 2009). Today, UVC lamps powered by a photovoltaic system with an associated hydraulic pump and filter can ensure complete inactivation of pathogens with an electrical consumption between $[0{,}35 - 0{,}6]\ kWh/m^3$ (Lui et al., 2014 ; Younis et al., 2019 ; Nyangaresi et al., 2018). Solar water disinfection, SODIS, is an interesting low-tech alternative process that uses the germicidal effect of UV-A and UV-B radiation contained in solar irradiation, combined with a thermal effect close to the pasteurisation principle. Water to be treated is placed in a transparent bottle exposed to the sun. A 3 Log (or 99.9%) reduction of Escherichia coli can be achieved with 5 hours of exposure to the midday sun (Wegelin et al., 1994).

Filtration-based water treatment is the mechanical removal of micro-organisms and macromolecules from water. This technology is widely used in developing countries to obtain drinking water. Water purification by membrane filtration is based on pressurising water to establish a pressure difference across a membrane to separate macromolecules and/or micro-organisms from the water to be treated (Aimar et al., 2010). The choice of an appropriate membrane module depends on the nature of the micro-organisms and additives present in the water. For surface water treatment, ultrafiltration is recommended as it offers a good compromise between the required applied pressure and the retention capacity of the micro-organisms. It has been found that an ultrafiltration membrane with a pore diameter of about 10 nm can achieve a retention of more than 99.999% (5 Log reduction) of bacteria, protozoa and viruses (Jacangelo, 1995). For some years, researchers have been interested in the water treatment process using PV-driven pumps to pressurise the water to be treated. The results, based on processes found in the literature, show an operation requiring an electrical consumption varying between 0.35 and $1\ kWh/m^3$ (Chew and David, 2019 ; Schäfer et al., 2018 ; Davey and Schäfer, 2009). These PV systems commonly use several hydraulic pumps: a first one to pump the water, which is pre-filtered and stored in a tank before being treated, and a second pump that pressurises the water so that it can be filtered through the membrane to produce drinking water (Fig.1).

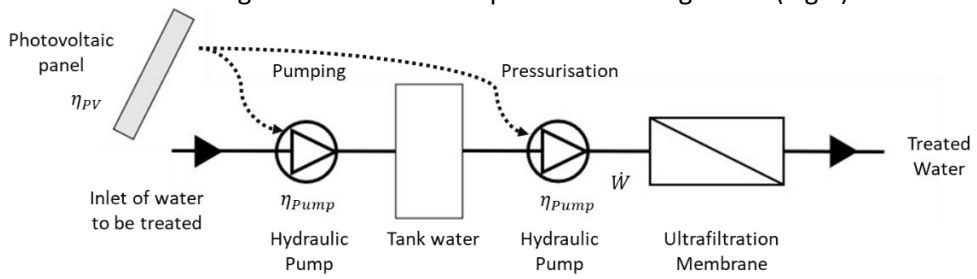

Figure 1: Membrane filtration process for remote locations driven by photovoltaic energy

Membrane filtration driven by low temperature solar energy

Unlike membrane filtration processes presented in the literature that uses PV panels, the thermo-hydraulic water treatment innovative process, illustrated by figure 2, uses solar thermal energy delivered by solar collectors to perform membrane filtration. This process is a simplified version of the thermo-hydraulic process previously developed specifically for desalination by Lacroix et al. (2020) at PROMES-CNRS laboratory. It consists of two mains parts interconnected : a first assembly consisting of a solar collector thermally feeding a thermodynamic Rankine-like engine cycle that produces the hydraulic work required for the water pressurisation; a second hydraulic assembly composed of the pressurisation and energy recovery device and the ultrafiltration membrane. The thermodynamic cycle uses *n-butane* as a heat transfer fluid which is vaporised by an evaporator and the thermal energy supplied by the solar collector. This vapour pressurises a volume of water contained in a transfer cylinder (not included in figure 2). The pressurisation and energy recovery device is operated by this

hydraulic energy in order to ensure the pumping of contaminated water, the water flow circulation in the process and the pre-pressurisation between the atmospheric pressure P_{atm} (Pa) and the low pressure of the process P_{low} (Pa). A set of distributor and valves, not shown in this diagram, switch the operating phases of the pressurisation and energy recovery device for continuous use.

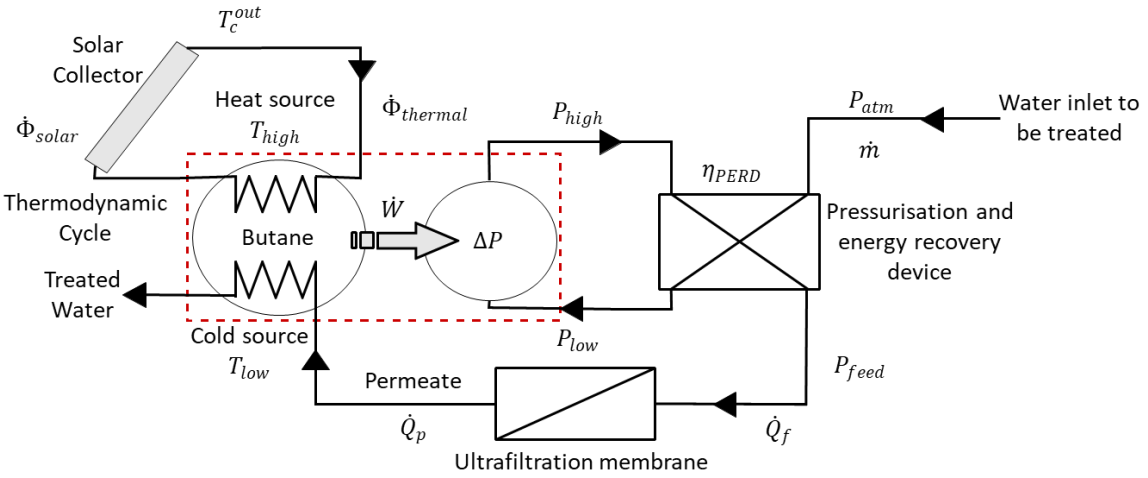

Figure 2: Solar thermal membrane filtration process

The heat $\Phi_{thermal}$ (W) provided by the solar collector is used as a source for the thermodynamic cycle (Eq. 1).

$$\Phi_{thermal} = \Phi_{solar} . \eta_{coll} = I_{inc} . S_{coll} . \eta_{coll} \quad (1)$$

With Φ_{solar} (W) the solar energy, η_{coll} $(-)$ the solar collector efficiency, I_{inc} (W/m^2) the solar irradiation and S_{coll} (m^2) the solar collector surface.

The thermal energy supplied by the solar collector at T_{high} (K) is converted by the Rankine like engine into hydraulic work $\dot{W}$ (W) (Eq.2) by exploiting the evaporation/expansion process of the working fluid (butane) at high pressure P_{high} (Pa) and temperature T_{high} and its condensation at low pressure P_{low} (Pa) at water temperature T_{low} (K). The work thus produced is exploited by 2 transfer cylinders (not represented) alternatively connected to the evaporator and the condenser, to pressurise at P_{high} a mass flow rate $\dot{m}$ (m^3/s) of water to be treated which is previously pre-pressurised at P_{low} thanks to the hydraulic energy recovery device.

$$\dot{W} = \dot{m} * (P_{high} - P_{low}) \quad (2)$$

The pressurisation and energy recovery device, illustrated in figure 3, is composed of a tandem double-acting hydraulic cylinder which is similar to a Clark pump type pressure exchanger (Thomson et Miranda, 2000). Thanks to the water pressurised at the evaporator pressure P_{high} in the transfer cylinder, this device allows, on the one hand, to pump the water in a first chamber at atmospheric pressure P_{atm} and to pre-pressurise it at the pressure P_{low} corresponding to the condenser pressure of the Rankine cycle, and, on the other hand, to feed via the second chamber the membrane module with water still pressurized at a residual pressure, the feed pressure of the membrane P_{feed} (Pa) lower than P_{high}. The balance of forces applied to this tandem double-acting hydraulic cylinder, which is characterized by a hydraulic efficiency η_{PERD} $(-)$ and a surface piston S_{cyl} (m^2), is defined by the equation 3.

$$\eta_{PERD} S_{cyl} (P_{high} + P_{atm}) = S_{cyl} (P_{low} + P_{feed}) \quad (3)$$

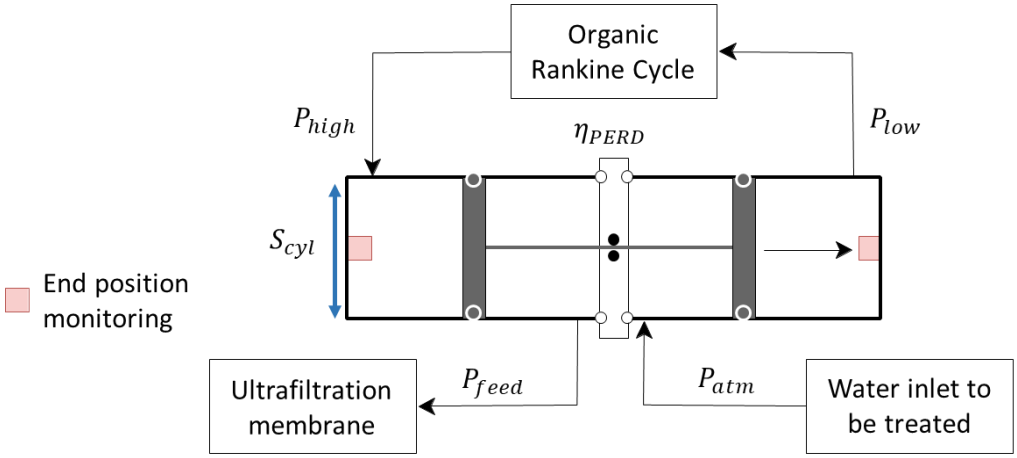

Figure 3: Operation of the pressurisation and energy recovery device

The remaining pressure (P_{feed}) enables the ultrafiltration membrane to operate and allows the separation of the microorganisms from the water. The hydraulic power $\Phi_{hyd}\ (W)$ (Eq. 4) that is produced by the thermodynamic process associated to the tandem hydraulic cylinder is then defined as :

$$\Phi_{hyd} = \dot{Q}_f * \left(P_{feed} - P_{atm}\right) \tag{4}$$

With $\dot{Q}_f$ the membrane feed flow (m^3/s).

The flow $\dot{Q}_p\ (m^3/s)$ of clean water that is produced by the membrane (permeate) is a function of the transmembrane pressure difference and the product $(L_{memb}.S_{memb})$ representing respectively the permeability of the membrane $(m/s.Pa)$ and its surface (m^2) (Eq. 5). The permeate flow is latter used as a cold source by the Rankine like cycle to release the heat of condensation of the working fluid (butane):

$$\dot{Q}_p = (LS)_{memb} * \left(P_{feed} - P_{atm}\right) = (LS)_{memb} * \Delta P_{memb} \tag{5}$$

A part not shown of the principal diagram, but which is important for the operation of the process is the backwash procedure. An additional double – acting tandem hydraulic cylinder with two pistons of different surface area is arranged to pump a given volume of permeate to backwash through the membrane and remove clogging particles caught on the membrane surface. This operation is triggered in a specific way depending on the water quality to maintain the correct permeability of the membrane in the long term (Chang et al., 2017). A set of solenoid valves allows the filtration process to be interrupted and the membrane cleaning action to be started.

In order to evaluate the specific energy consumed by such a thermo-hydraulic process, a numerical model has been developed considering steady state operating conditions and the associated heat and mass balance for each of the components of the process leading to a set of 25 equations to be solved. Several assumptions are made: (1) pure water is used, the permeability of the membrane is presumed to be constant and backwash is not taken into account ; (2) the chosen membrane has an active surface $S_{memb} = 4\ m^2$ and a permeability $L_{memb} = 180L/(h.m^2.bar) = 5.10^{-10}\ (m/s.Pa)$; (3) an efficiency $\eta_{PERD} = 0.85$ is assumed for the double acting tandem cylinder used as pre-pressurisation device. The choice of a specific membrane affects the optimal operating conditions of the process. In the considered case, in order to limit water or energy losses, the membrane must tend to a "dead-end" filtration, i.e. the ratio $Y_{memb}\ (-)$ between the permeate and the feed flow rates must be close or even equal to 1. According to equation 5, this ratio is function of feed flow $\dot{Q}_f$ and ΔP_{memb}. Figure 4.a represents the obtained transmembrane pressure as a function of solar collector outlet temperature T_c^{out} (°C). The transmembrane pressure difference varies between 0 and 3 bars in order to respect the manufacturer's recommendations and to preserve the good quality of the filtration.

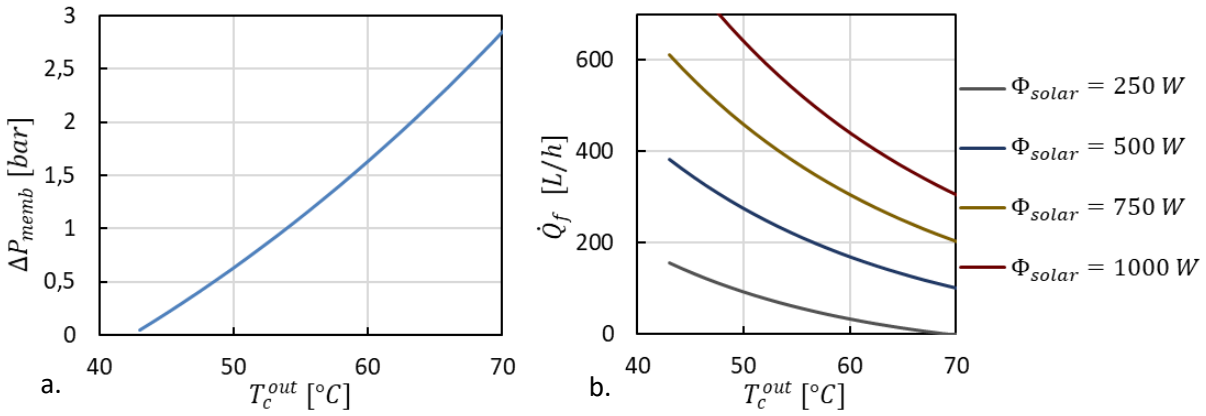

Figure 4: a. Transmembrane pressure obtained as a function of collector outlet temperature; b. Feed rate obtained as a function of solar power and collector outlet temperature

The feed flow rate results from two parameters : the input solar power Φ_{solar} and the high operating pressure P_{high} in the thermodynamic cycle, resulting from the outlet heat of the solar panel at T_c^{out}. The figure 4.b shows the feed flow rate obtained as a function of the solar power and T_c^{out}. These two previous graphs have opposite dynamics for the variables of transmembrane pressure and feed rate. This results in optimums for the permeate flow, which correspond to "dead-end" filtration, i.e. the ratio $Y_{memb} \approx 1$. Figure 5 shows the theoretical permeate production for different solar power values. An optimum can be observed for each solar intensity. For the characteristics of the chosen membrane and with a conventional solar collector of 2 m², the permeate production is maximized for a given operating outlet collector temperature : it is about 300 L/h for 500 W with T_c^{out} of 48°C and 580 L/h for 1000 W with T_c^{out} around 52°C.

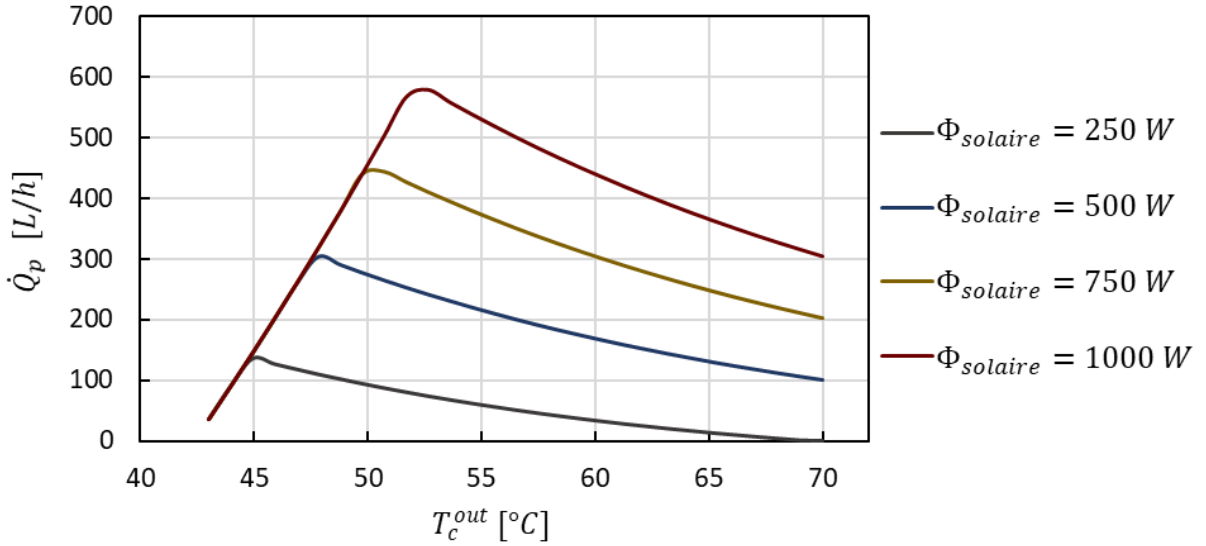

Figure 5: Production of permeate obtained as a function of collector outlet temperature

Discussion and comparison of energy performance

The specific energy consumption indicator (SEC) is chosen here to rank the different solar-operated systems presented above. Although this criterion alone does not provide a full representative view of the quality of the process, it nevertheless provides a relevant way to compare the various technologies discussed.

In the case of membrane filtration, there are several types of energy involved in the process. Firstly, the final energy used for membrane separation: hydraulic energy. The corresponding criterion is defined, the $SEC_{hydraulic}$ (Eq. 7), which corresponds to the difference in pressure used per cubic

meter of clean produced water, i.e. the daily volume of permeate obtained $\int \dot{Q}_p \, dt \; (m^3)$. In the PV-powered process, this hydraulic energy comes from a set of pumps that are powered by electricity. Then a more appropriate criterion to evaluate this consumption is the $SEC_{electrical}$. In the second type of membrane filtration, which is thermally driven, the hydraulic energy is provided by the Rankine-like cycle that uses thermal energy. In this case, a $SEC_{thermal}$ is more relevant (Eq. 8). It is highly dependent on the efficiency of the thermodynamic cycle and its operating temperatures.

For the two processes presented, the starting energy corresponds to the solar radiation that is either collected by a PV panel or a solar collector. Then, the definition of a SEC_{solar} is the most suitable criterion for comparing the processes in terms of area of implemented solar collectors or panels. It is defined by equation (9).

$$\mathbf{SEC_{hydraulic}} = \int \frac{\dot{W}}{\dot{Q}_p} \, dt \left[\frac{kWh}{m^3}\right] \qquad \mathbf{SEC_{thermal}} = \int \frac{\Phi_{thermal}}{\dot{Q}_p} dt \left[\frac{kWh}{m^3}\right] \qquad \mathbf{SEC_{solar}} = \int \frac{\Phi_{solar}}{\dot{Q}_p} dt \left[\frac{kWh}{m^3}\right] \quad (7\text{-}9)$$

For a realistic assessment of performance and technologies comparison, a solar efficiency of 20% for photovoltaic panels and 50% for solar thermal collectors is generally assumed (Slaoui, 2019; Kumar and Rosen, 2011).

The daily variations in solar radiation can also affect the operation and performance of these water treatment processes. In the case of the thermal membrane filtration process, the optimum couple between collector outlet temperature and solar energy input cannot be achieved at all times. Thus, a compromise must be found by implementing a thermostatic valve to reduce the variation of the collector outlet temperature and by designing the appropriate surface of the solar collector to maximise the permeate production. For a concrete use case, the solar process is equipped with an ultrafiltration membrane with a surface of $4 \; m^2$. As described in figure 5, an interesting production of permeate is obtained for T_c^{out} around 50°C ± 2°C for solar powers varying between 250 and 1000 W. According to the irradiation of the summer season 2020 in the south of France (Perpignan), a surface of $2 \; m^2$ for the solar collector allows to collect a solar Φ_{solar} up to 1000 W.

The other elements of the process (thermodynamic cycle, cylinder) are dimensioned with the numerical model in steady state in order to reach the outlet collector temperature of $50°C$. The operation of such a designed process has been simulated considering real solar irradiation conditions corresponding to the 2020 summer season in Perpignan, France. A production of 3,5 cubic meters per day could then realistically be achieved. It corresponds to an average SEC_{solar} of 2.5 kWh/m^3.

Table 1 summarises the energy efficiencies of the different potabilisation process technologies solar driven by photovoltaic or thermal panels. UV technology, sometimes considered as not very robust (problems with light transmission, lamp efficiency, recontamination) (Amano et al., 2020), is interesting according to the SEC criterion. Taking into account the efficiency of the PV panel (20 %) and according to literature values (Lui et al., 2014; Younis et al., 2019; Nyangaresi et al., 2018), between 2 and 3 kWh of solar energy are needed to produce one cubic metre of drinking water. Membrane filtration processes, whether powered by photovoltaic or thermal energy, are in the same range of energy efficiency. The advantage of a solar thermal water treatment process is that it uses mainly thermal or hydraulic components of proven robustness. Thermal inertia phenomena reduce the impact of variations in solar irradiation. On the other hand, the presence of electrical components in the process powered by a photovoltaic system is sensitive to on/off cycles which can be frequent on cloudy days. However, the operation does not require the use of a working fluid in a thermodynamic cycle, which makes the process simpler to manage.

	UV PV-powered	**UF PV-powered**	**UF Solar thermal**
$SEC_{hydraulic}$ $[kWh/m^3]$	-	0.1 – 0.3	0.1 – 0.3
$SEC_{thermal}$ $[kWh/m^3]$	-	-	1 – 2.5 *
$SEC_{electrical}$ $[kWh/m^3]$	0.36 – 0.6	0.35 – 1	-
SEC_{solar} $[kWh/m^3]$	1.8 – 3	1.75 – 5	2 – 4 *

*: simulated result

Table 1: Summary table of specific energy consumption of the different water treatment technologies that can be implemented in remote regions

Conclusion

Disinfection of water in remote areas is a critical, location-specific issue. Ultrafiltration is a relevant technology to solve the problem of access to drinking water in remote areas of developing countries. The reliable, simple and energy-efficient nature of the filtration process makes it suitable for small decentralised systems. Energy requirements can be met in a variety of ways, using electricity from renewable resources, solar thermal energy or other means not mentioned here (hand pump, gravity…). This study shows the energy relevance of a solar thermal powered water treatment process using the retention capacity of an ultrafiltration membrane. Compared to the other processes mentioned, the thermo-hydraulic process is characterised by an order of magnitude lower energy consumption, while the adaptability and robustness of the process is improved by the integration of thermal and hydraulic components. However, further work is needed, such as a numerical model in dynamic regime and its validation on an experimental bench to evaluate more precisely its performance and its technical-economic relevance.

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