Design of a Modular Solar Driven Multi-Effect Distillation System for Producing Clean Drinking Water in Canada's Northern Indigenous Communities

Luka Khorbaladze[1], Jean Duquette[1]
[1]Carleton University, Ottawa, Canada

Abstract

Canada's northern Indigenous communities often face harsh living conditions, and many depend on bottled water on a daily basis due to frequent long-term drinking water advisories that are in effect. Solar thermal assisted multi-effect distillation has been shown to be a sustainable solution for producing clean water for domestic use. Nonetheless, there is a lack of research regarding its suitability in northern Canadian climates. In this study, a numerical model of a modular three-tank multi-effect distillation (MED) system driven by a solar thermal collector is developed and used to assess its ability to provide clean water to a hypothetical multi-unit residential building located in the Canadian Indigenous remote community of Moose Factory, Ontario. Results show the proposed MED system can produce around 920 kg of distillate per day under design conditions, which satisfies the water consumption requirements of the residents of the case study building. This model will be improved upon to increase distillate output and system efficiency.

Introduction

Indigenous communities located in northern remote areas of Canada have faced challenges in recent years with accessing clean drinking water (Blunt, 2023). Years of negligence, mismanagement, and delays, as well as a lack of any formal national strategy for addressing these challenges have exacerbated the problem (Stefanovic, 2020).

A promise was made by the federal government in 2015 to terminate all long-term drinking water advisories for all Canadian Indigenous communities by March 2021. Unfortunately, in late 2020, this promise was delayed to an unspecified future date as an additional $1.5 billion in funding was still needed to end the remaining water advisories in all affected communities (Stefanovic, 2020) Currently, there are twenty-eight long-term drinking water advisories in place on Indigenous reserves in Canada, with twenty-four of them being in remote Indigenous communities in Ontario (Blunt, 2023). These advisories are usually in place for a year or longer and signify that tap water can only be consumed if it is boiled first. This typically causes communities to become reliant on non-renewable energy sources such as diesel for clean water provision, which in turn increases local greenhouse gas emissions (Indigenous Services Canada, 2021). Diesel is a common source of energy that remote Indigenous communities rely on for heating and electricity generation purposes (Pembina Institute, 2021). There has been progress in displacing diesel as the primary energy source in these communities in recent years. For example, over the last five years, its usage has been decreased by approximately 12 million litres per year. Nonetheless, the total diesel usage remains high in these locations, at roughly 682 million litres per year (Pembina Institute, 2021).

One technology that has the potential to provide clean water to remote Indigenous communities, while simultaneously reducing GHG emissions, is solar thermal assisted multi-effect distillation (MED). Multi-effect-distillation is a type of distillation process in which pure water (*i.e.*, drinking water) is separated from feedwater (*i.e.*, contaminated or salt water) via an evaporation process (Palenzuela et al., 2015). MED systems are advantageous in that they are reliable, involve minimal labour, operate at low temperature, and can easily combine with other thermal sources like solar energy (Rahimi & Chua, 2017). Solar-driven multi-effect distillation systems harness solar thermal energy using solar thermal panels or parabolic concentrators to fuel the process. The evaporative process occurs in pressure-controlled evaporator vessels called effects.

Numerous studies have successfully demonstrated the operation of this combined process. For example, Xia et al. (2018) integrated a multi-effect heat recovery system for seawater desalination with a passive solar compound parabolic concentrator (CPC) system in an experimental study performed in Shanghai, China. This study showed the effectiveness of a low-maintenance desalination system powered by solar energy, which required no external energy for pump operation as pressure differences in the system were sufficient to promote flow. This experiment was able to produce 4.23 L of fresh water per day per m^2 of solar collector area, with no required auxiliary energy consumption. In a larger scale experimental study, Askari & Ameri (2018) combined a solar Rankine cycle powered by a linear Fresnel solar field with a multi-effect desalination

system. The system which was located in Iran included 14 distillation effects, a total effect area of 37707 m^2, and a solar field area of 4.78 km^2, and was capable of producing up to 100 million L of fresh water per day. Leblanc et al. (2009) conducted an experimental study in Australia utilizing a similar (but smaller scale), low-temperature solar-thermal multi-effect desalination system. They found that a three-effect system, with effect and condenser heat transfer areas of 1 m^2 each, could provide between 900 to 2300 L of freshwater production per day depending on the solar pond supply temperature, with recovery rates of between 35-55%. They also developed a numerical model of their system and found that the simulated distillate production was slightly greater than the values obtained experimentally. This overcompensation was largely due to the simplifying assumptions used in the model which included discounting thermal losses in the system and neglecting the effect of non-condensable gasses. The latter assumption was found to have minimal impact on the overall system performance.

Although many studies in the literature have shown the viability of solar MED water purification in hot climates with high solar irradiation, there is a lack of research focusing on solar MED system operation in non-optimal climates such as northern Canada. Furthermore, most studies previously conducted are aimed at small-scale experimental or mid- to large-scale commercial/industrial solar MED systems. To the authors' knowledge, no work has been conducted to date on determining these systems' performance at the residential or multi-unit residential building (MURB) scale. The main objective of this research is to assess the technical feasibility of utilizing a solar MED system for meeting the daily clean water requirement of a MURB located in a northern Canadian Indigenous community. A sub-objective of this research is to develop a novel solar MED design for operation in remote locations that prioritizes system efficiency and modularity and minimizes complexity.

Methodology

A steady-state numerical model is developed of the proposed solar MED system in the MATLAB® environment and integrated into TRNSYS. The system is sized and operated to meet the daily potable water requirements (faucet only) for 24 residents living in a hypothetical 12-unit MURB located in the Canadian remote Indigenous community of Moose Factory, Ontario. A verification of the model is conducted by comparing system performance results with those obtained in the literature. System performance is quantified via calculation of the recovery ratio (RR) and performance ratio (PR) - both are dimensionless parameters commonly used to assess MED systems. The following sections provide a detailed description of the methods used to develop the model and output the results.

Case Study Community

Moose Factory is an Island community located in northern Ontario with a population of approximately 2546 (Statistics Canada, 2023). The community is in the northern section of the Moose River, nearby where the river joins James Bay. Due to its location, there is no road access to the community. Transport options to reach Moose Factory are therefore limited to boat transport in the summer and fall, ice roads in the winter, and helicopter travel in the spring (Moose Cree First Nation, 2018).

Estimation of Daily MURB Clean Water Requirement

The solar MED system proposed in the current study is designed to meet the potable water requirements (faucet only) for 24 residents occupying a hypothetical 12-unit MURB in the case study community. Figure 1 is a rendering of the MURB used in the analysis. According to Statistics Canada, a 2019 survey of drinking water plants reported that the average daily per capita usage of residential domestic water in Canada was roughly 215 litres (Statistics Canada, 2021). This quantity includes water usage for drinking, dishwashing, clothes washing, toilet water, personal hygiene, and all other residential uses. As the proposed solar MED system aims to provide potable water for drinking, dishwashing, and personal hygiene only, it is assumed that the required quantity can be estimated from faucet usage. Since faucet usage accounts for approximately 17% of the average daily per capita usage of residential domestic water in Canada, the benchmark for a clean water provision system to the MURB is estimated to be 36.55 L/person/day (Safe Drinking Water Foundation, 2017). Since there are 24 residents in the MURB, the total potable water requirement amounts to roughly 877.2 L/day.

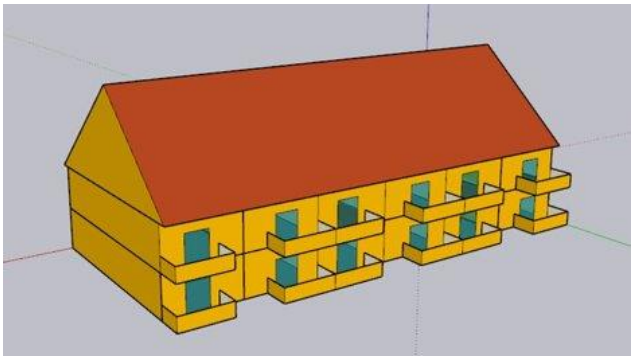

Figure 1: Rendering of multi-unit residential building (MURB) used in the analysis (Carleton University, EcoGen Energy, 2023)

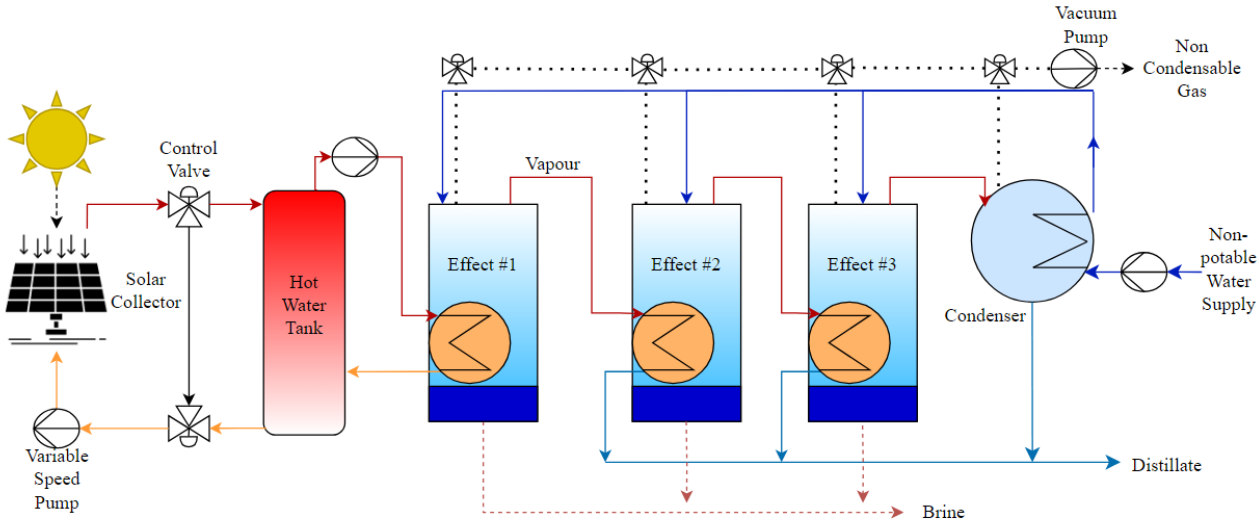

Figure 2: Schematic of proposed three-effect solar MED system

Solar MED System Layout and Operation

The proposed solar MED system consists of a solar array, a hot water storage tank, three evaporators/effects, and a condenser. The system also contains multiple control valves, circulation pumps, and a vacuum pump. The layout of the system is depicted in Figure 2.

Each effect contains a heat exchanger, a space for vapour formation, a water pool, and space for brine collection. The effects have an input for the feedwater (*i.e.*, the non-potable water supply), as well as outputs for non-condensable gasses, formed vapour to be used as the heat source for evaporation in the following effect, and brine removal. The 1st effect differs from the others as it uses hot water from the hot water tank as the heat source input into the heat exchanger. The 2nd and 3rd effects use the latent heat of evaporation of the steam generated in the previous effect as the heat source. The steam then condenses into fresh potable water (*i.e.*, distillate). Multi-effect distillation improves upon the efficiency of a single distiller by utilizing latent energy in the produced steam as a source of heat in the 2nd and 3rd effects, thereby producing more potable water with less energy demand from the hot water tank.

The condenser acts as a heat exchanger to condense the generated steam in the final effect into distillate, while simultaneously preheating the incoming feedwater. The addition of a condenser also increases the overall system efficiency as higher temperature feedwater requires less heat input from the hot water tank to evaporate. Falling film horizontal tubes are typically used in the evaporators and condenser as they provide high efficiency of heat transfer (Li, Goswami, & Stefanakos, 2013).

The vacuum pump allows the effects and the condenser to be operated at a lower pressure to reduce the saturation temperature, allowing for evaporation of feedwater at lower temperatures (< 333 K). The vacuum pump also removes non-condensable gasses from the evaporators and the condenser.

Solar MED System Model

A numerical model of the proposed solar MED system is developed in the TRNSYS environment. The MED portion of the system is modelled in MATLAB® and called into TRNSYS via one of its interface components - Type 155. Type 155 allows for the seamless execution of commands from MATLAB® scripts in the TRNSYS environment. The solar MED system is modelled using a series of thermodynamic mass and energy equations. The following assumptions are made in formulating the model:

- The system operates at steady state (*i.e.*, the solar thermal collector and hot water tank are not explicitly modelled in TRNSYS. It is assumed that the water entering the MED from the hot water tank is at constant temperature and mass flow rate, and that all other input parameters remain fixed),
- The effect of non-condensable gasses is neglected,
- The distillate is salt free,
- Heat losses between effects is negligible,
- The specific heat capacity of water is constant (*i.e.*, 4.174 kJ/kgK),
- The temperature distribution in the effects is uniform in space,
- The properties of distillate, brine, and steam are temperature and pressure dependent.

The equations for the 1st effect are governed by mass and energy balances between the incoming feedwater and hot water entering the heat exchanger. A mass flow balance of the effect is given by the following equation:

$$\dot{m}_{fw} = \dot{m}_{vout,1} + \dot{m}_{brine,1} \quad (1)$$

where $\dot{m}_{fw,1}$ (kg/s) represents the mass flow rate of the feedwater entering the effect, and $\dot{m}_{vout,1}$ (kg/s) and

$\dot{m}_{brine,1}$ (kg/s) represent the mass flow rate of the vapour leaving the effect, and the mass flow rate of brine, respectively.

The balance of brine concentration in the feedwater is given by the following equation:

$$X_{fw}\dot{m}_{fw} = X_{brine,1}\dot{m}_{brine,1} \quad (2)$$

where X_{fw} and $X_{brine,1}$ (both in weight percent) represent the concentration of brine in incoming feedwater and the exiting brine solution, respectively.

The energy balance of the 1st effect is given by the following equation:

$$\dot{m}_{hxin}(Cp)(T_{hxin} - T_{hxout}) = \dot{m}_{vout,1}\Delta h_{vout,1} + \dot{m}_{brine,1}h_{brine,1} + \dot{m}_{fw}(Cp)(T_{sat,1} - T_{fw}) \quad (3)$$

The terms on the left-hand side of the equation represent the net input energy from the heat exchanger, where $\dot{m}_{hxin}$ (kg/s) is the mass flow rate of hot water entering the heat exchanger, Cp (kJ/kgK) is the specific heat capacity of water, and T_{hxin} (K) and T_{hxout} (K) are the temperature of the fluid entering and leaving the heat exchanger, respectively. The terms on the right-hand side of the equation represent the input energy from the feedwater and the output energy from evaporation and exiting brine. $\Delta h_{vout,1}$ (kJ/kg) represents the latent heat of evaporation of steam, $h_{brine,1}$ (kJ/kg) represents the enthalpy of brine, and $T_{sat,1}$ (K) represents the saturation temperature of water vapour, at a given saturation pressure. The enthalpy of the brine is calculated using the following correlation for LiBr water solutions (El-Dessouky & Ettouney, 2002):

$$h_{brine,1} = X_{brine,1}\sum_{i=0}^{4} a_i {T_{sat,1}}^i + (1 - X_{brine,1})\sum_{i=0}^{2} b_i {T_{sat,1}}^i + X_{brine,1}(1 - X_{brine}) \sum_{i=0}^{4}\sum_{j=0}^{3} c_{ij}(2X_{brine,1} - 1)^i {T_{sat,1}}^j \quad (4)$$

where,

$$a_0 = 508.668, a_1 = 18.6241,$$
$$a_2 = 0.0985936, a_3 = -2.500979 * 10^{-5}$$
$$a_4 = 4.15801 * 10^{-8}, b_0 = 1.617155702,$$
$$b_1 = 4.10187485, b_2 = 0.00071766$$
$$c_{00} = -1021.61, c_{10} = -533.08,$$
$$c_{20} = 483.628, c_{30} = 1155.13$$
$$c_{40} = 640.622, c_{01} = 36.8773,$$
$$c_{11} = 40.2847, c_{21} = 39.9142$$
$$c_{31} = 33.3572, c_{41} = 13.1032$$
$$c_{02} = -0.186051, c_{12} = -0.191198$$
$$c_{22} = 0.199213, c_{32} = -0.178258,$$
$$c_{42} = -0.07751, c_{03} = -7.51277 * 10^{-6}$$
$$c_{13} = c_{23} = c_{33} = c_{43} = 0$$

The correlations for determining the latent heat of evaporation and the saturation temperature are given as follows (El-Dessouky & Ettouney, 2002):

$$\Delta h_{vout,1} = 2501.897149 - 2.407064037\,{T_{sat,1}}^2 + 1.192217\text{x}10^{-3}\,{T_{sat,1}}^2 - 1.5863\text{x}10^{-5}\,{T_{sat,1}}^3 \quad (5)$$

$$T_{sat,1} = \left(42.6776 - \frac{3892.7}{\left(\ln\left(\frac{P_{sat,1}}{1000}\right) - 9.48654\right)}\right) - 273.15 \quad (6)$$

The heat transferred to the heat exchanger from the hot water tank, Q_1 (kW), is assumed to be carried out using a cross-flow heat exchanger. The following expression applies:

$$Q_1 = \dot{m}_{hxin}(Cp)(T_{hxin} - T_{hxout}) = UA_{hx}\Delta T_{lm} \quad (7)$$

where A_{hx} (m^2) is the area of the heat exchanger, ΔT_{lm} (K) is the log mean temperature difference corresponding to the crossflow heat exchanger, and U (kW/m^{2}K) is the overall heat transfer coefficient for a fouled evaporator.

The log mean temperature difference of the crossflow heat exchanger is expressed as:

$$\Delta T_{lm} = \frac{(T_{hxin} - T_{sat,1}) - (T_{hxout} - T_{fw})}{\log\left((T_{hxin} - T_{sat,1}) - (T_{hxout} - T_{fw})\right)} \quad (8)$$

and the correlation for U is given by (El-Dessouky & Ettouney, 2002):

$$U = 1 \times 10^{-3}\left(\begin{matrix}1939.4 + 1.40562\,T_{sat,1} - \\ 0.0207525\,{T_{sat,1}}^2 + \\ 0.0023186{T_{sat,1}}^3\end{matrix}\right) \quad (9)$$

Finally, the temperature of the vapour exiting the evaporator, T_{vo} (K), is calculated using the following equation:

$$T_{vo,1} = T_{sat,1} - BPE \quad (10)$$

where BPE (K) is the boiling point elevation which represents the change in the boiling point of a liquid depending on the presence of solute in the solvent. With regards to the concentration of the brine, the following relations applies:

$$BPE = AX_{fw} + B{X_{fw}}^2 + C{X_{fw}}^3 \quad (11)$$

$$A = 0.08325 + 0.0001883\,(T_{sat}) + 0.00000402\,({T_{sat}}^2) \quad (12)$$

$$B = 0.0007625 + 0.0000902\,(T_{sat}) - 0.00000052{T_{sat}}^2 \quad (13)$$

$$C = 0.0001522 - 0.0000030\,(T_{sat}) - 0.000000030\,{T_{sat}}^2 \quad (14)$$

The schematic of the energy balance corresponding to the 1st and 2nd effects is shown in Figure 3.

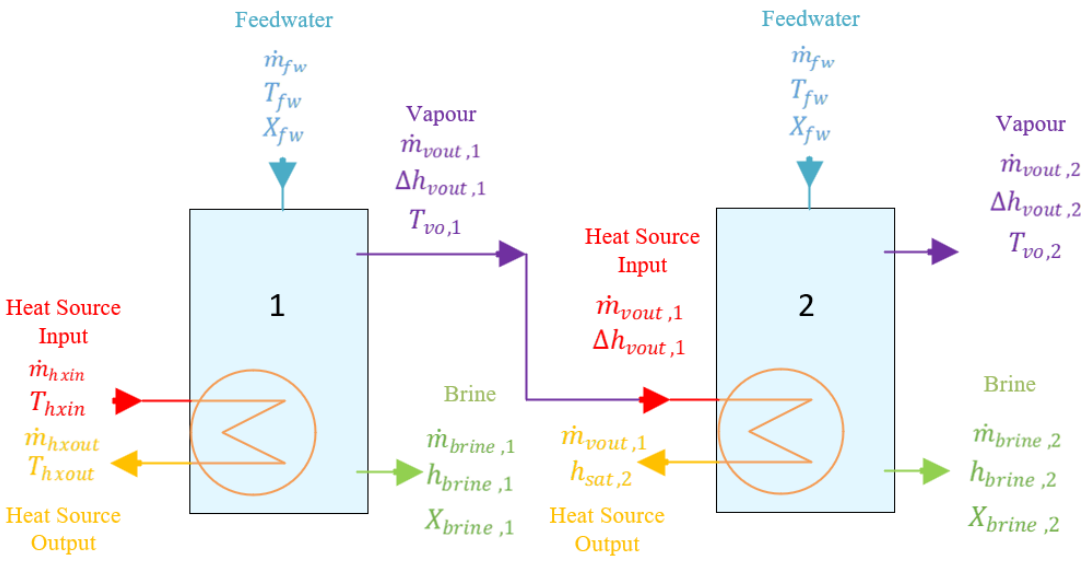

Figure 1: Schematic of energy balance in the 1st and 2nd effects (The 3rd effect is not shown as it is identical to the 2nd effect).

The governing set of equations for the 2nd and 3rd effects are the same as the 1st effect except for slight changes in the energy balances. This is due to the heat source being the vapour produced in the previous effect instead of the water from the hot water tank. The energy balance in the 2nd and 3rd effects is given by the following equation:

$$\dot{m}_{vout,i-1}\Delta h_{vout,i-1} = \dot{m}_{vout,i}\Delta h_{vout,i} + \dot{m}_{brine,i}h_{brine,i} + \dot{m}_{fw}Cp * (T_{sat,i} - T_{fw,i}) \quad (15)$$

The terms on the left-hand side represent the energy input into the 2nd effect, where $\dot{m}_{vout,i-1}$ (kg/s) is the mass flow rate of vapour produced in the previous effect, and $\Delta h_{vout,i-1}$ (kJ/kg) is the latent heat of evaporation of the vapour produced in the previous effect. The terms on the right-hand side of Equation 15 represent the same parameters as listed in Equation 3, where the subscript i denotes which effect (2nd or 3rd) is being analysed.

The heat transferred to the heat exchanger in the i^{th} effect from the produced vapour in the previous effect, Q_i (kW), is given by

$$Q_i = \dot{m}_{vout,i-1}(\Delta h_{vout,i-1}) \quad (16)$$

where $\dot{m}_{vout,i-1}$ (kg/s) is the mass flow rate of vapour produced in the previous effect, and $\Delta h_{vout,i-1}$ (kJ/kg) is the latent heat of evaporation of the vapour produced in the previous effect.

The vapour used as the heat source condenses in a cross-flow heat exchanger during this process, and its enthalpy is described by the following correlation for saturated water (El-Dessouky & Ettouney, 2002):

$$h_{sat,i} = -0.033635409 + 4.207557011T_{sat,i} - 6.200338 \times 10^{-4}{T_{sat,i}}^2 + 4.459374 \times 10^{-6}{T_{sat,i}}^3 \quad (17)$$

The condenser (shown in Figure 2) is similarly modeled by using mass and energy balance equations. The energy balance in the condenser is expressed as:

$$\dot{m}_{vout,3}(\Delta h_{vout,3}) = \dot{m}_{cw}Cp(T_{fw} - T_{cw}) \quad (18)$$

where $m_{vout,3}$ (kg/s) is the mass flow rate of vapour produced in the 3rd effect, $\Delta h_{vout,3}$ (kJ/kg) is the latent heat of evaporation of steam, $\dot{m}_{cw}$ (kg/s) is the mass flow rate of the cool feedwater entering the condenser, and T_{cw} (K) is the initial temperature of the cool feedwater, that is to be preheated to T_{fw} (K).

Heat transfer in the condenser is modelled using the following expression that applies to a crossflow heat exchanger:

$$\dot{m}_{vout,3}(\Delta h_{vout,3}) = A_c U_c \Delta T_{lm,c} \quad (19)$$

where A_c (m^2) is the area of heat exchanger in the condenser, U_c (kW/m^{2}K) is the overall heat transfer coefficient, and $\Delta T_{lm,c}$ (K) is the log mean temperature difference across the condenser heat exchanger. The correlation for the overall heat transfer coefficient of the condenser is given by (El-Dessouky & Ettouney, 2002):

$$U_c = 1 * 10^{-3}\begin{pmatrix} 1617.5 + 0.1537\ T_{sat} - \\ 0.1825\ {T_{sat}}^2 + \\ 0.00008026 * {T_{sat}}^3 \end{pmatrix} \quad (20)$$

The log mean temperature difference of the condenser is expressed as:

$$\Delta T_{lm,c} = \frac{(T_{vo,3} - T_{cw}) - (T_{vo,3} - T_{fw})}{\log\left((T_{vo,3} - T_{cw}) - (T_{vo,3} - T_{fw})\right)} \quad (21)$$

Equations 1-21 are solved in MATLAB®. Initially, the equation set for three effects is solved and the set of equations for the condenser is solved afterwards. As the condenser also acts as a preheater for the incoming

feedwater, the temperature output of the preheated feedwater after the first iteration is assumed to be the feedwater temperature entering the effects in the next iteration. Several iterations are repeated in the model until the preheated feedwater temperature reaches a relatively constant value.

Performance Metrics

Solar MED system performance is typically quantified using the following dimensionless parameters: The recovery ratio (RR), and the performance ratio (PR). The recovery ratio is defined in Equation 22 as the ratio between the produced freshwater (*i.e.*, distillate) flow rate and the input feedwater flow rate (Joo & Kwak, 2013).

$$RR = \frac{\dot{m}_{vout,1} + \dot{m}_{vout,2} + \dot{m}_{vout,3}}{\dot{m}_{fw}} * 100 \qquad (22)$$

The performance ratio (PR) is an energy efficiency term that relates the energy input and output of the MED system. Equation 23 represents this as the ratio between the total rate of freshwater production multiplied by the latent heat of evaporation, divided by the heating power input in the 1st effect (Alsehli et al., 2020).

$$PR = \frac{(\dot{m}_{vout,1} + \dot{m}_{vout,2} + \dot{m}_{vout,3})\Delta h_{vout}}{Q_1} \qquad (23)$$

Model Verification

The proposed solar MED model is verified by comparing simulated parameter results with values obtained from the literature. The input conditions shown in Table 1 are from an experimental study conducted by Joo & Kwak (2013) in which they evaluate the performance of a small-scale solar MED system. Although the values of A_{hx} and A_c were not given explicitly in their study, they were calculated to be roughly 1.15 m^2 (based on the other values provided).

Table 1: Input parameters and values taken from experimental study in the literature (Joo & Kwak, 2013)

Input parameter	Value
$\dot{m}_{fw}$	0.03 kg/s per effect
$\dot{m}_{hxin}$	0.91 kg/s
$\dot{m}_{cw}$	1.06 kg/s
T_{sat}	333 K
T_{cw}	295 K
T_{fw}	302 K
T_{hxin}	348 K
X_{fw}	4.2%
T_{sat2}	328 K
T_{sat3}	323 K
Heating power	40 kW

The input parameters of the proposed solar MED system model were set at these values and the following outputs were calculated: freshwater production, PR, and RR. As the concentration of total dissolved solids was not provided in the experimental data, it is assumed to be 4.2%. This value is taken from a study conducted by Ghenai et al. (2021) in which they analyse a hybrid MED system driven by solar thermal energy for high salinity sea water. The hybrid system is a good point of comparison since the MED design, feedwater flow rate, and temperature are nearly identical to that of the reference system (Ghenai, Kabakebji, Douba, & Yassin, 2021). Table 2 shows the freshwater production, PR, and RR of the proposed system model relative to the experimental study performed by Joo & Kwak (2013). The system is assumed to operate for 8 hours/day at design conditions.

Table 2: Comparison of freshwater production, performance ratio (PR), and recovery ratio (RR) between proposed model and experimental study (Joo & Kwak, 2013)

Output parameter	Proposed model	Joo & Kwak, 2013
Freshwater production	1037 kg/day	1055 kg/day
PR	2.12	2.02
RR	36.4%	36.2%

The output parameter values from the proposed solar MED model align closely with those from the experimental study (with each modelled value deviating no more than ± 5% from the experimental value).

Results and Discussion

To more closely meet the daily potable water requirements of the case study MURB, the input parameters of the proposed solar MED model are adjusted to the values shown in Table 3.

Table 3: Adjusted model input parameters to meet daily potable water requirements of case study MURB

Input parameter	Value
$\dot{m}_{fw}$	0.025 kg/s per effect
$\dot{m}_{hxin}$	0.91 kg/s
$\dot{m}_{cw}$	0.075 kg/s
T_{sat}	333 K
T_{cw}	293 K
T_{fw} (preheated)	315 K
T_{hxin}	348 K
X_{fw}	4.2%
T_{sat2}	328 K
T_{sat3}	323 K
A_{hx}	0.85 m^2
A_c	0.85 m^2
Heating Power	33 kW

Inputting these values in the proposed model (and assuming that the system operates for 8 hours/day) results in a daily freshwater production of 920 kg/day (or L/day). This value is slightly greater than the calculated minimal required amount for the MURB (*i.e.*, 877.2 L/day). To gauge the system's performance, both PR and RR are also computed and shown in Table 4. The performance metrics from three additional experimental studies in the literature are also shown in Table 4 for comparison.

Table 4: Performance ratio (PR), and recovery ratio (RR) of adjusted model relative to values from experimental data.

Parameter	PR	RR (%)
Adjusted model results	2.39	45.1
Joo & Kwak, 2013	2.02	36.2
Xia, et al. 2018	2.00	40.0
Alsehli, et al. 2020	2.50	42.0
Leblanc, et al. 2009	N/A	35-55

The computed values of RR and PR fall within the range of the experimental studies shown in Table 4 which indicates that the modelled system is performing as expected with a high level of confidence.

Although these results are promising, the methods utilized in the current study contain the following limitations:

- The system is modelled using steady state conditions.
- The solar thermal collector and hot water tank are not explicitly modelled. It is assumed that hot water is supplied to the 1st effect at a fixed mass flow rate. Thus, the effects of seasonal solar availability and daily solar variability at the case study location are not considered.
- A basic MED system with three effects is modelled. It is assumed that heat is only supplied to the 1st effect and no heat is recovered from the hot brine.

Potential areas of future work include:

- Adding a solar collector and sensible hot water tank model to the current TRNSYS model. Steps will be taken to size these components appropriately for a given location. It is assumed that the system will only operate in the late spring, summer, and early fall due to the limited solar availability during the winter months in northern Canadian communities. Moreover, the seasonal period for which the system can operate shortens considerably the more north a given community is located. Therefore, and assessment will be made of the annual freshwater storage volume (and associated insulation requirements) needed for a given MURB application as the latitude increases.
- Developing a transient model of the proposed system. The model will consider variable heat input to the MED system based on local solar availability and account for pressure/temperature variations occurring within the MED vessels.
- Identifying and developing a suitable solar collector model (*e.g.*, evacuated tube, flat plat, or parabolic concentrator) that can provide hot water at the input conditions required by the MED system.
- Implementing design improvements to the proposed system such as recovering heat from the produced brine and including a parallel hot water supply line to all effects (not only the 1st effect) to improve the overall thermal efficiency of the system.
- Assessing the cost of the proposed system relative to other means of providing clean drinking water to remote Indigenous communities.

The solar MED system proposed in the current study provides an alternative sustainable pathway for supplying water locally at the community level. Purifying water locally using solar energy can greatly reduce GHG emissions relative to diesel-based water purification systems and shipping bottled water over great distances. With further advancement, modular solar MED systems can play a key role in solving the long-term drinking water advisories that are currently in place in many Canadian Indigenous communities and help prevent such crises in the future.

Conclusion

In this study, a steady-state model of a proposed solar driven multi-effect distillation system was developed for freshwater provision to a reference multi-unit residential building located in Moose Factory, Ontario. The model was developed in TRNSYS (with components developed in MATLAB®) and was verified via a comparison with experimental data from the literature. The performance of the solar MED system was evaluated by calculating the MED performance ratio (2.39), recovery ratio (45.1%), and the daily freshwater production rate (920 kg/day). Both the performance ratio and the recovery ratio were found to be similar to those obtained from experimental studies in the literature with systems operating under similar conditions. The amount of freshwater produced by the system was selected based on the per capita residential water usage for 24 residents living in the reference building and assumed an 8-hour operation time at design conditions. Future iterations of the proposed model will prioritize improving system efficiency to increase freshwater output and investigate potential system performance in various northern remote Canadian locations.

Acknowledgement

The authors would like to acknowledge and thank the Natural Sciences and Engineering Research Council (NSERC) for their financial support of this research project.

References

Alsehli, M., Saleh, B., Elfasakhany, A., Ayman, A. A., & Bassuoni, M. (2020). Experimental study of a novel solar multi-effect. *Journal of Water Reuse and Desalination, 10*(2), 120-132.

Askari, I. B., & Ameri, M. (2018). Solar Rankine Cycle (SRC) powered by Linear Fresnel solar field and integrated with Multi Effect (MED) system. *Renewable Energy, 117*, 52-70.

Blunt, M. (2023, March 22). *'We have to fix it faster': 28 First Nations communities still under boil water advisories*. Retrieved June 20, 2023, from Global News: https://globalnews.ca/news/9571066/first-nations-drinking-water-issues-world-water-day-2023/#:~:text=The%20federal%20government%20says%20138,in%2028%20communities%20in%20Ca.

Carleton University, EcoGen Energy. (2023). *Building Integrated Thermal Energy Systems (BITES)*. Ottawa: Carleton University Faculty of Engineering and Design.

El-Dessouky, H., & Ettouney, H. (2002). *Fundamentals of Salt Water Desalination*. Elsevier Science & Technology.

Ghenai, C., Kabakebji, D., Douba, I., & Yassin, A. (2021). Performance analysis and optimization of hybrid multi-effect. *Energy, 215, Part B*.

Indigenous Services Canada. (2021, March 10). *Progress update on the Government of Canada's commitment to clean water in First Nations communities*. (Government of Canada) Retrieved June 20, 2023, from https://www.canada.ca/en/indigenous-services-canada/news/2021/03/progress-update-on-the-government-of-canadas-commitment-to-clean-water-in-first-nations-communities.html

Joo, H.-J., & Kwak, H.-Y. (2013). Performance evaluation of multi-effect distiller for optimized solar. *Applied Thermal Engineering, 61*(2), 491-499.

Leblanc, J., Andrews, J., & Akbarzadeh, A. (2009). Low-temperature solar–thermal multi-effect evaporation desalination. *International Journal of Energy Research, 34*, 393-403. doi:10.1002/er.1642.

Li, C., Goswami, Y., & Stefanakos, E. (2013). Solar assisted sea water desalination: A review. *Renewable and Sustainable Energy Reviews, 19*, 136-163.

Mooose Cree First Nation. (2018). *Visiting Moose Factory/Directions*. Moose Cree First Nation: https://web.archive.org/web/20181203085112/http://www.moosecree.com/tourism/directions.htm

Palenzuela, P., Alarcon-Padilla, D.-C., & Zaragoza, G. (2015). In *Concentrating Solar Power and Desalination Plants: Engineering and Economics of Coupling Multi-Effect Distillation and Solar Plants*. Springer International Publishing.

Pembina Institute. (2021). Diesel Reduction Progress in Remote Communities Research Update. *Renewables in Remote Communities Conference*. Whitehorse.

Rahimi, B., & Chua, H. (2017). In *Low grade heat driven multi-effect distillation and desalination* (pp. 5-7). Cambridge, MA: Elsevier.

Safe Drinking Water Foundation. (2017, January 23). *Water Consumption*. (Safe Drinking Water Foundation) Retrieved February 18, 2024, from https://www.safewater.org/fact-sheets-1/2017/1/23/water-consumption

Statistics Canada. (2021, August 17). *Survey of Drinking Water Plants, 2019*. Retrieved February 18, 2024, from https://www150.statcan.gc.ca/n1/daily-quotidien/210817/dq210817c-eng.ht

Statistics Canada. (2023, November 15). *Census Profile, 2021 Census of Population*. Retrieved from https://www12.statcan.gc.ca/census-recensement/2021/dp-pd/prof/index.cfm?Lang=E.

Stefanovic, O. (2020, December 2). *Indigenous Services minister acknowledges Liberals won't meet promised drinking water target*. (CBC) Retrieved from https://www.cbc.ca/news/politics/indigenous-services-minister-drinking-water-target-1.5824614

Xia, N., Xiao, H. S., Li, S. F., Liu, Z. H., & Shao, Z. X. (2018). Performance study on a passive solar seawater desalination system using. *Applied Energy, 213*, 343-352.