An Integrated System of Electricity and Potable Water Production for Naval Cadets by Solar Concentration on POLYSUN

จักริน มาลัยโรจน์ศิริ[1] ภาณุกร วัฒนจัง[2]
Jakrin Malairojsiri[1] Panukorn Wattanajung[2]

Received: October 19, 2023
Revised: November 6, 2023
Accepted: November 19, 2023

Abstract

The POLYSUN software was developed to design and simulate sustainable energy systems: Photovoltaic system (PV), Photovoltaic Thermal system (PVT), Concentrated Photovoltaic Thermal system (CPVT). In this study, the CPVT system is proposed to be operated with Direct Contact Membrane Distillation (DCMD) to produce both electricity and clean water from seawater to match the requirements of a naval-cadet regiment in Royal Thai Naval Academy (RTNA), Thailand. The system will utilise heat waste from the CPVT system to desalinate seawater via the DCMD.

The aims of this project are to design and simulate this hybrid system on POLYSUN to match the requirements of 100 units: 400 cadets in the regiment with the available area of 100 m x 100 m by supporting of literature reviews. The concentration tracking system of 100 collectors with nominal power at 1,878 W/collector is designed to cover the annual consumption electricity at 13,308 kWh and daily water consumption at 2,000 litres or 5 litres/person/day. The specific requirements of the DCMD are to feed seawater at 70°C and permeate water at 25°C into the DCMD with flow rate of feeding heat and permeate at 1,689 litres/hour. Furthermore, the financial assessment needs to be considered including the Levellised Cost of Electricity (LCOE) and the Return on Investment (ROI) as well as the Feed-in-Tariff (FiT) for 25-year lifetime. All in all, although the hybrid system can support both electricity and potable water for naval cadets, this system cannot make a profit within 25 years to have the ROI. The feasible reason is the daily electric consumption of naval cadets is different from other departments. Namely, the routine of daily electric consumption usually requires after sunset. In summary, this system has high-cost investment when calculated from the naval-cadet daily electric consumption and a recent policy: an electric fee of bureaucratic departments and a FiT at 3.10 Bath/kWh and 2.20 Bath/kWh, respectively.

Keywords: Potable Water Production, Naval Cadets, Solar Concentration, POLYSUN

[1]อาจารย์ ฝ่ายศึกษา โรงเรียนนายเรือ
Lecturer, Academic Branch, Royal Thai Naval Academy
E-mail: jakrin.m@navy.mi.th
[2]อาจารย์ ฝ่ายศึกษา โรงเรียนนายเรือ
Lecturer, Academic Branch, Royal Thai Naval Academy
E-mail: Panukorn.w@navy.mi.th

1. Introduction

1.1 Multijunction Cells and Solar Concentration

Solar energy, derived from photons, is harnessed using photovoltaic technology from solar spectrum levels. Materials' conductivity depends on the energy band gap; The energy band gap is exemplified in Figure 2 including GaAs, Si, and Ge. Advancements in solar tech have considerably increased efficiency by more than 20% up to 47.6% [1], achieved through stacked solar cells and concentration methods, as exemplified in Figure 1 [2, 3].

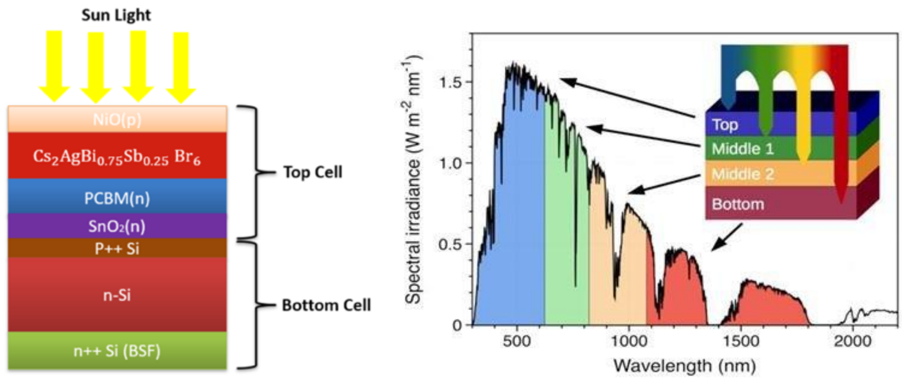


Figure 1 Solar Energy is Collected by Stacking Different Semiconducting Materials [2, 3].

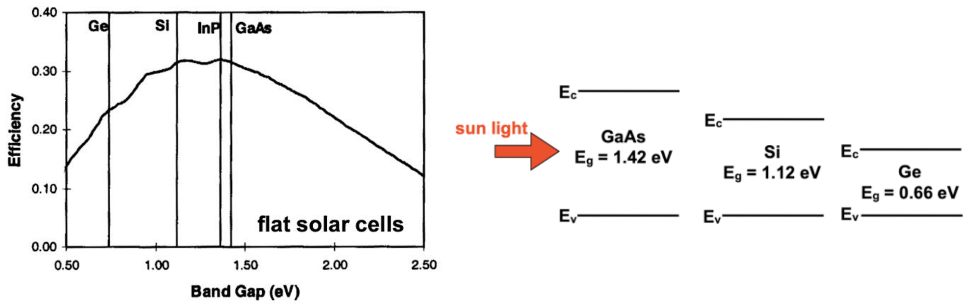


Figure 2 Multiple Bandgap Cells of GaAs, Si and Ge [4, 5].

With regards to Concentrated Photovoltaic Thermal system (CPVT), concentrated units could be numeral suns such as 1 sun and 100 suns, depending on how much of the concentrated density. Moreover, Solar concentration techniques normally focus sunlight onto either a single point or a line, using mirrors or lenses. Point focus systems concentrate sunlight for tasks like generating heat or electricity, while line focus systems broaden the concentration area, enabling applications such as producing steam for electricity generation. These methods optimize solar energy utilization, playing a crucial role in renewable energy solutions. However, these systems typically require liquid to cool down the solar cells from the high temperature of concentration which can damage cells. Hence, cooling the cell is inevitably required to keep the system secure. The maximum power density (P_{max}) could be calculated from V_m and J_m. Efficiency is calculated from electrical power out, which is P_{max} and optical power in (P_{opt}). Moreover, efficiency can be computed from the fill factor (FF), as expressed in Figure 3 and equations (1) – (3) [4, 5].

$$P_{max} = V_m J_m \tag{1}$$

$$P_{opt} = \text{Concentration x Power Density} \tag{2}$$

$$\eta = \frac{P_{max}}{P_{opt}} = \frac{V_m J_m}{P_{opt}} = \frac{J_{PV} V_{oc} FF}{P_{opt}} \tag{3}$$

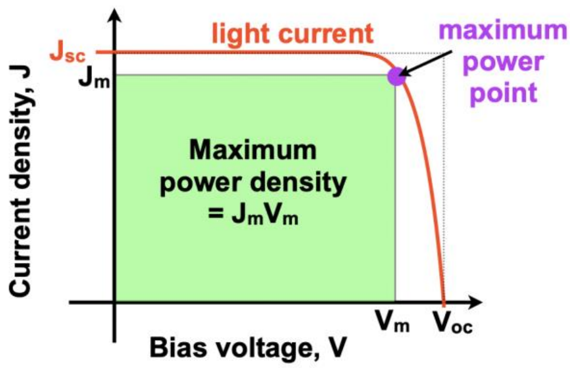


Figure 3 The Maximum Power Density [4, 5].

1.2 Membrane Distillation

Membrane Distillation (MD) is a thermal process that uses specialized hydrophobic membranes to separate saltwater and freshwater. Advanced MD membranes with micro-porous structures, like those made through co-axial electrospinning, enable efficient vapor transport, creating a temperature gradient and allowing water vapor to pass through the membrane, as illustrated in Figure 4 [6]. This process results in freshwater on one side and helps reduce the need for frequent membrane replacements due to the degradation of the MD.

Figure 4 The Characteristic of Membrane Distillation [6].

However, membrane distillation has various types, which can be mainly classified into four types including Direct Contact Membrane Distillation (DCMD), Air Gap Membrane Distillation (AGMD), Sweeping Gas Membrane Distillation (SGMD), and Vacuum Membrane Distillation (VMD). Notably, DCMD Configuration is considered to provide the highest flux with lowest cost compared to other types [7, 8].

1.3 Harnessing Heat Waste to A Hybrid System

Membrane Distillation (MD) can utilize heat waste with specific temperature requirements, relying on temperature differences between feeding and permeate sides; The gap temperature will encourage the process of water production. Hence, the chosen DCMD, which can operate with feed temperatures of 40-70°C and permeate temperatures of 20-25°C, suits coastal regions like Thailand. This is because sea water can be used to cool down the cells, preventing cells burning. Moreover, heat waste can be harnessed for the DCMD process. The system's temperature is regulated by an auxiliary boiler and a three-way valve to maintain the desired levels. In addition to this, an auxiliary boiler is proposed to back up the temperature of the tank when the temperature is lower than the expectation. Meanwhile, a three-way valve is prepared in the case that the temperature passed the collectors are beyond the expected temperature. This is because the sunlight during a day fluctuates.

1.4 Financial Investment

The financial investment is a crucial contemplation in systems to be proven whether they are worthwhile to be invested. In the consideration of total costs, the total costs are yearly calculated which is called annuitised capital cost (A). The annuitised capital cost can be divided by total energy production to have the LCOE. Remarkably, discounting and interest are not the same since discounting implies that the summary of money in the future which is used to calculate the present value of the future cash flow, while real interest rate is monetary interest rate minus rate of inflation. In addition to this, inflation is the increase of prices with time eroding the real value of money [9]. The present value, net present value and present value of annuity can be observed in Equations (4) – (7):

$$\mathrm{V_p} = \frac{V_n}{(1+r)^n} \tag{4}$$

$$\mathrm{NPV} = \frac{V_1}{(1+r)^1} + \frac{V_2}{(1+r)^2} + \frac{V_3}{(1+r)^3} + \cdots + \frac{V_n}{(1+r)^n} \tag{5}$$

$$\mathrm{A} = \mathrm{V_p}\,\frac{r}{1-(1+r)^{-n}} \tag{6}$$

$$\mathrm{NPV} = \mathrm{NPV\ (benefit/income) - NPV\ (costs)} \tag{7}$$

Where V_p is the present value, V_n is the value in n year, r is the discount rate, A is an annuity, and n is the number of years. If amount V_p is borrowed from the bank now, a summary of A must be paid back every year for n years [9]. In terms of investment, if NPV of the whole project is higher than zero, profit is made, and the project is worth doing.

In the process of financial assessment, total costs need to be analysed with the benefit of Net Present Value (NPV_B) and the costs of Net Present Value (NPV_C). NPV_B normally receives from the selling electricity to the grid system, while NPV_C is calculated from the system costs. The system costs can be distributed into two categories: capital costs and annual costs. In addition, Capital Costs (CC) are installation, site improvement, and components [10], while Annual Costs (AC) are Annual Cost Fixed Charged (AC_{fixed}), Annual Cost Maintenance (AC_{MT}), Annual Cost of Replacement (AC_{MR}), Annual Cost Operation and Maintenance ($AC_{O\&M}$) [11]. The amortization factor (a) can be calculated from equation (8), where i is the interest rate, while n is the lifetime [12]

$$a = \frac{i(1+i)^n}{(1+i)^n - 1} \tag{8}$$

Moreover, discount rate, interest rate, inflation, and project lifetime are to be considered. Hence, the literature reviews are used to support database using in this project. In this project, the discount rate of the system is proposed to be 3% [13], while the inflation rate is computed as 3% from the average inflation over 20 years in Thailand [14]. Considering the grid system, Feed in Tariff (FIT) policy is promoted to encourage people to use power generation from renewable energy including wind, solar, and hydro energy. Typically, the FIT is determined on the basis of the LCOE produced from renewable energy in order to have the ROI. The LCOE and the ROI as well as the capacity of the system can be calculated from equations (9) and (10) below [9].

$$\text{LCOE} = \frac{\text{A} + \gamma}{\text{Actual Energy to Grid System}} \tag{9}$$

$$\text{Capacity Factor (\%)} = \frac{\text{Actual Energy to Grid System}}{\text{Optimal Energy Generation}} \times 100\% \tag{10}$$

Where A is the annuitised capital cost (Baht/year), γ is the annual running cost (Baht/year) and n is the number of the payback. According to the Metropolitan Electricity Authority (MEA), the average rate of the electricity power price for bureaucratic departments and FIT are 3.10 Baht/kWh and 2.20 Baht/kWh, respectively [15].

2. Objectives

To design and simulate a hybrid system for electrical generation and producing potable water for 400 naval cadets with an available area of 100 m x 100 m at the RTNA, Thailand by the Concentrated Photovoltaics Thermal (CPVT) system on POLYSUN.

To design a Multiphysics simulation model of the CPVT system that will be used to power a membrane distillation (MD) water purification system and choose the appropriate MD configuration. The system will be simulated to examine whether the ROI can be achieved within 25 years. The electrical fee and the FiT will be analysed.

3. The Methods of Research

To begin with the design process, selecting a suitable membrane configuration is the first step, followed by designing the hybrid system for electricity and clean water production. Databases need to be set up according to consumption requirements. Before choosing thermal and electrical components in POLYSUN, each component must be calculated for proper choices. The number of collectors will be calculated based on the available area of 100 m x 100 m, and then the system will be simulated to meet both thermal and electrical requirements. Finally, the hybrid system will be proven whether this system can undergo the financial assessment from the LCOE and the ROI as well as Grid’s electrical fee.

3.1 The CPVT for the RTNA, Thailand

The RTNA, a part of the Samutprakarn province, where seawater temperatures range from 27 to 30 degrees Celsius, is conducive for desalination. Solar irradiation values range between 1,300 and 1,400 kWh/m²/year [16], thereby providing ample sunlight for solar systems, as shown in Figure 5.

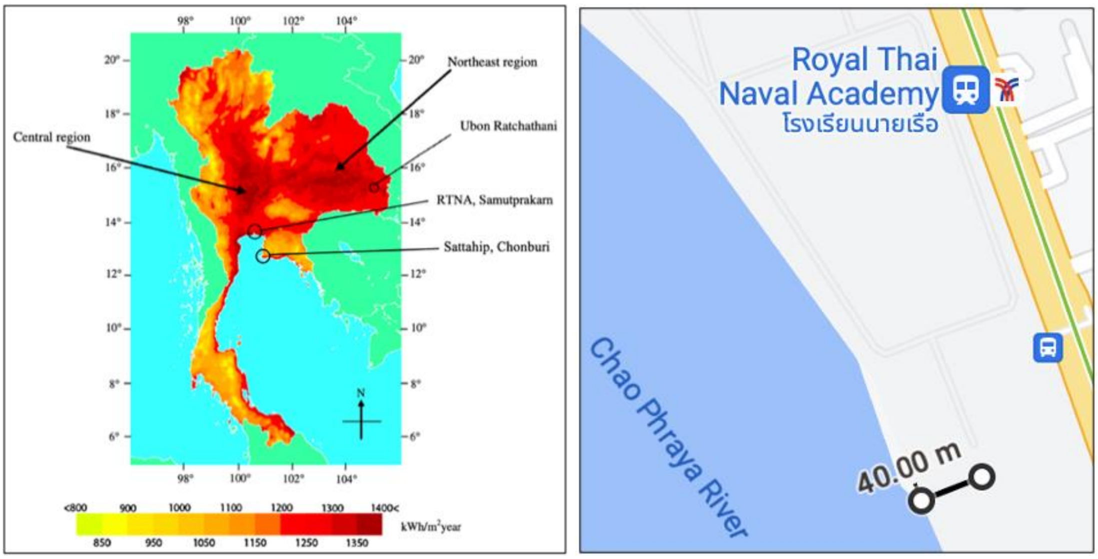


Figure 5 Solar Irradiation of Thailand (Left) and The Location of the RTNA (Right) [16].

With regards to electricity and water demand, 400 cadets in a naval regiment in the RTNA are proposed to be a criterion in this project. To begin with, drinking water consumption over a year is highly estimated from an athlete (5 litres/person/day), while the annual electricity consumption is calculated based on the MEA. The electricity demand, as illustrated in Figure 6, for 400 cadets is approximately 13,308 kWh/year, while water demand is 2,000 litres/day, calculated from 5 litres/person/day.

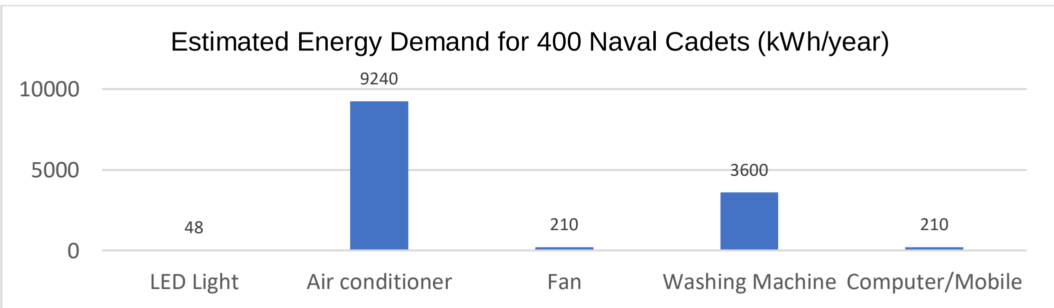


Figure 6 Estimated Electricity Consumption in a Year of the RTNA.

3.2 Choosing an Appropriate MD Configuration

Due to the high amount of potable water requirement for a naval unit and the advantages of high permeate flux produced in the membrane, DCMD is an appropriate MD configuration for designing in this project [11, 12, 15]. The requirement for electricity and drinking water can be observed in Table 1.

Table 1 The Criteria of the Design in this Project.

The Location of the RTNA, Thailand (Lat 13°36.72'N, Long 100°35.4'E)		
Average Seawater Temperature (Min. – Max.)	°C	27-30
Naval Cadets	Number	400
Electricity Demand	kWh_e/year	13,308
Daily Consumable Water Demand	Litres/day	2,000

Regarding the clean water production rate, the spiral-wound DCMD module from AquaStill (Sittard, The Netherlands) will be chosen for this project in accordance with the literature review. The specific characteristics of the spiral-wound DCMD membrane module can be observed in Table 2 [16].

Table 2 The Specific Characteristics of The Spiral-Wound DCMD Membrane Module.

Total Membrane Surface Area	m^2	36
Total Height of The Module	m	6
Total Length of Envelope	m	45
Total Width of Envelope	m	12
Total Channels of The Feed and Distillate	Units	30

According to Duong et al. [17], two modes can be operated: co-current and counter-current; The counter-current mode and 25°C are chosen due to higher rate of water flux and feasible heat temperature, as shown in Figure 7.

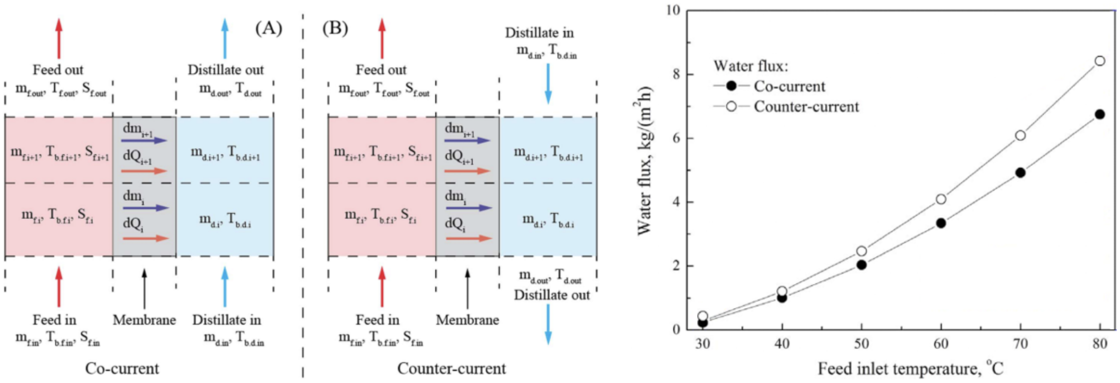


Figure 7 DCMD Modes: Co-Current and Counter-Current (Left), and Water Flux Rate (Right) [17].

3.3 Design A Hybrid System

To begin with, a hybrid system must meet the conditions of electricity and freshwater, according to Table 1. Because seawater is expected to be heated by the CPVT before sending to DCMD at 70°C, seawater will be pumped into the tank to absorb heat and then passed to DCMD. However, the temperature of the tank depends on the temperature of the CPVT collectors, which might be fluctuated. Namely, it can be higher or lower than 70°C according to the weather condition. Therefore, an auxiliary boiler is required to heat the tank temperature in case the temperature is lower than 70°C. Meanwhile, a three-way valve is required to mix the temperature of the water with cold water if the temperature is higher than 70°C. Moreover, since the required MD configuration is DCMD, another permeate tank is required in the process. The basic summary of a hybrid design can be observed in Figure 8. The flow rate can be calculated from size of pipe and velocity, as shown in equations (11) and (12).

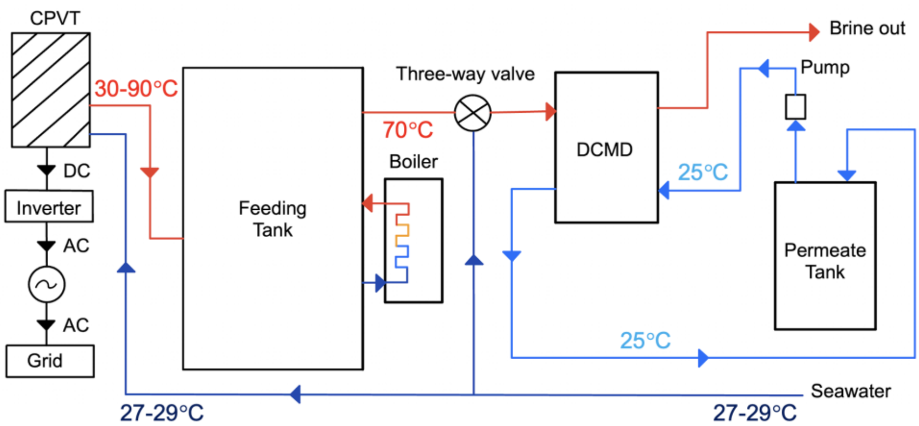


Figure 8 The Design of The CPVT System with DCMD Membrane.

$$\Omega = \mathrm{vA} \tag{11}$$

$$\mathrm{A} = \frac{\pi D^2}{4} \tag{12}$$

Where Ω is the flow rate (m^3/s), v is velocity (m/s), A is area of the cross section (m^2), π is the ratio of a circle's circumference to its diameter, and D is the diameter [18]. The flow rate of pipes can be calculated as 1.689 m^3/h, where D is 2 inches/0.048 m and an acceptable velocity is 0.5 m/s. A permeate tank is indispensable for DCMD since the cold feed, which is seawater, cannot be used as a coolant. The head of permeate tank is designed as 2 m. The flow rate of hot side and feeding permeate is 1,689 litres/hour. The size of a pump is required to be calculated, as expressed in equation (13).

$$\mathrm{P} = \frac{\rho g h \Omega}{\eta\,(3.6 \mathrm{x} 10^3)} \tag{13}$$

Where P is a pump power (W), η is efficiency, ρ is density of liquid (kg/m^3), g is the gravity (m^2/s), h is head (m), and Ω is the flow rate (m^3/s). The size of a pump is approximately 20 W computed from η is 60%, Density of seawater is 1,023.6 kg/m^3, g is 9.82 m^2/s, h is 2 m, and the flow rate is 1.689 m^3/h [19].

The design is proposed to operate by feeding seawater at 70°C for 11 hours (6 am to 5 pm) during the daytime to utilise heat from solar radiation. According to Figure 7 (right), it can produce clean water at about 66 litres/m^2 from 6 litres/m^2h, which is around 475.2 litres/day. However, daily consumable water demand is 2,000 litres/day which is higher than the ability of water production. As a result, the design needs to be reconsidered at about five modules to have the specific requirements at 2,376 litres/day, which can cover the consumable water demand at 2,000 litres/day.

Pumping a large volume of seawater out of the small tank in short time can affect the temperature of the boiler. Therefore, the chosen size of tank should be feasible. In this case, a 10,000L insulated water tank is chosen. Moreover, an electric boiler is required to heat and maintain an appropriate temperature of the tank storage before passing through the three-way valve at 70°C. Notably, a three-way valve will mix hot and cold water to maintain a setting temperature of 70°C at the DCMD. Hot water at 70°C and permeate water at 25°C are used for feeding the membrane. The power requirement of boilers can be calculated from an equation below:

$$P = \frac{E}{t} = \frac{mc\Delta T}{t} \tag{14}$$

Where E is energy (J), m is the mass of the substance (kg), c is the specific heat which depends on each material and phase (J/kg°C), t is time (s) and ΔT is the different temperatures [18]. The total power requirement of boilers can be given as 83.18 kW, where m is 1,728.58 kg/h, c is 3,850 J/kg°C, ΔT is 75-25°C. In the case of the CPVT specifications, point-focus type of concentration, which is Polycrystalline, is chosen; Nominal power STC is 1,878 W; Gross area is 16.38 m^2/module with biaxial tracking. Soiling, Cable losses and mismatching losses are calculated at 2%. In this study, the proposed design is 100 modules of collectors according to the available area of the RTNA, 100 m x 100 m.

4. Results

4.1 Electricity and Potable Water Production

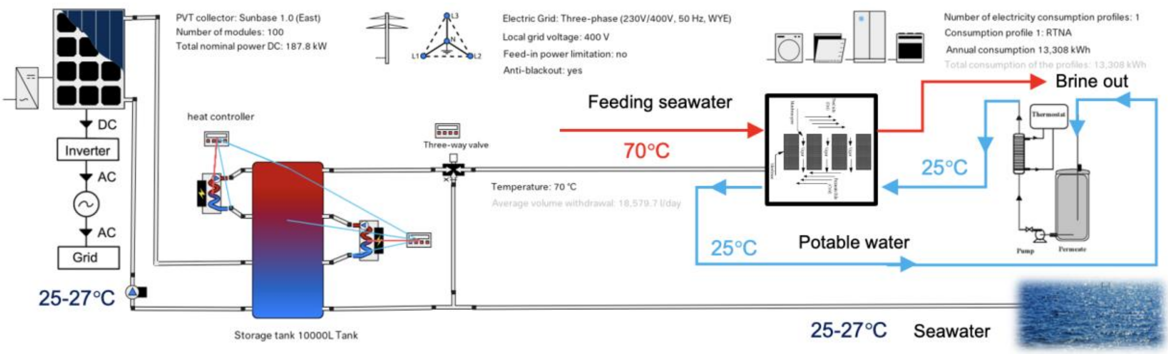


Figure 9 The Hybrid System Designed by the POLYSUN.

Figure 9 illustrates the schematic of the hybrid system in accordance with naval-cadet requirements, while Figure 10 shows the results after simulating the system; Own AC production (Eacp) exceeds the total electricity consumption (Ecs) and covers the requirement of thermal system (Qaux), which requires feeding at 70°C for 11 hours.

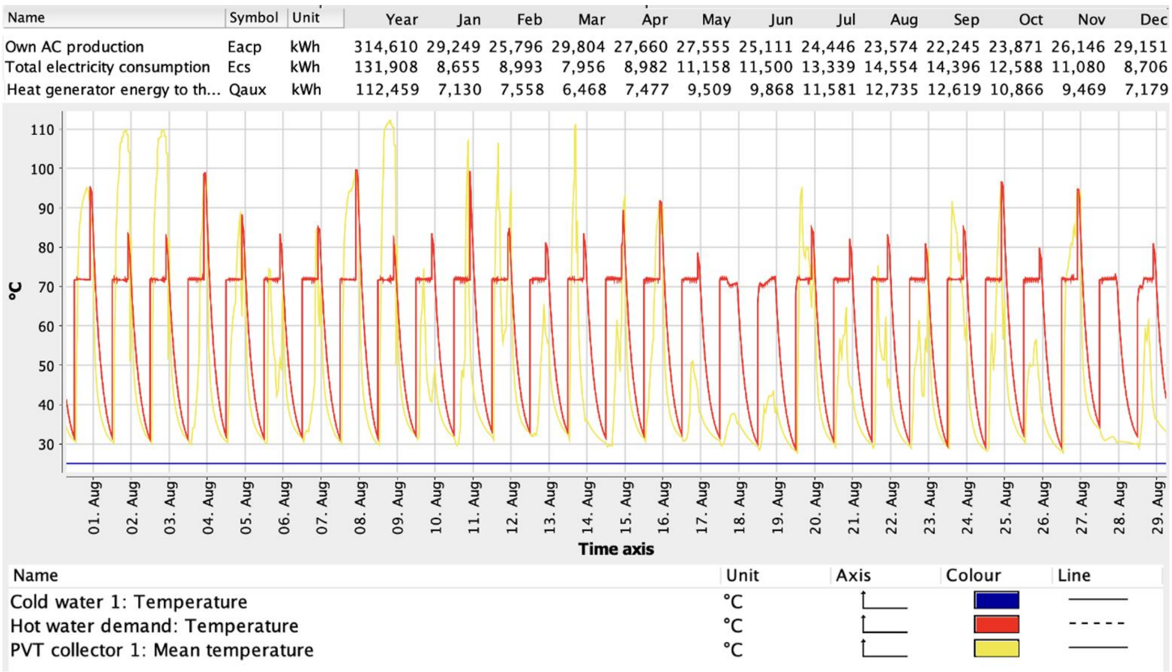


Figure 10 The Temperatures of Collectors (Yellow), MD (Red) and Seawater (Blue) by Times with the amount of Qaux, Eacp and Ecs over a Year.

4.2 System Costs

Table 3 The Estimated System Costs of the 100-CPVT System.

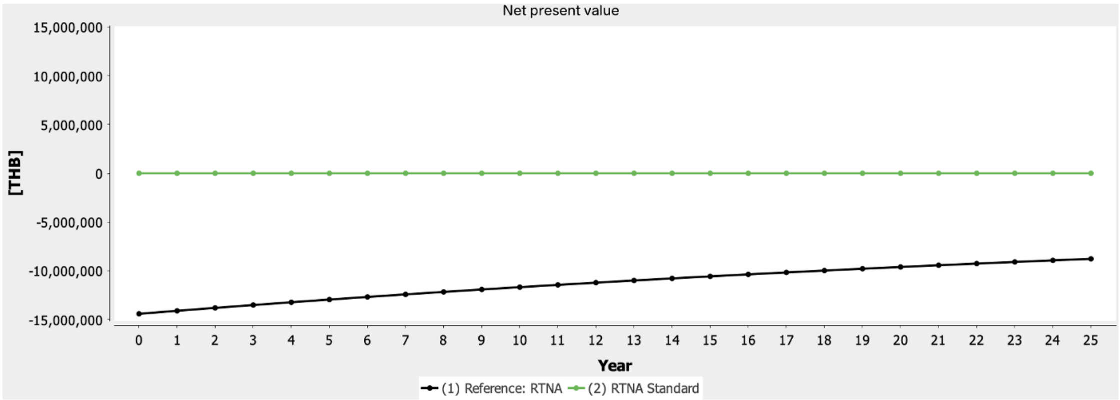
Item	Unit	Size	Cost Unit	Estimated Cost	Thai Baht
The system cost of components					
Freshwater	m^3	25	$21/$m^3$	$525	18,375
10,000L Tank	Unit	1	$10,000	$10,000	350,000
1,000L Tank	Unit	1	$1,000	$1,000	35,000
Pumps	Unit	2	$40/unit	$80	2,800
Pipes	m	70	$0.55/m	$39	1,348
Electric boiler 80kW	Unit	1	$3,500	$3,500	122,500
Total Cost of Components	**$15,765 or 551,775 Baht**				

Table 4 The Estimated System Costs of the 100-CPVT System. (Continued)

The system cost of the DCMD					
Membrane	m^2	36	$36/$m^2$	$1,296	45,360
MD Equipment	Unit	1	$2,500	$2,500	87,500
Total Cost of MD			$3,175 or 111,108 Baht		
Installation (25% of total cost of MD)			$949 or 33,215 Baht		
Total Capital Costs			**$4,124 or 144,323 Baht**		
Plant life (n) = 25 years, Discount rate (i) = 3%, Amortization factor (a) = 0.057 per year					
AC_{fixed} (a x CC)			9,466.27 Baht/year		
AC_{MT} (20% of AC_{fixed})			1,893.25 Baht/year		
AC_{MR} (20% of total cost MD)			26,572 Baht/year		
$AC_{O\&M}$ (AC_{MT} + AC_{MR})			28,465.25 Baht/year		
Total AC of DCMD (AC_{fixed} + $AC_{O\&M}$)			**$1,083.75 or 37,931.52 Baht/year**		
The system cost of the CPVT over a year					
Solar Collection	m^2	1,638	$150/$m^2$	$245,700	8,599,500
Site Improvement	m^2	1,638	$25/$m^2$	$40,950	1,433,250
Plant System	kW	187.8	$90/$kW_e$	$16,920	591,570
Inverter	W_{dc}	187,800	$0.06/$W_{dc}$	$11,268	394,380
Soft Cost	W_{dc}	187,800	$0.41/$W_{dc}$	$76,998	2,694,930
Total Capital Costs	**$391,818 or 13,713,630 Baht**				
AC_{MT}	kW	37.64	$66/$kW_{year}$	$2,484.2	86,948
Total AC of CPVT	**$2,484.2 or 86,948 Baht/year**				
Total Capital Costs of system	**$411,707 or 14,409,728 Baht**				
Total Annual Costs of System	**$3,568 or 124,880 Baht/year**				

According to the estimated system costs [20, 21, 22] of the DCMD with the 100-CPVT system in Table 3, the system cannot amortize within 25 years for a recent policy: LCOE and FiT at 3.10 Bath/kWh and 2.20 Bath/kWh, respectively, as presented in Figure 11.

Name	Symbol	Unit	Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
To external grid	Eteg	kWh	237,833	24,490	21,157	24,951	22,533	19,716	17,339	16,892	15,484	14,439	17,005	19,571	24,256
From external grid	Efeg	kWh	55,130	3,896	4,354	3,103	3,856	3,318	3,727	5,784	6,464	6,589	5,723	4,506	3,811



Description	Symbol	Unit	Reference: RTNA	RTNA Standard
Investment costs	Iinvest	THB	14409728.00	0.00
Net present value	NPV	THB	-8771703.81	0.00
Yearly maintenance costs	AOM	THB/a	124880.00	0.00

Figure 11 The 100-CPVT systems: NPV (Black) and Standard (Green).

5. Conclusions

In capsulation, this project is proposed to be designed and simulated on POLYSUN to match the requirements of electricity and potable water for 400 cadets in a naval regiment. The tracking solar concentration with nominal power at standard condition of 1,878 W is chosen to operate at the RTNA, Samutprakarn due to the advantage of high efficiency. Nonetheless, the concentrated collectors are to be cooled down so that cells would not be burned. Hence, the RTNA, where closed to sea water, can utilise sea water to cool this system. As a result, heat waste from this system should be took merits. An advisable solution is to produce pure water through membrane distillations. Hence, the DCMD is selected to be designed in this project due to the high amount of water flux production and cost saving. However, the specific requirements for this system are calculated to support electricity and clean water production based on the number of naval cadets. In addition, the temperatures between high side and clow side are imposed at 70°C and 25°C for DCMD, both flowing into the system at a rate of 1,689 litres/hour. The simulation shows that the available area of 100 collectors can cover the annual consumption electricity at 13,308 kWh and daily water consumption at 2,000 litres or 5 litres/person/day. However, the system is unable to achieve profitability within a 25-year period necessary for the ROI. This is primarily because the electricity consumption patterns among naval cadets markedly diverge from other departments. Specifically, their customary utilization of electricity commences post-sunset, setting them apart from the standard routines prevalent in other units. On the other hand, the profitability will be made at 2.20 Bath/kWh if the daily electric consumption of the cadets requires only on the day-time, which is different from 0.9 Bath/kWh from the current policy rates: an electrical fee of 3.10 Bath/kWh and a FiT of 2.20 Bath/kWh. Finally, the calculation of LCOE for 25 years is 4.00 Baht/kWh, and therefore the FiT should be at least 4.00 Baht/kWh to have the ROI within 25 years.

References

[1] NREL. Best Research-Cell Efficiency Chart. [Internet]. [place unknown]: [National Renewable Energy Laboratory]; 2023 [updated 2023 Sep 31]. Available from: https://www.nrel.gov/pv/cell-efficiency.html

[2] Roser M. Why did renewables become so cheap so fast? [Internet]. [place unknown]: [publisher unknown]; 2020 [updated 2020 Dec 1]. Available from: https://ourworldindata.org/cheap-renewables-growth

[3] Ikeri HI, Onyia AI, Asogwa Pu. Investigation Of Optical Characteristics of Semiconductor Quantum Dots For Multi Junction Solar Cells Applications. Int J Innov Sci Res Technol. 2019 Feb;10(8):3532.

[4] Letcher T, Fthenakis VM. A Comprehensive Guide to Solar Energy Systems: With Special Focus on Photovoltaic Systems. 1st ed. London: Academic Press; 2018.

[5] Ioannou A. Solar Generation Thermal and Photovoltaic. [place unknown]: [publisher unknown]; 2022.

[6] Sorokin S. Membrane Distillation Explain 3D Animation. 2022. In: Behance [Internet]. [place unknown]: [publisher unknown]; 2022 – [cited 2023 Sep 2]. [about 1 screen]. Available from: https://www.behance.net/gallery/134585055/Membrane-distillation-Explain-3D- animation.

[7] El-Bourawi MS, Ding Z, Ma R, Khayet M. A framework for better understanding membrane distillation separation process. J Memb Sci. 2006 Nov 15;285(1-2):4-29.

[8] Eykens L, Reyns T, De Sitter K, Dotremont C, Pinoy L, Van der Bruggen B. How to select a membrane distillation configuration: Process conditions and membrane influence unraveled. Desalination. 2016 Dec 1;399:105-15.

[9] Ioannou A. Economics, Environmental & Social Issue. [place unknown]: [publisher unknown]; 2022.

[10] Fernandes M, Schaefer LA. Levelized cost of energy of hybrid concentrating photovoltaic-thermal systems based on nanofluid spectral filtering. Solar Energy. 2021 Oct;227:126-36.

[11] Soomro MI, Kim WS, Kim CN. Performance and cost comparison of different concentrated solar power plants integrated with direct-contact membrane distillation system. Energy Convers Manag. 2020 Oct;221:113193.

[12] Banat F, Jwaied N. Economic evaluation of desalination by small-scale autonomous solar-powered membrane distillation units. Desalination. 2008 Mar;220(1-3):566-73.

[13] Yoomak S, Patcharoen T, Ngaopitakkul A. Performance and economic evaluation of solar rooftop systems in different regions of Thailand. Sustainability. 2019;11(23):6647.

[14] Thailand Inflation Rate. In: Indices BoTaE, editor. 2022. Available from: https://tradingeconomics.com/thailand/inflation-cpi

[15] Metropolitan Electricity Authority (MEA) [Internet]. Bangkok: Metropolitan Electricity Authority (MEA); 2023. Tariff Calculation: Type 4 Large General Service; 2023 [cited 2023 Sep 5]; [about 1 screen]. Available from: https://www.mea.or.th/en/our-services/tariff-calculation/other

[16] Kengpol A, Rontlaong P, Tuominen M. A Decision Support System for Selection of Solar Power Plant Locations by Applying Fuzzy AHP and TOPSIS: An Empirical Study. J Softw Eng Appl [Internet]. 2013 Sep [cited 2023 Oct 1];6(9):470-81. Available from: http://dx.doi.org/10.4236/jsea.2013.69057

[17] Duong H, Xia L, Ma Z, Cooper P, Ela W, Nghiem LD. Assessing the performance of solar thermal driven membrane distillation for seawater desalination by computer simulation. J Memb Sci. 2017;542:133-42.

[18] Urone PP, Hinrichs R. College Physics. Houston, Texas: OpenStax; 2012.

[19] Falcone G. Fluid Flow, Wind, Hydroelectric, Wave & Tidal Generation. [place unknown]: [publisher unknown]; 2022.

[20] Fernandes M, Schaefer LA. Levelized cost of energy of hybrid concentrating photovoltaic-thermal systems based on nanofluid spectral filtering. Solar Energy. 2021 Oct;227:126-36.

[21] Soomro MI, Kim WS, Kim CN. Performance and cost comparison of different concentrated solar power plants integrated with direct-contact membrane distillation system. Energy Convers Manag. 2020 Oct;221(7):113193.

[22] Banat F, Jwaied N. Economic evaluation of desalination by small-scale autonomous solar-powered membrane distillation units. Desalination. 2008;220(1-3):566-73.