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Article

Supply of energy required for water-ammonia absorption refrigeration cycle for an industrial refrigerator using solar parabolic collectors and photovoltaic panels: case study Malaysia

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ABSTRACT

Conventional water-ammonia absorption refrigeration system in the industry uses heat energy generated by non-renewable energy sources such as the burning of natural gas, but it is just a matter of time before natural gas becomes depleted. Then, non-renewable energy often produces greenhouse gases that are harmful to the environment. Therefore, solar energy can be used as an alternative to supply the energy required by the absorption refrigeration cycle (ARC). Parabolic trough collectors (PTC) can supply the required heat energy to the reboiler, whereas photovoltaic (PV) panels can supply the electrical energy to the pump of an ARC. To prove the feasibility of using solar energy as a more sustainable alternative, a simulation of the PTC and PV models is conducted, and the average energy generated by each model is obtained. The result of this research proved that Malaysia is a suitable location for the implementation of solar technologies as the amount of solar radiation is sufficiently high throughout the year.

1. Introduction

Non-renewable energy holds a dominant proportion of the world's energy demand, whereas the technology of renewable energy is much younger as compared to that of non-renewable energy. However, since non-renewable does not have an infinite amount of supply, renewable energy, such as solar energy, has gained much attention from various fields throughout the last few decades [1]. The transition to solar energy is advantageous due to its freely available nature [2]. While dual-axis sunlight trackers are well-developed and mature [3], an intelligent tracking program is crucial for optimizing solar PV panel generation [4]. Given Malaysia's abundant renewable energy potential, the development of a hybrid renewable energy system for villages is anticipated [5-6]. Furthermore, the growing interest in establishing a hydrogen hub is essential for examining the generation, transmission, distribution, and consumption of hydrogen in the East Asian market [7]. Therefore, implementing voltage generation using fuel cell technology has been initiated to find out the electrical equivalent component's values [8].

On the other hand, there is the presence of sunlight, and using proper equipment and tools, it can even be used to power up industrial processes such as industrial refrigeration systems. Most researchers discuss only the use of solar collectors to capture heat from direct sunlight and convert it to thermal energy for the reboiler in the absorption refrigeration system to operate. The most possible explanation is that the component in an absorption refrigeration system that requires the most power input is the reboiler, which is commonly located at the bottom part of the generator. Nonetheless, although most power is consumed by the generator in the form of heat, there is still a small fraction of power being consumed by the pump in the form of electrical energy. The aim of this research project is to simulate parabolic trough collector (PTC) and photovoltaic (PV) panels using MATLAB for the supply of energy required by water – ammonia absorption refrigeration in Malaysia.

1.1 Water-ammonia absorption refrigeration system

Water – ammonia absorption refrigeration system is one of the most common methods of absorption refrigeration cycles (ARC). Throughout the entire ARC, the only component that requires a large amount of thermal energy is the reboiler, whereas the part that requires electrical energy is the pump located before the generator. Hence, these two components will be the main concern as the power required by these two components is the key to determining the scale of the photovoltaic (PV) system and parabolic trough collectors (PTC). Different scale of ARC requires different amount of heat and also electrical energy. Niasar et al. [9] have developed a hybrid integrated structure where the ARC system inside the structure receives high-temperature steam from the steam turbine; its reboiler and pump use 10839 kW of heat energy and 69.21 kW of electrical energy, respectively.

1.2 Existing design of solar-powered water-ammonia absorption refrigeration system

Over the last few decades, a great deal of research has been conducted on solar-powered water–ammonia absorption refrigeration systems. Abdulateef et al. [1] performed an investigation on a solar-powered absorption refrigeration system by constructing a real-life prototype under the climate of Malaysia. The experimental setup consists of an evacuated tube solar collector connected to a water–ammonia absorption refrigeration system and can produce a cooling capacity of up to 1.5 tons. They pointed out that for a solar-powered absorption refrigeration system to operate, the outlet temperature of the collector has to be higher than the cut-in/cut-off temperature, in which the cut-in/cut-off temperature is essentially the minimum operating temperature of the generator.

2. Methodology

2.1 Water-ammonia absorption refrigeration parameters

The heat energy required by the pump and electrical energy required by the reboiler are extracted from [9] and are shown in Table 1.

Table 1. The energy required by the reboiler and pump

Parameter	Value
Heat energy required by reboiler (kW)	10,839
Electrical energy required by pump (kW)	69.21

2.2 Parabolic trough collector (PTC) model

Sodhal et al. [10] introduced an equation that can be used to calculate the optical efficiency of the PTC.

$$\eta_{opt} = \rho\tau\alpha\Upsilon K(\theta)X_{end} \quad (1)$$

Where ρ is the mirror reflectance, τ is the transmittance of the glass envelope, α is the absorptance of the receiver, Υ is the intercept factor, $K(\theta)$ is the incident angle modifier, and X_{end} is the end loss. The outlet temperature of the Heat Transfer Fluid (HTF) can be obtained using the equation as shown in [11] which is shown below.

$$T_{out} = T_{in} + \frac{Q_{gained}}{\dot{m}Cp} \quad (2)$$

Where T_{in} is the inlet temperature, Q_{gained} is the useful heat gain, $\dot{m}$ is the mass flow rate and Cp is the heat capacity of the fluid. Additionally, the thermal efficiency of PTC is determined by the useful heat gained by the collector part towards the direct normal incident radiation and area of the aperture [11].

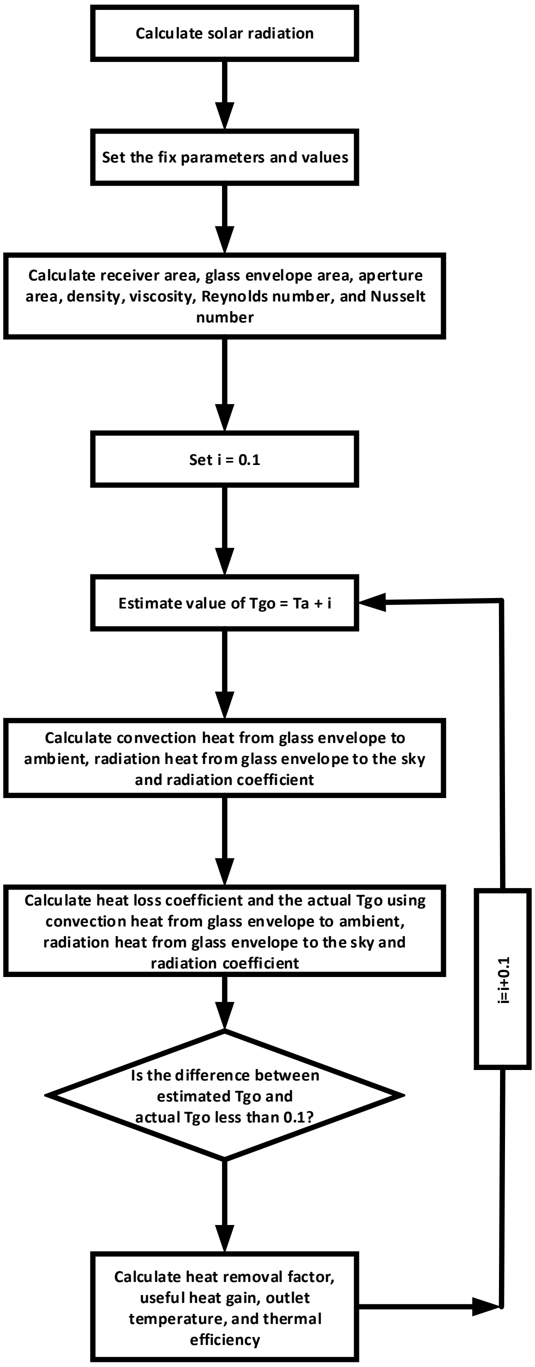


Figure 1. Flowchart of PTC model

The equation is shown below:

$$\eta_{th} = \frac{Q_{gained}}{G_B A_a} \quad (3)$$

Where G_B is the beam of solar radiation and Q_{gained} can be expressed as shown below:

$$Q_{gained} = F_R\left(G_B\eta_{opt}A_a - A_rU_L(T_{in} - T_a)\right) \quad (4)$$

Where F_R is the heat removal factor, A_a is the aperture area, A_r is the receiver area and U_L is the heat loss coefficient of the collector. The overall flow of the PTC model is shown in Figure 1**Error! Reference source not found.**.

2.3 Photovoltaic (PV) model

The net current of the solar module will be the difference between the photocurrent (I_L) and the normal diode current, as shown below [12]:

$$I = I_L - I_o\left[\exp\left(\frac{q(V+IR_s)}{nkT} - 1\right)\right] - \frac{V+IR_s}{R_p} \quad (5)$$

Where q is the charge of the electron, k is the Boltzmann constant, n is the diode quality factor, R_s is the series resistance, R_p is the parallel resistance, T is the absolute cell temperature, and I_o is the diode saturation current. The maximum power of solar panels can be obtained using Ohm's law and is expressed as follows:

$$P_{max} = V_{max}I_{max} \quad (6)$$

Then, the maximum efficiency of the solar cell is essentially the ratio of the maximum dissipated power over the incident light power and is described as shown below:

$$\eta = \frac{P_{max}}{P_{in}} \quad (7)$$

The overall flow of the PV model is shown in Figure 2.

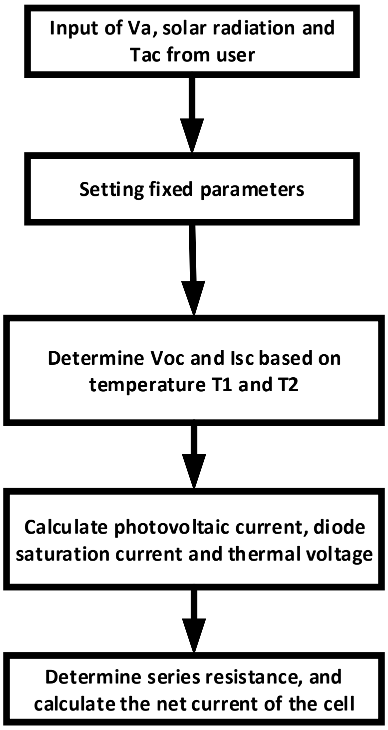


Figure 2. Flowchart of PV model

3. Results and discussion

3.1 Number of modules required

The amount of average solar irradiance in Kuching was measured to be 636.19 W/m^2using light meter [13]. Meanwhile, the amount of average solar irradiance in Kuching obtained through simulation in this paper is approximately 643.40 W/m^2, whereas the beam of solar radiation is around 514.711 W/m^2. This shows that the solar radiation model being developed is fairly accurate. By looking at Figure 3**Error! Reference source not found.**, it shows that the solar r adiation intensity in Kuching is very consistent throughout the year, which means that it is appropriate to implement solar technology in Kuching.

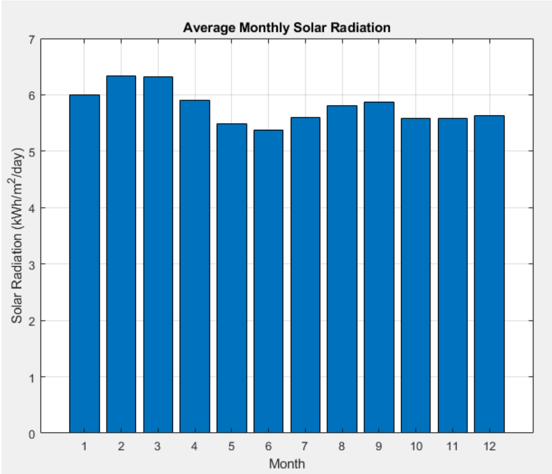


Figure 3. Annual solar radiation of the PTC model

For modeling the PTC module, Figure 4 shows the monthly average optical efficiency of the PTC module in Kuching, whereas Figure 5 illustrates the monthly average thermal efficiency. The average optical efficiency throughout the year was calculated to be around 24.77%, while the average thermal efficiency was calculated to be around 26.56%. Then, Figure 6 shows the monthly average heat energy being captured by a single PTC module; the monthly heat energy being generated is measured in terms of kilowatt hour per square meter.

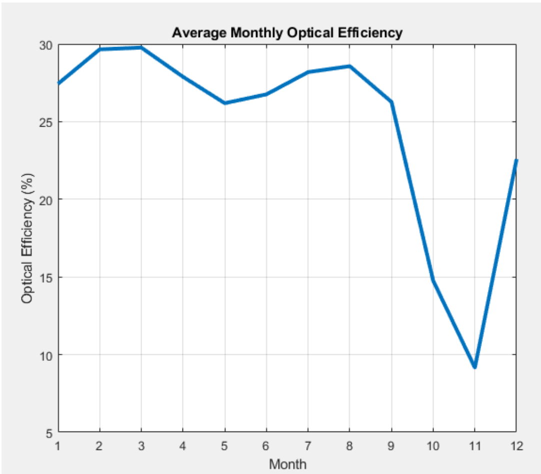
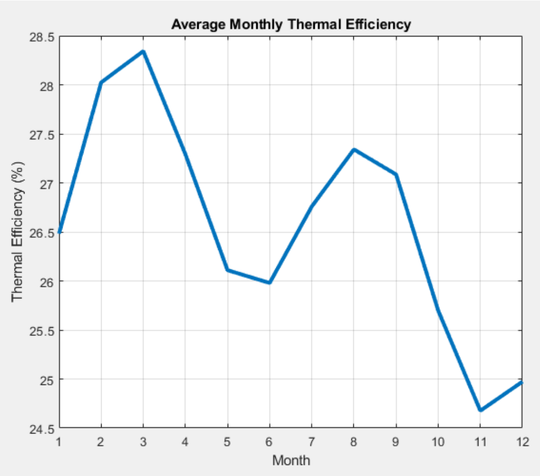


Figure 4. The annual optical efficiency of the PTC model

After converting the value to in terms of kilowatts for calculation purposes, the average heat generated by a single PTC module is approximately 1.86 kW. On the other hand, for modeling the PV panel, Figure 7 shows the monthly average electrical energy being generated by a single PV panel; the average maximum power was calculated to be around 183.43 W. The energy generated by a single PTC module and PV panel will be used to calculate the number of PTC modules and PV panels required to supply the energy required by the reboiler and pump, as shown in Table 1. The number of modules



required for PTC modules and PV panels is shown in Table 2.

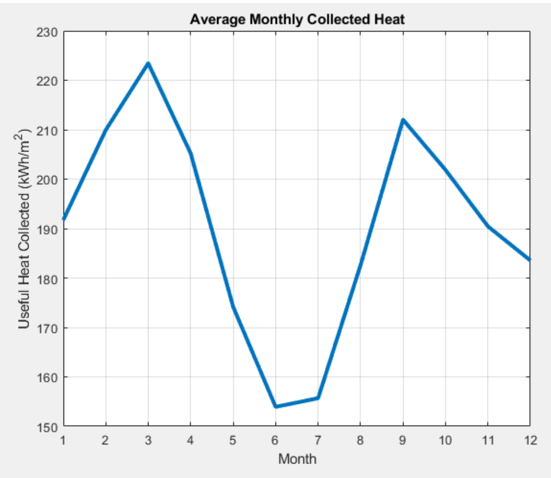


Figure 5. Annual thermal efficiency of the PTC model

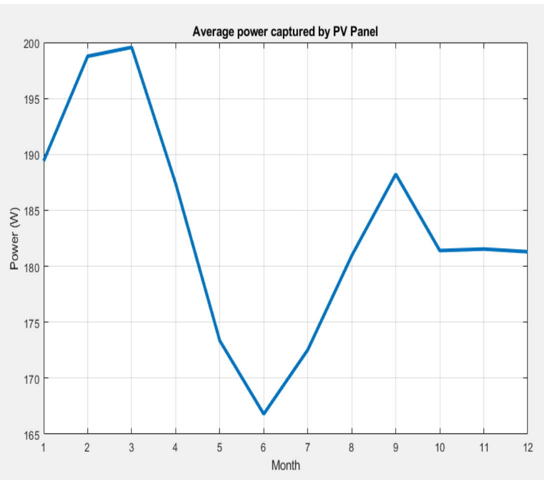


Figure 6. Annual useful heat collected from the PTC model

Figure 7. Annual average power from PV panel

Table 2. Number of PTC modules and PV panels required

Type	Energy required (kW)	Energy generated per module (kW)	Number of modules required
PTC	10,839	1.86	5828
PV	69.21	0.183	379

3.2 Cost analysis

The cost to implement PTC technology is approximately 4,156 $\$/kW$ as of year 2012 [14]. As explained by the National Renewable Energy Laboratory, the capital cost for solar generation technology decreases by around 4% every 5 years due to technological improvement [15]. Hence, the approximate capital cost for PTC technology as of the year 2022 is 3,823 $\$/kW$. The amount of heat energy required by the reboiler is around 10,839 kW, which means that the cost to implement the simulated PTC model in Kuching stands at around 41,437,497 $. After converting the cost to be in terms of Malaysian ringgit, the cost is around RM172,413,137. Meanwhile, the cost to implement the simulated PV model in Kuching will be relatively cheaper as compared to the PTC system because the energy demand of the pump is significantly much smaller than that of the reboiler. The cost of implementing Q.Peak Duo-G5 solar panel is around 2.7 $\$/W$ as of the year 2021 [16-17]. The electrical energy required by the pump is 69.21 kW, which indicates that the cost required to implement the PV model is around 186,867 $, which can be converted to approximately RM 781,104. Table 3 compares the implementation cost of different technologies.

Table 3. The implementation cost of different technology

Technology	Capital cost
PTC	RM 172,413,137.00
PV	RM 781,104.00

To determine the payback period of both PTC and PV technology, the levelized cost of energy (LCOE) for PTC and PV technology has to be determined. The annual energy required to be produced by PTC is calculated to be 39,020,400 kWh, whereas PV is calculated to be 249,156 kWh. If the payback period is set to be 10 years, the LCOE for both PTC and PV is estimated to be around RM0.58 per kWh and RM0.37 per kWh. The annual revenue for both technologies is calculated as shown in Table 4. Assuming the annual revenue for both PTC and PV is constant for the next 10 years, Table 5 and Table 6 are the steps taken to calculate the LCOE for both PTC and PV in Microsoft Excel, respectively.

Table 4. Annual revenue of PTC and PV

Technology	Interval	Revenue
PTC	Daily Revenue	RM 62,866.00
	Monthly Revenue	RM 1,885,986.00
	Annual Revenue	RM 22,631,832.00
PV	Daily Revenue	RM 256.00
	Monthly Revenue	RM 7,682.00
	Annual Revenue	RM 92,187.00

Table 5. The payback period of PTC

Levelized Cost of Energy Template (LCOE)

Assumptions (in '000s)	
Initial Investment Cost ($)	41,437,497
Operations and Maintenance Costs ($	487,755
O&M Growth Rate (%)	5.00%
Annual Fuel Costs ($)	-
Annual Electricity Output (kWH)	39,020,400
Project Lifespan (years)	
Discount Rate (%)	1.00%
Entry Date	1/1/2022

Total Costs	Entry	Construction	Operations	Operations	Operations	Operations	Operations	Operations	Operations	Operations	Operations
Date	1/1/2022	1/1/2023	1/1/2024	1/1/2025	1/1/2026	1/1/2027	1/1/2028	1/1/2029	1/1/2030	1/1/2031	1/1/2032
Year Frac (From Start Date)		1	2	3	4	5	6	7	8	9	10
Initial Investment	41,437,497	-	-	-	-	-	-	-	-	-	-
O&M Costs	-	-	487,755	512,143	537,750	564,637	592,869	622,513	653,638	686,320	720,636
Fuel Costs	-	-	-	-	-	-	-	-	-	-	-
Discount Factor		99.0%	98.0%	97.1%	96.1%	95.1%	94.2%	93.3%	92.3%	91.4%	90.5%
Present Value of Costs	41,437,497	-	478,144	497,081	516,767	537,233	558,510	580,629	603,624	627,530	652,383
NPV of Total Costs	**$46,489,397**										

Total Energy Output	Entry	1	2	3	4	5	6	7	8	9	10
Yearly Output	-	-	39,020,400	39,020,400	39,020,400	39,020,400	39,020,400	39,020,400	39,020,400	39,020,400	39,020,400
Discount Factor	-	99.0%	98.0%	97.1%	96.1%	95.1%	94.2%	93.3%	92.3%	91.4%	90.5%
Present Value of Costs	-	-	38,251,544	37,872,816	37,497,837	37,126,572	36,758,982	36,395,032	36,034,685	35,677,906	35,324,659
NPV of Total Output	**330,940,032 kWH**										

LCOE	$0.14/kWH

Table 6. The payback period of PV

Levelized Cost of Energy Template (LCOE)

Assumptions (in '000s)	
Initial Investment Cost ($)	186,867
Operations and Maintenance Costs ($	1,315
O&M Growth Rate (%)	5.00%
Annual Fuel Costs ($)	-
Annual Electricity Output (kWH)	249,156
Project Lifespan (years)	10
Discount Rate (%)	1.00%
Entry Date	1/1/2022

Total Costs	Entry	Construction	Operations	Operations	Operations	Operations	Operations	Operations	Operations	Operations	Operations
Date	1/1/2022	1/1/2023	1/1/2024	1/1/2025	1/1/2026	1/1/2027	1/1/2028	1/1/2029	1/1/2030	1/1/2031	1/1/2032
Year Frac (From Start Date)		1	2	3	4	5	6	7	8	9	10
Initial Investment	186,867	-	-	-	-	-	-	-	-	-	-
O&M Costs	-	-	1,315	1,381	1,450	1,522	1,598	1,678	1,762	1,850	1,943
Fuel Costs	-	-	-	-	-	-	-	-	-	-	-
Discount Factor		99.0%	98.0%	97.1%	96.1%	95.1%	94.2%	93.3%	92.3%	91.4%	90.5%
Present Value of Costs	186,867	-	1,289	1,340	1,393	1,448	1,506	1,565	1,627	1,692	1,759
NPV of Total Costs	**$200,487**										

Total Energy Output	Entry	1	2	3	4	5	6	7	8	9	10
Yearly Output	-	-	249,156	249,156	249,156	249,156	249,156	249,156	249,156	249,156	249,156
Discount Factor	-	99.0%	98.0%	97.1%	96.1%	95.1%	94.2%	93.3%	92.3%	91.4%	90.5%
Present Value of Costs	-	-	244,247	241,828	239,434	237,063	234,716	232,392	230,091	227,813	225,558
NPV of Total Output	**2,113,143 kWH**										

LCOE	$0.09/kWH

4. Conclusion

To conclude this final year research project, it has been proven that it is possible to supply the energy required by a water-ammonia absorption refrigeration system purely using solar energy. The amount of average solar irradiance in Kuching obtained through simulation is approximately 643.40 W/m^2. This has proven that Malaysia is a suitable location for the implementation of solar technologies as the amount of solar radiation is sufficiently high throughout the year. Then, the average heat collected by a single PTC is calculated to be 1.86 kW, and the average power generated by a single PV panel is 183.43W. To cope with the energy demand of the reboiler and pump, approximately 5828 PTC modules and 379 PV panels will be required. Integrating solar technologies into a water-ammonia absorption refrigeration system can be beneficial because the energy generation process does not generate any sort of greenhouse gases that can harm the environment. Then, the payback period of the PTC and PV model is reasonable which shows that solar technologies are a long-term investment worth considering. If the payback period is set to 15 or even 20 years, LCOE will be even lower, which makes it even more attractive. Future research could incorporate the use of thermal energy storage (TEM) into the simulation model of PTC and conduct a cost analysis to determine the new payback period. The use of TEM would increase the overall capital cost of the PTC system but will generate better annual revenue due to its capability to store heat and release it whenever necessary.

Ethical issue

The authors are aware of and comply with best practices in publication ethics, specifically with regard to authorship (avoidance of guest authorship), dual submission, manipulation of figures, competing interests, and compliance with policies on research ethics. The authors adhere to publication requirements that the submitted work is original and has not been published elsewhere.

Data availability statement

The manuscript contains all the data. However, more data will be available upon request from the corresponding author.

Conflict of interest

The authors declare no potential conflict of interest.

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