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Analyze the Effects of Implementing a Solar Thermal Hot Water System on Oman's Economy and Environmental Factors

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Abstract

An analysis is conducted on eleven governorates in Oman to assess the environmental and financial advantages of implementing a solar hot water system. The conservation of natural gas is measured by comparing it to the absorption of solar energy on a daily, monthly, and yearly basis. The study considers the monetary value of natural gas and the duration required to recover the initial investment in order to evaluate the environmental and economic benefits. Muscat realises its maximum capabilities. The examined solution enables annual savings of up to 106.03 USD and 927.01 kilogrammes of CO_2 in Muscat, and a minimum of 74.74 USD and 653.48 kilogrammes of CO_2 in Dhofar.

Subject Areas

Renewable Energy

Keywords

Solar Energy, Solar Thermal System, Payback Period

1. Introduction

The use of solar energy has both monetary and ecological advantages. Using the right solar energy technologies, it is feasible to generate electricity, heat water and steam, and heat and cool buildings. By eliminating the need for fossil fuels, greenhouse gas emissions can be lowered through the implementation of these technologies.

The biggest potential for solar energy usage is in the Oman region. About 1527 kilowatt hours per square meter per year of solar energy hits Oman. It is estimated that Oman receives an average of 2741 hours of sunshine per year [1].

The solar thermal industry is boosted by this possibility. When it comes to sales of flat plate solar collectors, Oman ranks third globally [2]. More than 12 GWth [3] of flat plate solar collectors have been built so far. Flat-plate solar collectors are commonly used in Oman's thermosiphon solar hot water systems. The promise of solar energy and the ever-increasing cost of fossil fuels both contribute to the system's rising appeal. Numerous manufacturers can be found in every state. As a result, many households are switching to solar hot water systems instead of using traditional fuels like electricity or natural gas.

Both thermosiphon and flat plate collector solar thermal hot water systems have been the subject of extensive study. A thorough analysis of several water-heating methods was conducted by Ibrahim *et al.* [3]. They evaluate solar hot water systems in relation to more common alternatives. Wang *et al.* [4] examined the theory, applications, commercial potential, and research activity around solar water heating technology. The thermosiphon solar water collector was investigated computationally and experimentally by Zelzouli [5]. They looked at how performance was affected by both collector loss and storage tank loss. The cost-effectiveness of a home solar hot water system was compared by Hazami *et al.* [6] to that of electric, gas, and town gas water heaters. The TRNSYS program was used to conduct a case study based on a scenario typical to Tunisia. The annual savings for the flat plate collector system was determined to be 8118 kWh, while the savings for the evacuated tube collector system were found to be 12,032 kWh. Kalogirou [7] installed a thermosiphon solar hot water collection system, which has positive effects on the environment. He calculated the payback period and the life cycle savings of a system of that size for a household of four. Solar energy's annual contribution to meeting energy needs is projected to hit 79%. Parametric research was conducted by Jafarkazemi [8] to determine the effect of mass flow rates and working fluids on the energy and exergy efficiency of a flat plate solar collector. For the purpose of assessing thermosiphon flat plate solar collectors, Kalogirou *et al.* [9] created a new solver of the TRNSYS type. The solver model was tested in the lab in three distinct European climates. The model was fine-tuned to maximize savings in primary energy and minimum payback period. Ayompe and Duffy [10], using a solar water system with flat plate collectors, assessed the system's thermal performance. They ran the experiment to measure things like sun fraction, collected energy, pipe loss, and collector and system energy efficiency. In this experiment, Chen [11] compares two types of flat plate collectors. The researchers looked into how using ETFE foil affected collector efficiency. They also calculated the energy efficiency at various flow rates and volumes. Both the technical and financial viability of a 20,000 square foot space were explored by Taner and Dalkilic [12]. They determined how long it would take for the investment power energy plant to pay for itself.

The estimation of solar energy value is essential in the evaluation of any solar system. Using historical weather records as input, numerous mathematical models have been developed. The solar radiation model was discussed by Bakrc [13]. He merely outlined the sixty distinct models available. Reviewing 50 various models of global solar radiation, Menges *et al.* [14] provide their thoughts. Using a horizontal surface, they calculated the monthly average global radiation for Konya. Bulut and Büyükalaca [15] created a straightforward method for daily global radiation estimation using previously collected data. Sixty-eight different places in Oman are accounted for by this trigonometric functions-based model. Using parabolic equations, en and Tan [16] created a straightforward model of solar radiation. This model computes the expected global and diffuse radiation levels for Musandam, Oman over the course of a month. Mean daily maximum temperature, relative humidity, sea level pressure, vapor pressure, and hours of brilliant sunshine were some of the meteorological characteristics that Trabea and Shaltout [17] looked for a correlation between. The estimation model of global solar radiation over horizontal surface was developed using several linear regression models. The meteorological information on the Fourier series was enhanced by Dorvlo [18]. To calculate the solar radiation and air temperature, he used a linear combination of trigonometric functions as a model.

In this study, the environmental and financial benefits of installing thermosiphon hot water solar energy systems in seven cities across Oman with varying climates are estimated using a straightforward mathematical model. We calculate the savings in CO_2 emissions and the payback time for a flat-plate solar collector-based simple thermosiphon solar hot water system.

2. Research Methods

Solar energy is measured on slanted surfaces using a straightforward mathematical technique. A basic thermosiphon hot water solar energy system with two solar collectors, a cold-water tank, and a hot-water tank, was evaluated using solar energy gained from sloped surfaces. Benefits from solar energy can be evaluated with the following assumptions:

- The absorber surface area of the hot water solar energy system under study is 4 m^2.
- A 30˚ slope angle is chosen to allow for use throughout the year.
- An expertly built and placed collector can achieve an efficiency of roughly 80%.
- Solar energy is used for domestic purposes after being absorbed.
- When 1 Sm^3 of natural gas is consumed in a natural gas heater, 8250 kcal of energy is produced.
- The natural gas heater's emissions totaled 21857 kg CO_2 for every 1 Sm^3 of natural gas burned.
- Sm^3 of natural gas costs about $0.25.
- The typical cost of a solar hot water system's "key turn" is between $150 and $500. The cost varies widely based on variables like distance, tank size, shipping costs, labor rates, product name recognition, etc.

To calculate the average daily global solar radiation on a flat surface, scientists utilize a straightforward model [15] that takes into account average weather conditions over extended periods of time. Because it is based on long-term measurable data, this model accounts for both the climatic and geographical effects on the daily global sun radiation on a horizontal surface

$$H = I_2 + \left(I_1 - I_2\right)\left|\sin\left[\frac{\pi}{365}\left(d+5\right)\right]\right|^{1.5} \tag{1}$$

where I_1 and I_2 are the coefficients (**Table 1**) and d is the number of the day.

The exponential distribution is derived from hourly global solar radiation by using daily global solar radiation [19].

$$\Psi = \exp\left\{-4\left(1 - \frac{|\omega|}{sunset}\right)\right\} \tag{2}$$

$$I = H * \frac{\pi}{4 * t_0}\left\{\cos\left(90 * \frac{\omega}{sunset}\right) + \frac{2}{\sqrt{\pi}} * \left(1 - \Psi\right)\right\} \tag{3}$$

where t_0 is total daily duration of sunshine evaluated between sunset and sunrise. Sunset angle is

$$\cos\left(sunset\right) = -\tan\left(\phi\right) * \tan\left(\delta\right) \tag{4}$$

where declination angle is [20];

$$\delta = 23.45 * \sin\left(360 * \frac{284 + d}{365}\right) \tag{5}$$

And sunrise angle has the negative sign of sunset angle.

Hourly diffuse solar radiation is

$$I_d = \frac{\pi}{24} * \frac{\cos\left(\omega\right) - \cos\left(sunset\right)}{\sin\left(sunset\right) - \frac{\pi}{180} * sunset * \cos\left(sunset\right)} * H_d \tag{6}$$

And hourly beam radiation is

$$I_b = I - I_d \tag{7}$$

Table 1. Geological information and statistical values (16) of selected locations.

Oman governorates	Longitude (˚E)	Latitude (˚N)	Elevation (m)	I_1	I_2
Sharqiya	23.6567˚N	58.6208˚E	1500	21.41	2.57
Wusta	20.2950˚N	56.3294˚E	500	22.71	3.86
Batinah	24.3667˚N	56.7361˚E	200	24.15	5.27
Muscat	23.6100˚N	58.5400˚E	500	26.12	6.86
Musandam	26.1743˚N	56.2472˚E	2000	22.47	4.39
Buraimi	24.2350˚N	55.9622˚E	300	23.89	6.91
Dhofar	17.0197˚N	54.0843˚E	1800	19.86	2.47
Dakhiliyah	22.7361˚N	57.5339˚E	1700	22.71	3.86
Dhahirah	24.1798˚N	56.5167˚E	300	24.15	5.27

H_d is the diffuse part of the daily solar radiation and calculated as [21]

If $sunset \le 81.4^\circ$

$$\frac{H_d}{H} = \begin{cases} 1 - 0.2727K_T + 2.4495K_T^2 - 11.9514K_T^3 + 9.3879K_T^4 & \text{for } K_T < 0.715 \\ 0.143 & \text{for } K_T \ge 0.715 \end{cases}$$

and

$$sunset > 81.4^\circ \quad (8)$$

$$\frac{H_d}{H} = \begin{cases} 1 + 0.2832K_T - 2.5557K_T^2 + 0.8448K_T^3 & \text{for } K_T < 0.722 \\ 0.175 & \text{for } K_T \ge 0.722 \end{cases}$$

K_T is the clearness index and depends on the meteorological condition, Unfortunately, there are no specific measurements for Oman cities, Due to that reason $K_T = 0.64$ is chosen in the light

R_b is the ratio of the average beam radiation on the tilted surface to that on a horizontal surface,

$$R_b = \frac{\cos(\phi - \beta) * \cos\delta \cos\omega + \sin(\phi - \beta) * \sin\delta}{\cos\phi \cos\delta \cos\omega + \sin\phi \sin\delta} \quad (9)$$

Solar energy absorbed from tilted solar collector can be evaluated by

$$S = I_b * R_b * (\tau\alpha)_b + I_d * (\tau\alpha)_d * \left(\frac{1+\cos\beta}{2}\right) + \rho_g * (I_b + I_d) * (\tau\alpha)_g * \left(\frac{1-\cos\beta}{2}\right) \quad (10)$$

All governorates in Oman (shown in Figure 1), each of which is located in a

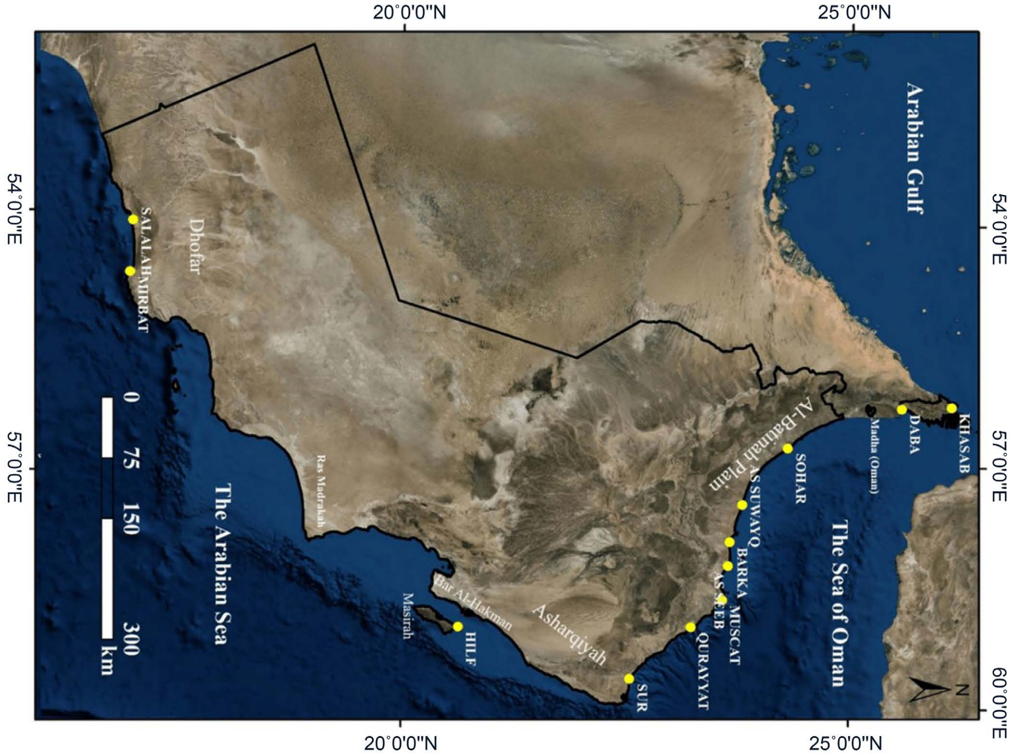

Figure 1. Location of investigated cities of Oman.

different climate zone, are studied. Table 1 provides geological data for the area of interest. At first, we determine how much solar radiation is absorbed by slanted surfaces. After that, we utilize our assumptions to determine how much energy can be harvested from a 4 m^2 collector. By avoiding the need to consume natural gas, we can reduce our carbon footprint and save money.

3. Result and Discussion

The aforementioned formula was realized in the MATLAB environment. Total sun radiation received by slanted surfaces per hour, year-round. Hourly total solar energy is used to calculate monthly and annual solar gain on slanted surfaces. Using the assumptions laid out in the Method section, we can calculate the energy equivalent of natural gas and the price of natural gas in equivalent form. Under the same conditions, the CO_2 emissions avoided can be estimated. Each potential dwelling is rated independently. Monthly solar gain, equivalent natural gas, equivalent natural gas price, and avoided CO_2 emission are shown alongside hourly total solar energy on a sloped surface for a sample month.

Muscat: Muscat has more people than any other Omani city. Muscat has a humid subtropical climate and may be found on the northern coast of Oman (Figure 2). The Arabian Sea and the Gulf of Oman have significant impacts on the climate of Muscat. High rates of evaporation cause more days of fog and less time spent in the sun. Figure 2 shows the hourly total solar energy on a slanted surface. According to Table 2, the highest possible levels of solar energy on a sloping surface occur on January 1 (155.39 W/m^2) and July 2 (443.02 W/m^2). The configured system is expected to gain 124,629 kWh of solar energy every

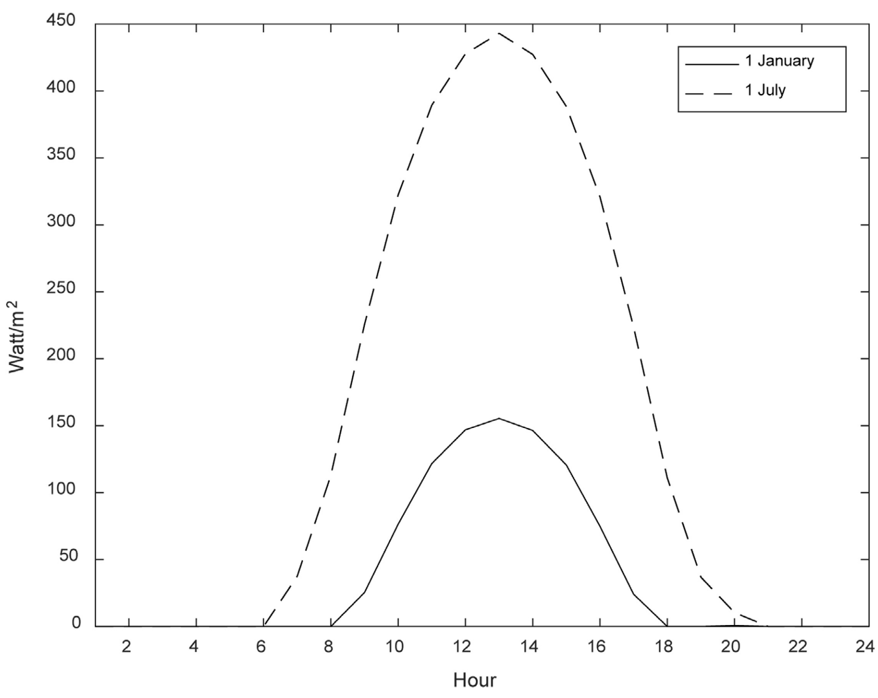

Figure 2. Hourly total solar energy on sloped surface for a winter and a summer day.

Table 2. Maximum absorbed solar energy by sloped surface.

	Batinah	Wusta	Buraimi	Muscat	Sharqiyah	Dhakiliyah	Dhofar
Max absorbed solar energy watt/m^2 (1 Jan)	155.39	219.28	284.78	351.77	228.29	381.88	153.88
Max absorbed solar energy watt/m^2 (1 Jul)	443.02	468.32	498.85	539.83	460.11	492.92	407.42

year. With that increase in solar power, we might have avoided emitting 692.47 kilograms of carbon dioxide and wasting 316.82 cubic meters of natural gas. This resulted in an annual return of $79.20 USD and a payback period of 1.89 - 6.31 years (Table 3). Benefits to Muscat's economy and environment are shown to fluctuate on a monthly base in Figure 3.

Wusta: The capital city of Oman, Wusta, may be found about in the geographic center of the country (Figure 4). The high altitude (894 m) and inland location of Wusta contribute to the city's cold semi-arid climate. Wusta has frigid, snowy winters and scorching, dry summers. Figure 4 depicts the hourly total solar energy on a sloping surface. Sunlight at its peak on a slanted surface occurs at 219.28 W/m^2 on January 1 and at 468.32 W/m^2 in July (Table 2). The configured system is expected to gain 137,481 kWh of solar energy every year. A total of 349.34 m^3 of natural gas and 763.55 kg of carbon dioxide emissions can be avoided because to this solar energy gain. That resulted in an annual return of 87.33 USD and a payback period of 1.71-5.72 years. Figure 5 shows how Wusta's economic and environmental benefits fluctuate from month to month.

Batinah: Batinah, a major city in the country's north, is seen in Figure 6. Summers in Batinah tend to get quite warm due to the region's typical Mediterranean climate. Batinah has hot, dry summers and wet, warm winters. The months of November through March have the heaviest precipitation. Maximum sun energy absorbed in zmir on 1 January is significantly high (284.78 watt/m^2) compared to both Muscat and Dhofar. Batinah is impacted by evaporation from the Aegean Sea, yet the land's mountainous terrain allows humid air from the sea to penetrate further inland. On July 1st, the solar radiation received was calculated to be 498.85 watts per square meter (Table 2). It is estimated that the configured system will gain 150,791 kWh of solar energy per year, which is equivalent to the energy gained from extracting 383.13 m^3 of natural gas and avoiding the production of 837.40 kg of carbon dioxide. That yielded a yearly return of $95.78 USD and a payback period of 1.5652 years. Figure 7 is a

Table 3. Summary of annual economic and benefits of configured hot water solar system.

Regions	Annual Solar Energy Gain (Watthour)	Annual Saved Natural gas (m^3)	Annual Saved Money (USD)	Annual saved CO_2 (kg)	Payback period (year)
Batinah	124,629	316.82	79.20	692.47	1.89 - 6.31
Wusta	137,481	349.34	87.33	763.55	1.71 - 5.72
Buraimi	150,791	383.13	95.78	837.40	1.56 - 5.22
Muscat	167,062	424.12	106.03	927.01	1.41 - 4.71
Sharqiyah	136,204	345.94	86.49	756.12	1.73 - 5.78
Dhakiliyah	160,533	407.94	101.99	891.64	1.47 - 4.90
Dhofar	117,584	298.98	74.74	653.48	2.00 - 6.68

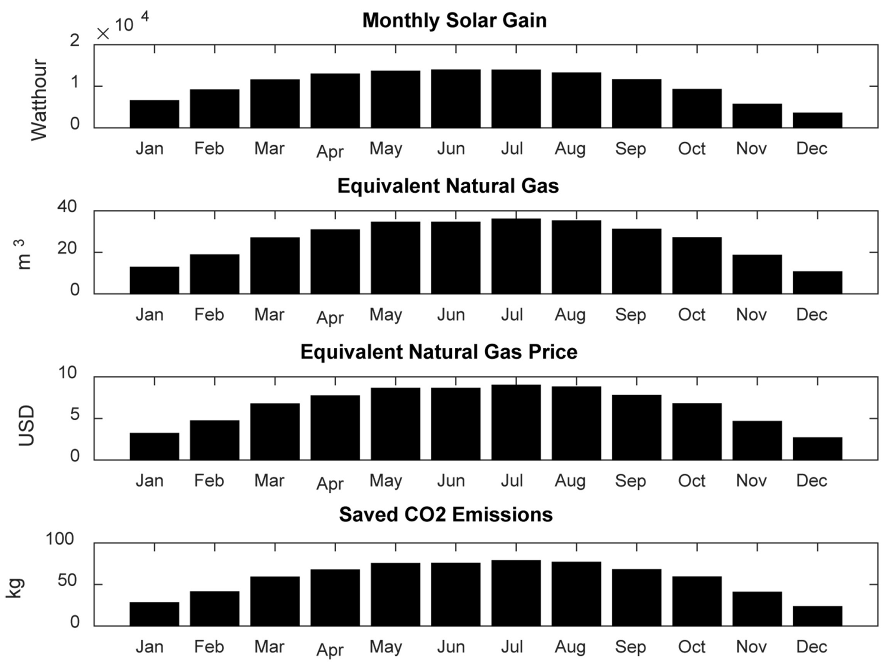

Figure 3. Monthly variation of solar gain, equivalent natural gas, equivalent natural gas price and saved CO_2 emissions for Muscat.

monthly summary of Batinah's economic and environmental benefits.

Buraimi: Buraimi is tucked away on the United Arab Emirates border (Figure 8). Summers in Buraimi are hot and dry, and winters are moderate and rainy, typical of the Mediterranean climate. With almost 3000 hours of sunshine per year, Buraimi is one of Oman's brightest spots. Muscat, thanks in large part to its geographical positioning, has the highest solar energy gain of the studied cities. Figure 8 shows that the peak solar radiation on a sloping surface occurs at 351.77 W/m^2 on January 1 and 539.83 W/m^2 in July. The system is expected to gain 167,062 Watthour of solar energy every year. Solar energy prevented 424.12 m^3 of natural gas use and 927.01 kg of carbon dioxide emissions. This resulted in

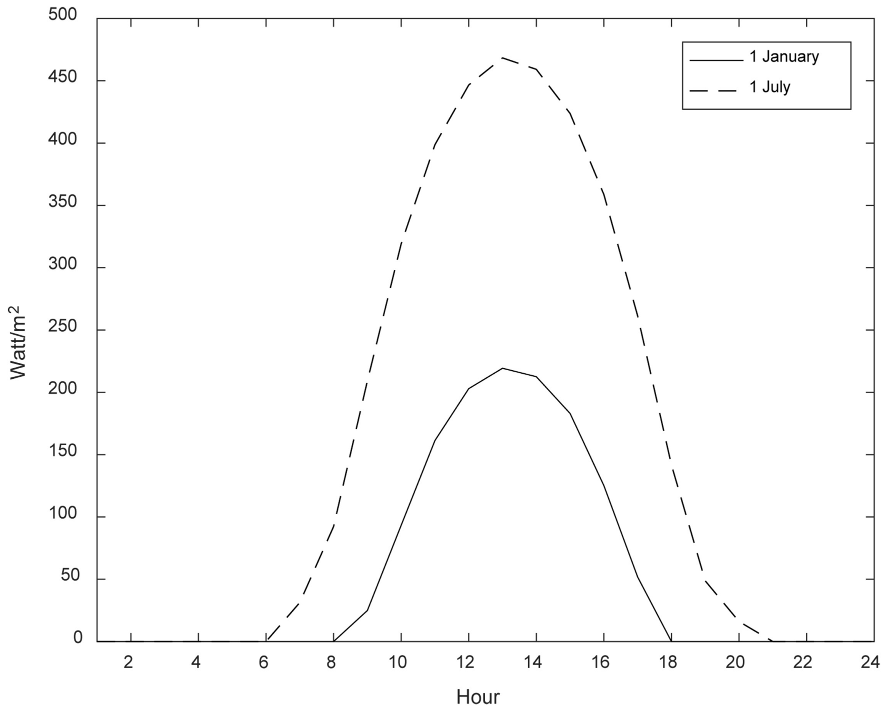

Figure 4. Hourly total solar energy on sloped surface for a winter and a summer day for Wusta.

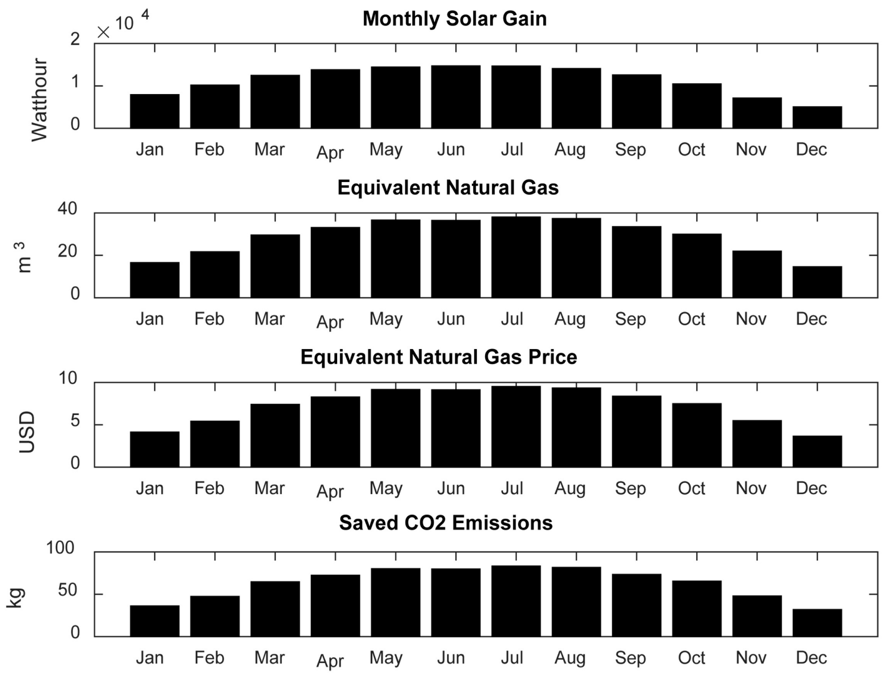

Figure 5. Monthly variation of solar gain, equivalent natural gas, equivalent natural gas price and saved CO_2 emissions for Wusta.

an annual return of 106.03 USD and a payback period of 1.41-4.71 years. Benefits to Muscat's economy and ecology may be seen fluctuating monthly in Figure 9 from Buraimi.

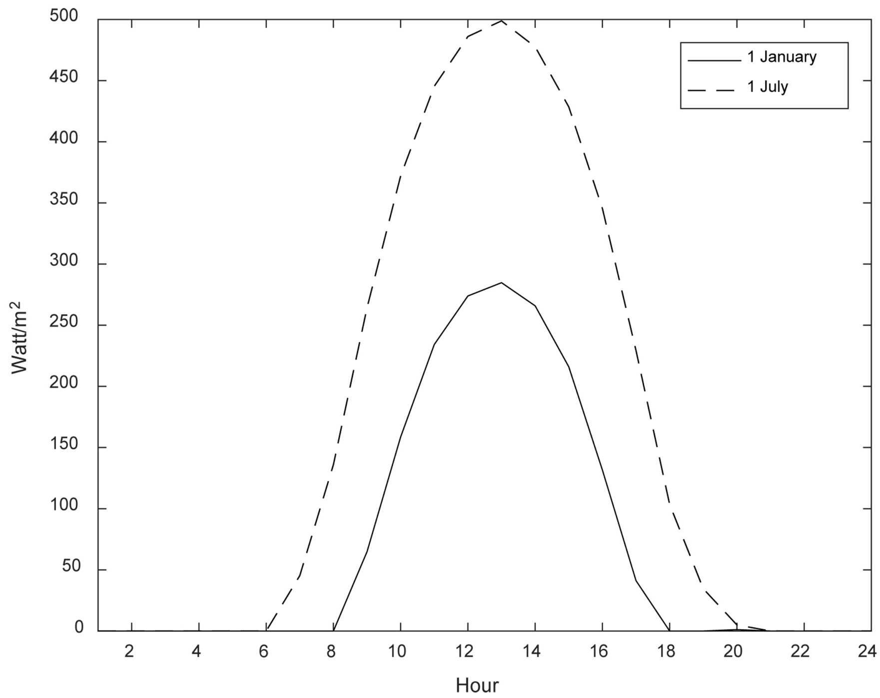

Figure 6. Hourly total solar energy on sloped surface for a winter and a summer day for Batinah.

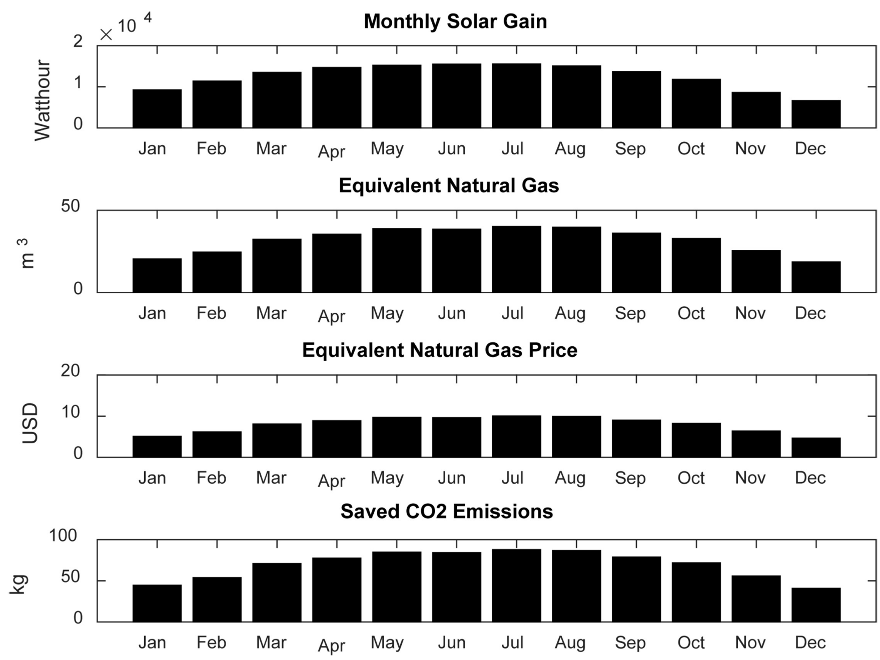

Figure 7. Monthly variation of solar gain, equivalent natural gas, equivalent natural gas price and saved CO_2 emissions for Batinah.

Sharqiyah: Figure 10 shows the location of the city of Sharqiyah in the eastern region of the Oman Region. Sharqiyah's climate is typical of the Mediterranean region: hot and dry in the summer and mild and wet with occasional snowfall in the winter. In the spring and summer, Sharqiyah's climate is impacted

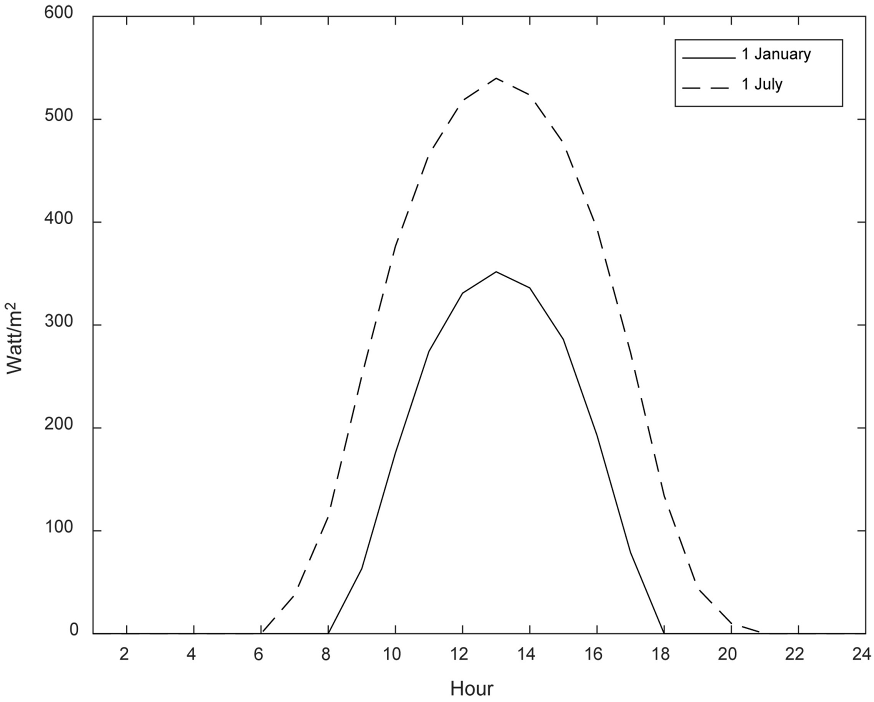

Figure 8. Hourly total solar energy on sloped surface for a winter and a summer day for Buraimi.

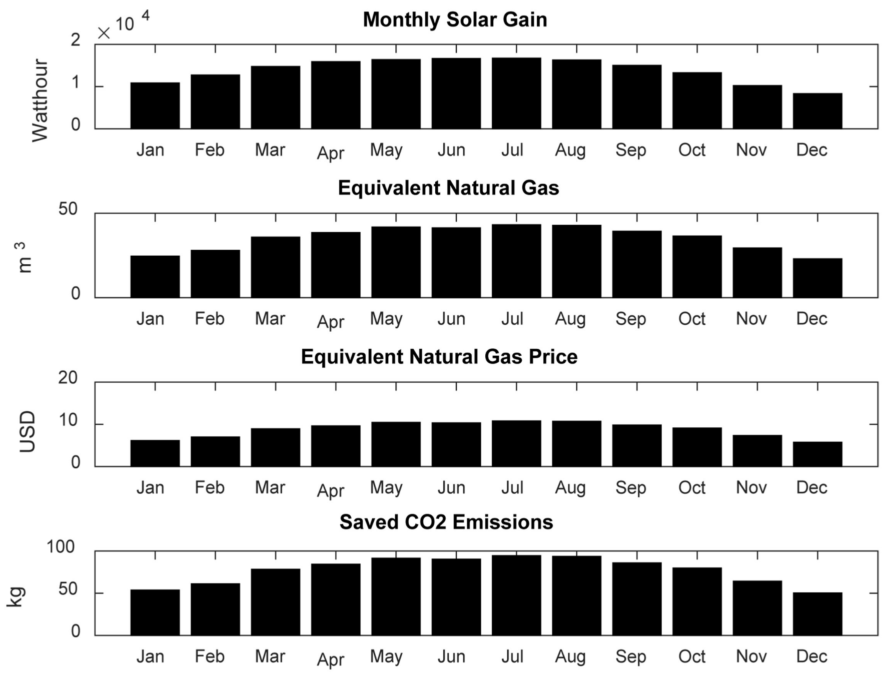

Figure 9. Monthly variation of solar gain, equivalent natural gas, equivalent natural gas price and saved CO_2 emissions for Buraimi.

by dust blowing in from the United Arab Emirates. On a slanted surface, the sun's rays are at their strongest at 228.29 W/m^2 on January 1 and at 460.11 W/m^2 in July (Figure 10). The system is expected to accumulate 136,204 kWh of solar energy every year. The use of solar energy avoided 345.94 m^3 of natural gas and 756.12 kg of carbon dioxide emissions. With a payoff of 1.73 - 5.78 years, the yearly return was 86.49 USD. **Figure 11** shows how Sharqiyah's economic and environmental benefits fluctuate from month to month.

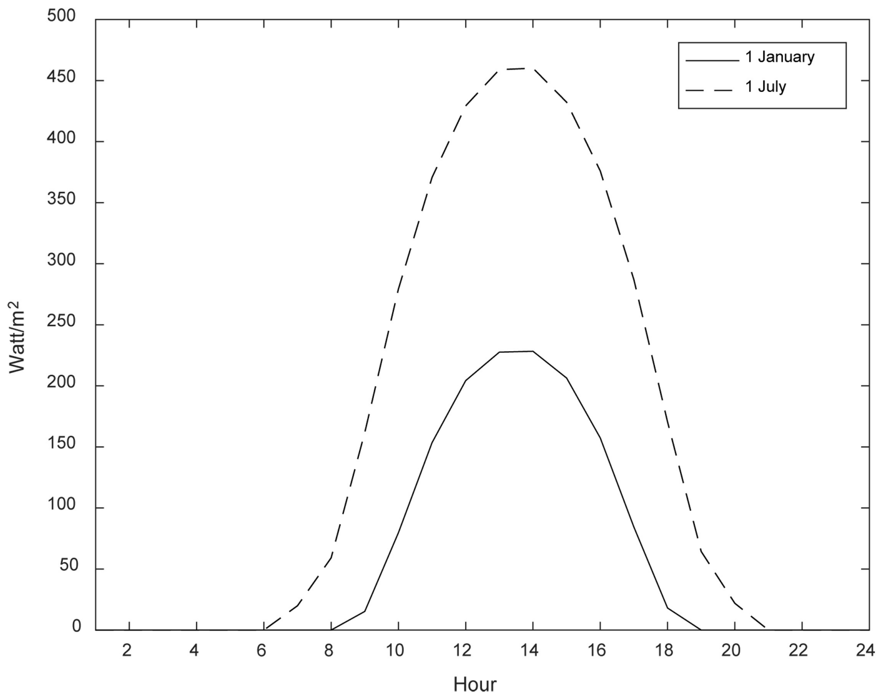

Figure 10. Hourly total solar energy on sloped surface for a winter and a summer day for Sharqiyah.

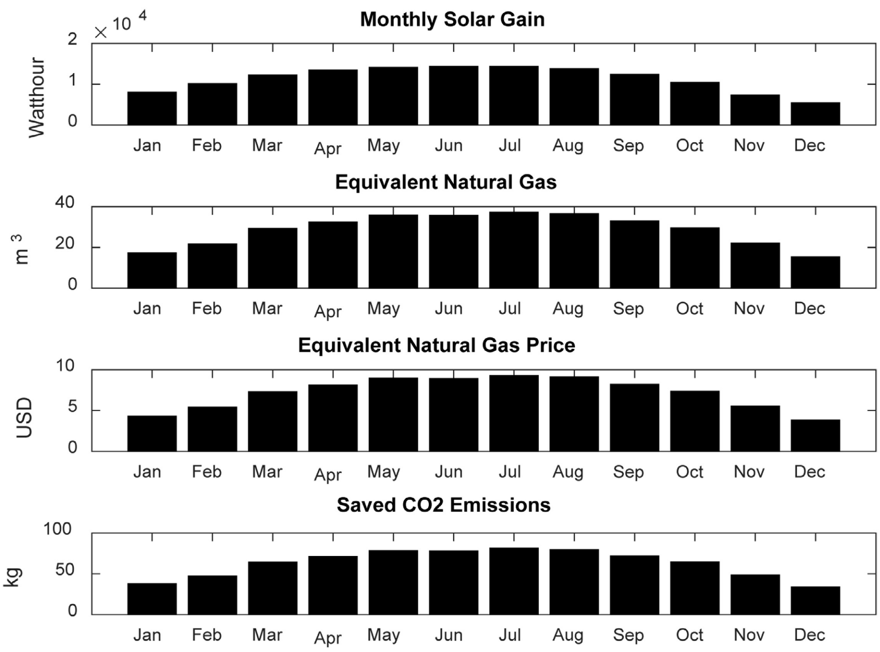

Figure 11. Monthly variation of solar gain, equivalent natural gas, equivalent natural gas price and saved CO_2 emissions for Sharqiyah.

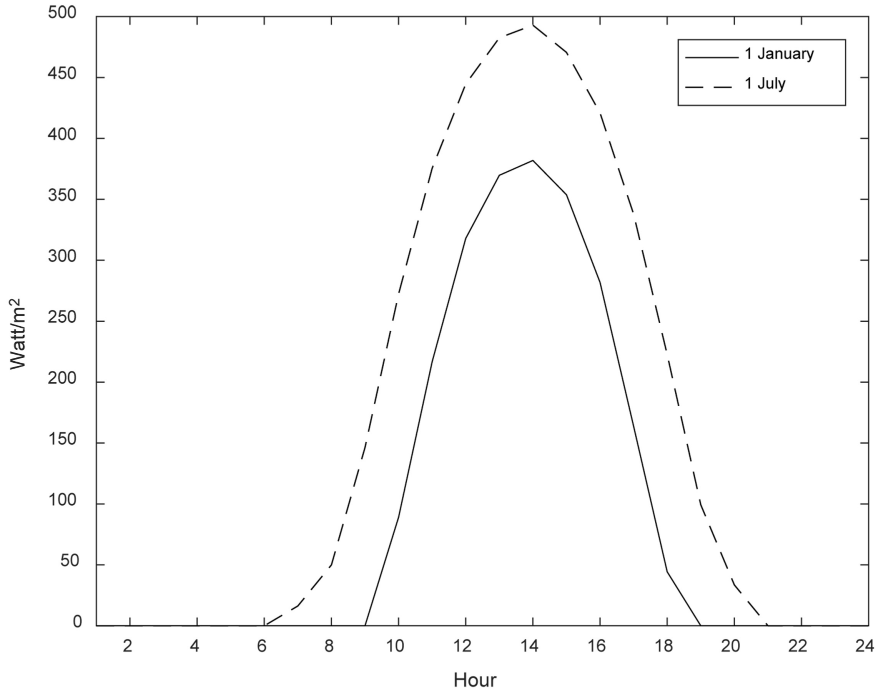

Figure 12. Hourly total solar energy on sloped surface for a winter and a summer day for Dhakiliyah.

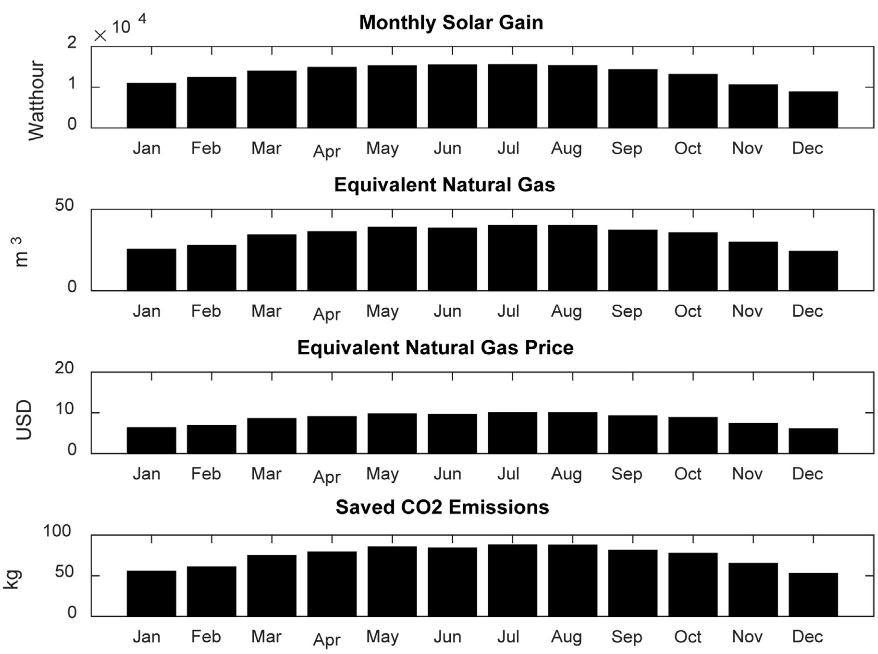

Figure 13. Monthly variation of solar gain, equivalent natural gas, equivalent natural gas price and saved CO_2 emissions for Dhakiliyah.

Dhakiliyah: Dhakiliyah is located in the country's north. Extremely cold, snowy winters and hot, dry summers characterize Dhakiliyah's humid continental climate. In the winter, Dhakiliyah is blanketed in deep snow. Figure 12 shows that the peak solar radiation on a sloping surface occurs on January 1st

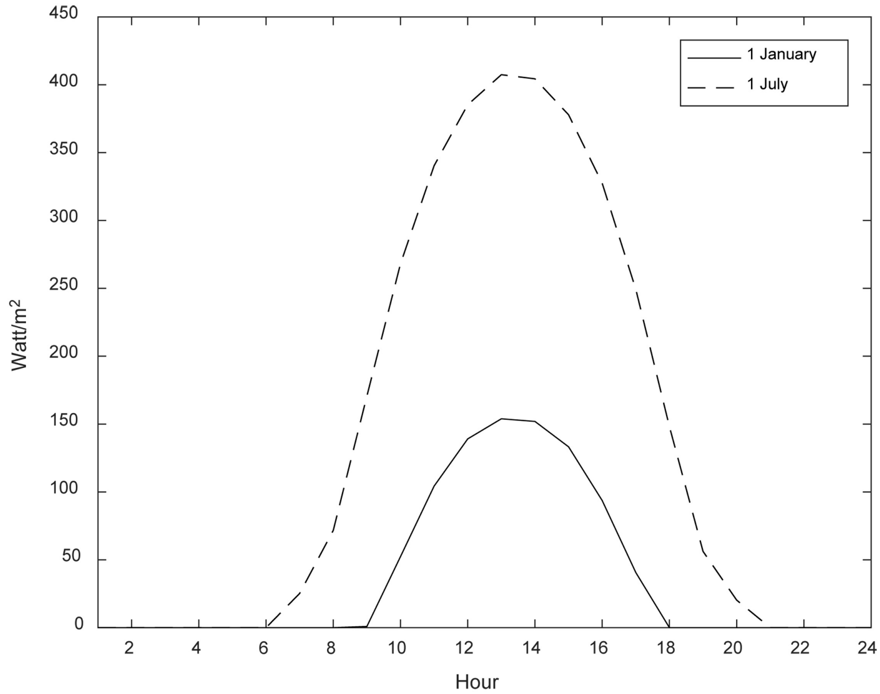

Figure 14. Hourly total solar energy on sloped surface for a winter and a summer day for Dhofar.

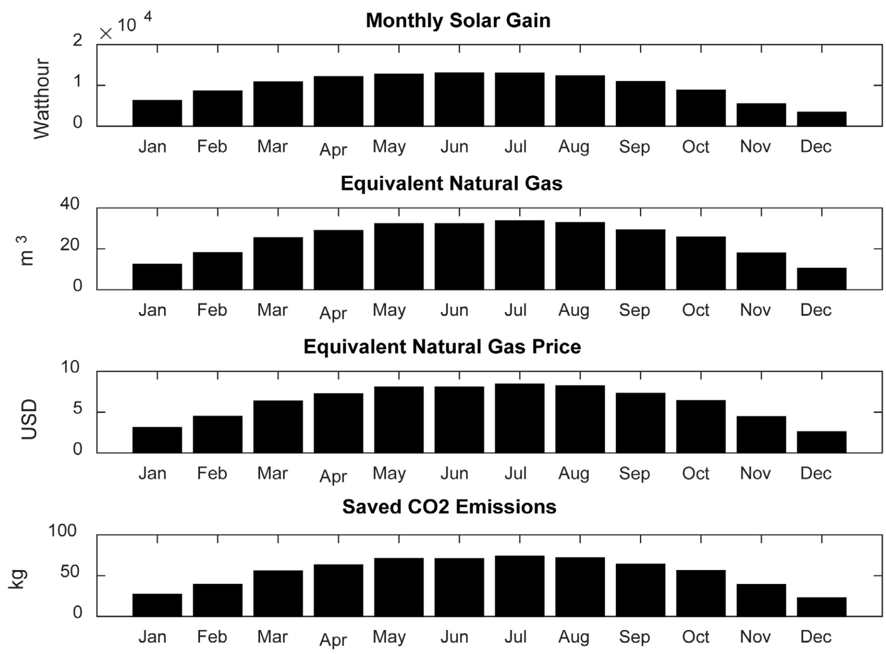

Figure 15. Monthly variation of solar gain, equivalent natural gas, equivalent natural gas price and saved CO_2 emissions for Dhofar.

with 381.88 W/m^2 and July 7th with 492.92 W/m^2. Dhakiliyah is unique in that it receives a lot of sunlight even in the dead of winter. Snow's reflective properties could be to blame for this phenomenon. The system is expected to gain 160,533 Watt-hour of solar energy every year. The use of solar energy has reduced fossil fuel use by 407.94 m^3 per year and cut CO_2 emissions by 891.64 metric tons. With a payoff of 1.47-4.90 years, the annualized return was 101.99 USD. Figure 13 shows the monthly changes in economic and environmental benefits to Dhakiliyah.

Dhofar: The province of Dhofar can be found in the south of the country. Long, chilly, rainy, and overcast winters are typical of Dhofar's humid subtropical climate. Figure 14 shows that the maximum solar energy received by a sloping surface is 153.88 W/m^2 on January 1 and 407.42 W/m^2 in July. It is estimated that the configured system will gain 117,584 Watthour per year in solar energy. This increase in solar power might save 298.98 cubic meters of natural gas and 653.48 kilograms of carbon dioxide equivalent. The payoff time increased from 0 to 2.00-6.68 years, with an annual return of 74.74 USD. Figure 15 shows the monthly variance in economic and environmental benefits for Dhofar.

4. Conclusions

The study looks into the financial and environmental advantages of installing modest solar hot water systems in seven different cities around Oman. Climate and topography vary from one metropolis to the next. The system's performance throughout the year is expressed through a straightforward theoretical model. In Dhakiliyah, the maximum solar energy absorbed by an absorber is calculated to be 381.88 watt/m^2, while in Muscat, it is 539.83 watt/m^2. In Dhofar, the least amount of solar energy absorbed by an absorber during the winter is determined to be 153.88 watt/m^2, while the maximum amount of solar energy absorbed during the summer is calculated to be 407.42 watt/m^2. Dhakiliyah may not seem like it would have the greatest solar potential in the winter, but the substantial snow carpet on the surface actually boosts the use of reflected sun energy. Due to its location on Oman's more solar-friendly southern coast, Muscat has the most solar potential during the summer months. However, Dhofar has the least amount of solar potential during both the winter and summer months. The evaporation of the Arabian Sea is the primary source of the extreme humidity that plagues Dhofar.

The solar hot water systems that have been researched have all had positive economic and environmental outcomes. Annual natural gas savings ranged from a high of 407.94 m^3 in Muscat to a low of 298.98 m^3 in Dhofar. Based on the findings, Muscat can save 106.03 USD, whereas Dhofar can save 74.74 USD. The results give a payback period of 1.41 - 4.71 years for Muscat and 2.00 - 6.68 years for Dhofar. In addition to the monetary benefits, the reduction in CO_2 emissions is calculated at 927.01 kg for Muscat and 653.48 kg for Dhofar. The above results are very attractive for utilization of hot water solar systems even for disadvantageous locations such as Dhofar.

Conflicts of Interest

The authors declare no conflicts of interest.

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Abbreviations and Acronyms

β	Slope angle
ϕ	Latitude
δ	Declination angle
ω	Hour angle
d	Day of year
CO_2	Carbon dioxide
I	Hourly global solar radiation
I_b	Hourly beam radiation
I_d	Hourly diffuse radiation
I_1	Coefficient of Eq1
I_2	Coefficient of Eq1
H	Daily global solar radiation on horizontal surface
K_T	Clearness index
USD	United States Dollar