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Research Article

Techno-economic analysis of a residential solar thermal-biodiesel heating and cooling system under the mediterranean climate

Nyasha Netsai BEMA[1], **Kemal MASERA**[1,*]

[1]*Department of Mechanical Engineering, Faculty of Engineering, Middle East Technical University Northen Cyprus Campus, Mersin, 99738, Turkiye*

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ABSTRACT

This case study focused on the design of an economic and sustainable solar-biodiesel thermal system to meet the growing heating and cooling energy demand in Cypriot residential buildings. While the application of solar thermal systems in the residential sector has been one of the most efficient solutions to energy shortage issues experienced globally, auxiliary systems are often neglected. Therefore, this study addresses intermittency issues of solar and wind energy by exploring biodiesel as an auxiliary energy source. Biodiesel as an auxiliary fuel eliminates the use of expensive energy storage systems such as solar PV batteries and PCMs in solar thermal applications The proposed system which integrates evacuated tube solar collectors, thermal energy storage tank, Lithium-Bromide absorption chiller and a biodiesel boiler is modelled using TRNSYS. Different from most studies this study implements a user-centered method in determining residential space conditioning energy demand through a survey. TMY data is used to represent the available solar energy resources in Cyprus. The 10.5kW proposed system demonstrated a performance capability by satisfying 37800kJ/h of space conditioning energy demand. Thermal energy from solar managed to meet 100% and 87.7% of the cooling and heating energy demand respectively. The cost analysis reflected a payback period of 7.3 years and total savings of $37,200 over 20 years, highlighting the energy and cost effectiveness of renewable energy thermal systems in residential buildings.

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INTRODUCTION

The motivation of this research is founded upon the growing energy demand for space heating and cooling systems in Cyprus. Electricity prices have been on the rise since natural gas prices are constantly fluctuating [1]. High energy demand has resulted in power outages, which inconveniences residents as their thermal comfort is disturbed especially during summer seasons. Considerable number of residents in Cyprus have resorted to using solar Photovoltaics, however, the limitation of solar PV grid integration is the unpredictability of solar energy. Integrating

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***Corresponding author.**
*E-mail address: nyashabema@gmail.com

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solar PVs into the grid is a complicated process as balancing available solar energy to instantaneously match energy demand is still a challenge faced by system operators [2]. Therefore, there is a need for practical sustainable solutions to meet the growing energy demand while maintaining thermal comfort within residential buildings. According to the IEA, energy consumption in residential buildings increased by 1% in 2022 and is expected to increase as the world population is increasing [3]. Space heating and cooling contributes a substantial amount of energy consumed in residential buildings. As of 2022, about 2 billion air conditioning units were in operation for space cooling, accelerating electricity demand in residential buildings. The addition in generational capacity has been noted during peak hours and is expected to rise over the coming years [3]. Additionally, there is limited research in the implementation of solar thermal systems in domestic homes [4]. For these reasons, alternative energy solutions and improved designs, such as the solar-biodiesel thermal system proposed in this study, are necessary in complying with Net Zero Emissions goals.

Use of biofuels is advantageous due to minimal environmental effects and economic benefits. Biofuels can be a better option for parameters such as thermal efficiency and fuel consumption [5]. Unlike wind and solar energy, biofuels are not intermittent. Biodiesel is biodegradable and non-toxic [6]. The contribution of biodiesel to atmospheric CO2 emissions is non-existent, reducing the GHG emission profile of biodiesel [6]. Biodiesel is the first generation of biofuel and a renewable clean-burning mono-alky ester fuel that is made from natural renewable feedstock such as soybean, cottonseed oil, canola oil, corn oil, jatropha and waste animal fats [7, 8] . Used cooking oil can also be recycled to produce biodiesel and new feed-stocks are emerging from further research and on the market [9]. Several factors and biodiesel properties such as anti-foaming, oxygen content, corrosion, chemical structure, conductivity, cetane number, and cold flow properties must be considered when using pure biodiesel instead of convectional diesel. These factors mainly depend on feedstock type [8]. Feedstock is the most expensive material in biodiesel manufacturing processes and contributes to 80% of the operating costs [8, 9]. The selection of cheaper feedstock such as waste fats and oils is advantageous because production cost is still a major challenge in biodiesel production. Apart from the feedstock, total production costs include cost of other reactants, nature of purification and the storage type [8]. Compared to natural gas, biodiesel can be a better alternative for auxiliary thermal energy systems in residential buildings. Shanableh et al. [10] studied the production of biodiesel from waste cooking oil and canola oil in North Cyprus. The results supported biodiesel production using waste cooking oil as an alternative fuel. Furthermore, Lopestro et al. [9] investigated the incorporation of biodiesel in a small community nanogrid to promote the production of biodiesel from waste oils. The results showed a 19% reduction in fossil fuel use. National Sustainable Agriculture Information Services encourages the formation of local biodiesel clubs to educate residents on safe homebrewing techniques [11].

Although many studies have investigated the application of thermal systems in residential buildings for space heating and cooling, the originality and novelty of this study is primarily based on the hybrid solar-biodiesel thermal system. Noro et al. [12] explored the potential of evacuated tube solar collectors (ETSC) to drive an absorption chiller during summer seasons. A gas boiler was integrated as an auxiliary system to drive the chiller and meet the cooling load in case of solar energy insufficiency. A similar study conducted by Sibilio et al, incorporated a gas boiler in the design of a solar thermal system for space heating and cooling in Italy. Although the system's performance surpassed that of a convectional system, and offered more economic and environmental benefits, the use of natural gas as a backup fuel decelerates green energy transition in residential buildings [13]. The same approach of adding an auxiliary boiler was taken by Hussein et al. [14] while modelling an absorption cooling system for residential purposes under Iraq weather conditions. Sarmouk et al. [15] developed and experimentally validated a TRNSYS model for space heating in Algeria. Although the experiment set up included a gas boiler for auxiliary purposes, only the solar mode was considered for the study. The exemption of the gas boiler from the numerical model conceals environmental effects of the system. Likewise, Marcos et al. conducted a solar powered air conditioning experiment in Spain to validate the efficiency of a highly efficient flat plate vacuum solar collector. The study incorporated an absorption chiller and storage tank. However, the solar system provided 65.3% of the heating energy demand, with fossil fuel covering the remaining [16].

Studies focusing on renewable energy systems often neglect the significancy of auxiliary systems energy sources. Careful consideration on the design of auxiliary systems is important to accelerate energy transition by minimizing dependency on fossil fuels. For instance, Redpath et al. [17] modelled a concentrated solar driven small scale absorption chiller which met 100% and 94% of heating and cooling energy demand respectively. Although the system contributed to CO2 savings of 3,966,247 tons per year, the remaining 6% supplied by the grid emphasizes the need for sustainable energy back-up solutions. Lebedeva et al. [18] analyzed the influence of PCMs in energy storage tanks and the results indicated a CO2 emission reduction of 5-7% and 21% decrease in the use of an auxiliary heater. However, CO2 emissions could further be reduced by opting for cleaner auxiliary energy sources. An economic analysis is of major importance when designing renewable energy systems. According to Pedro et al., the operation of a solar driven absorption chiller in Spain yielded less economic benefits when compared to an electric vapor compression chiller. However, this study focused solely on the cooling season, resulting in high investment costs and minimum savings per year [19]. In contrast, Salameh at al. [20] investigated the techno-economic performance of a solar driven Li-Br absorption chiller with an auxiliary electric heater and achieved better economic results. Despite high initial costs, the solar cooling system costs only 43.2% of what a convectional vapor compression system costs due to annual savings. However, the solar-driven absorption cooling system still consumed a considerable amount of electricity, which could be further reduced by the system proposed in the current study. Similarly, Düzcan et al. [21] compared thermal performances of flat plate and ETSCs in assisting an absorption chiller connected to an auxiliary electric heater.

In contrast to existing literature studies, which incorporates convectional fuels to power auxiliary energy systems, the proposed novel hybrid solar-biodiesel thermal system is distinguished by its dependency on 100% renewable and clean energy. This distinction represents a notable research gap due to its unique approach and ability of utilizing sustainable energy resources in line with the Net Zero Energy goals. This study aims to model and simulate a hybrid solar-biodiesel thermal energy system, which includes ETSC, an absorption chiller and a thermal energy storage tank (TES) to meet heating and cooling energy demand for a typical residential building in Cyprus. TMY (2022) weather data is used to calculate solar irradiance and determine the best tilt and azimuth angles using Ms Excel. The proposed system is modelled using TRNSYS 16. Heating and cooling loads were estimated by conducting a survey where 16 house owners residing in Cyprus were interviewed regarding their heating and cooling energy consumption. The authenticity of their answers was supported by local authority statistics [22]. Furthermore, the methodology approach taken in this study differs from existing literature in that, instead of estimating energy demand using ASHRAE standards, the study employed a survey approach to estimate energy consumption data from the users' (participants) perspective. The survey was conducted specifically for existing buildings, offering valuable insights into air conditioning use preferences of residents, thus reflecting real-world usage patterns. The scope of this study considers the unavailability of solar energy at nighttime and recommends use of biodiesel to supplement and meet the energy deficiency.

MATERIALS AND METHODS

The goal to design a novel hybrid solar-biodiesel thermal system to meet space heating and cooling energy demand is achieved by determining the space heating and cooling energy demand and estimating the solar energy available in Cyprus. An in-person survey was conducted to determine energy requirements while TMY (2022) data was used to develop a model in M.s Excel and estimate solar irradiance. System optimization and sizing were performed by selecting the necessary parameters and varying parameters such as the number of collectors and size of the TES tank. Simulations were performed using TRNSYS 16. The size of the absorption chiller was selected relative to the cooling energy requirements, to avoid oversizing the system. The results were analyzed based on the cost and thermal performance of the proposed system.

Case Study Location

Cyprus is in the Eastern part of the Mediterranean and, therefore, experiences hot summers above 40°C. According to Cyprus Met Department, the highest temperature recorded in Nicosia was 46°C in July 2023 and a total of 48 days (about 1 and a half months) had temperatures which exceeded 40°C [23]. Consequently, the electricity demand spiked due to the dependency on air conditioners.

Research Instrument

A structured interview was employed using questions in Table 1. Permission to conduct the survey was granted by the Middle East Technical University Northern Cyprus Campus Ethical Board (Bayek), after careful analysis of the interview questions and considerations of human safety. Cypriot house owners were asked questions regarding their heating and cooling energy consumption. In addition, electric bills were requested to verify participants' answers by matching their electricity usage to their electric bills. This control strategy was only useful in determining whether the participant overestimated or underestimated the actual usage, not in determining the actual air condition usage. The survey mainly focused on family houses and non-English-speaking participants were considered by using the local Turkish language to reduce communication barrier issues. A total of 16 households were interviewed and the data was collected and processed.

Data Normalization

Since the sample size of the survey (n) was 16, which is less than 30 and the standard deviation is unknown, t scores were used to estimate the mean and to construct the confidence interval for the population mean. Equation (1) shows the margin of error formula where T_c is the t score, S is the standard deviation of the sample population and n is the sample size. Margin of error represents the expected range for the true population parameter, the mean. The wider the range, the higher the uncertainty and the opposite is true for a narrow range or interval.

$$E = T_c \times \frac{S}{\sqrt{n}} \tag{1}$$

The confidence interval is constructed using equation (2) where x is the sample mean and μ is the population mean. The t score was found to be 2.31 from a 0.95 confidence level and degree of freedom of 15, (n-1).

$$\overline{x} - E < S\mu < \overline{x} + E \tag{2}$$

Table 1. Space conditioning interview questions

1. Do you have any solar system installed in your house for electricity YES NO production?
2. Do you depend on electrical energy from the National grid? YES NO
3. Do you use an air conditioning system? YES NO
4. How many air-conditioned rooms do you have in your house? Number: _____
5. Can you please tick the boxes for the hours you use the air conditioner during winter (mid- December to end-February)

☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24

Total number of boxes ticked :_____

6. Can you please tick the boxes for the hours you use the air conditioner during spring (March to mid-May)

☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24

Total number of boxes ticked :_____

7. Can you please tick the boxes for the hours you use the air conditioner during spring (mid-May-end-August)

☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24

Total number of boxes ticked :_____

8. Can you please tick the boxes for the hours you use the air conditioner during spring (September to end-November)

☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24

Total number of boxes ticked :_____

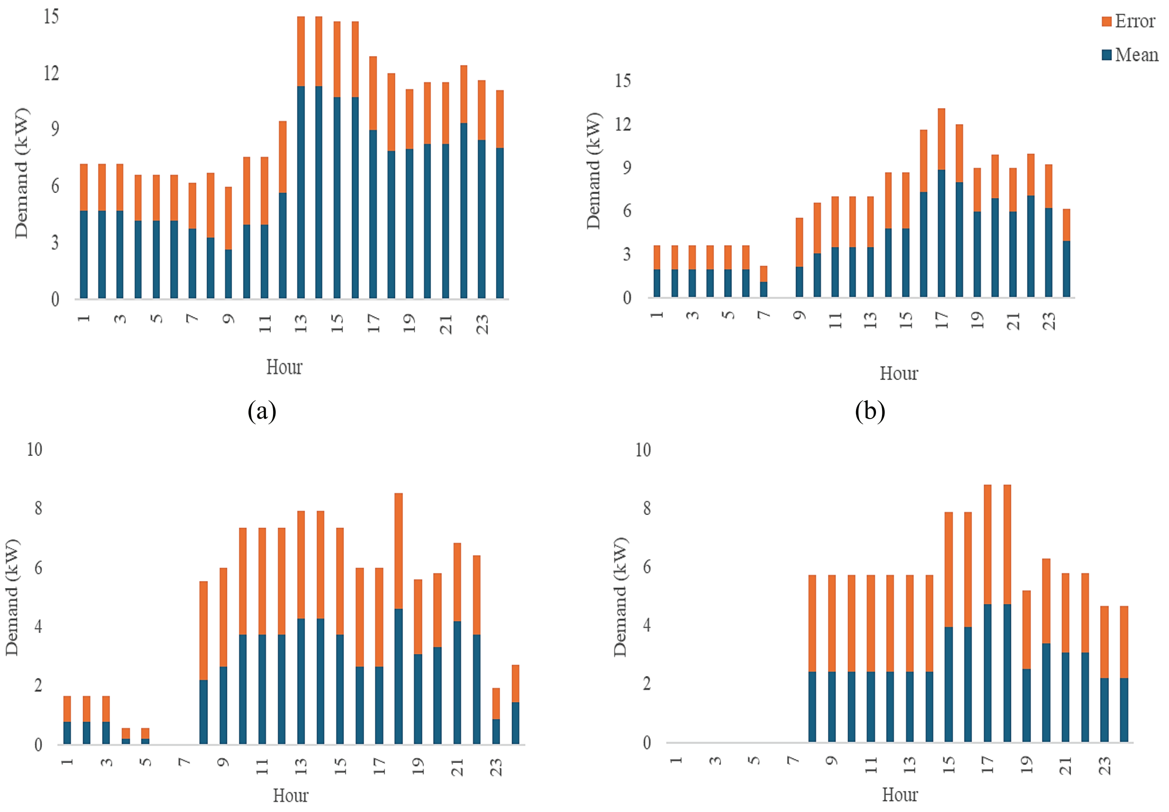
9. If known, please write the capacity of your air conditioning system ___Btu ____kWh
10. Are you willing to provide a receipt of your yearly/monthly electric bill YES NO

The data presented in **Figure 1** highlights a greater need for cooling energy during the summer period, (end of May-end of August). This is due to high temperatures reaching 45°C during mid-summer. The normalized average hourly energy consumption was calculated as 10.5kW which is equal to 3 air conditioning units of capacity 12000BTUs/12660kJ each. Energy demand is also high during summer months because of the summer school holidays which increases the population of people staying at home, using their air conditioners to cool their spaces. This highlights, to an extent, the effect of lifestyle and culture on energy consumption. It should be noted that this study does not represent the entire population of Cyprus, as it relied on voluntary participants, therefore, different air conditioner usage patterns may differ to non-participants. Despite normalizing the data and accounting for errors as presented in **Figure 1**, air conditioner usage is subjective [24]. Therefore, there is potential for overestimating or underestimating actual air conditioning usage, which possibly increase the inaccuracy of results.

Furthermore, the average hours of air conditioning use were determined, and it was realized that on a daily average, Cypriot residents use their air conditioners 12 hours during summer, 7 hours during winter, 4 hours during fall and 3 hours during the spring season. **Figure 2** shows the average air conditioner usage hours per seasons. The proposed system was modelled in order to meet daily space heating and cooling demand at these specific hours.

Solar Collector Optimization

The tilt and azimuth angles are important parameters which require accurate and careful analysis before installing



(a) (b) (c) (d)

Figure 1. Estimated average heating and cooling energy consumption in a typical Cypriot family house for the 4 seasons. (a) summer season, (b) winter season, (c) fall season and (d) spring season.

solar collectors. The tilted surface enhances irradiation absorption by optimizing light exposure and allows for an extended collector lifetime by avoiding early degradation caused by ground or dust pollution and other surface environmental effects. The best tilt and azimuth angles were optimized in Ms. Excel by using the solver add-in feature. The best tilt and azimuth angles for maximum irradiation absorption for each separate month are different. For this reason, the overall yearly best tilt and azimuth angles were selected as 30 °C and 0 °C respectively.

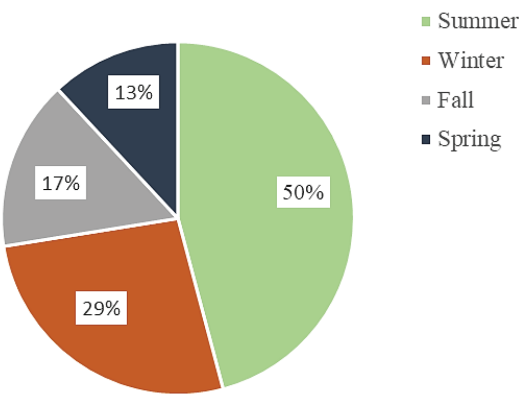


Figure 2. Estimated average and seasonal hours of air conditioner usage in a Cypriot family house.

System Description

The schematic of the proposed hybrid solar-biodiesel thermal system is shown in **Figure 3**. The solar energy harvested by the ETSC and absorbed by the HTF is transferred to the working fluid, (water) and stored inside the thermal energy storage tank. During winter seasons, this working fluid circulates through the indoor heat exchangers, to warm the cold space. After the working fluid warms the space by releasing its thermal energy, it returns to the thermal energy storage tank to collect energy and the cycle continues. During summer seasons, the working fluid from the TES tank is pumped into the absorption chiller, which produces chilled water for space cooling. The chilled water cools the space and returns to the absorption chiller. A biodiesel boiler is used as a back-up system, to heat the water in the storage tank when solar energy is unavailable.

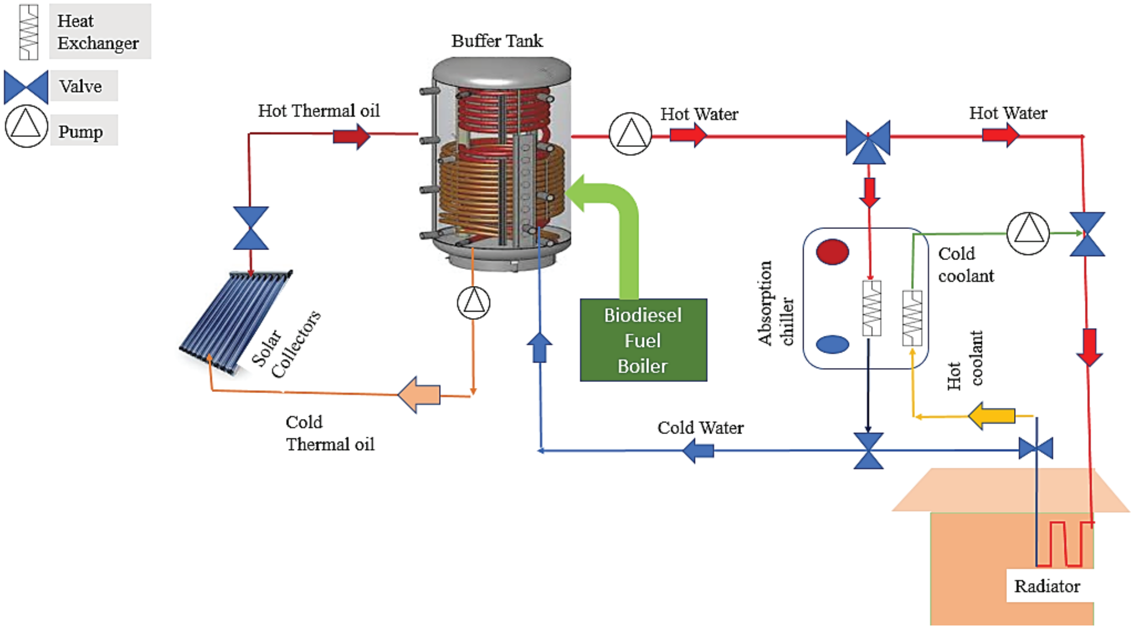


Figure 3. Schematic of the proposed thermal energy system for space heating and cooling. The system incorporates evacuated tube solar collectors, thermal energy storage tank, absorption chiller, biodiesel boiler and indoor radiators.

System's Design Specifications

The TRNSYS models are represented in **Figure 4** and **Figure 5** for space heating and cooling respectively. The TES tank was included in the TRNSYS 16 model as type 60c. **Table 2** shows the parameters and inputs used to design the system. Water was chosen as the working fluid and a heat exchanger (immersed coil) was also selected to transfer heat energy from the ETSC and promote uniform

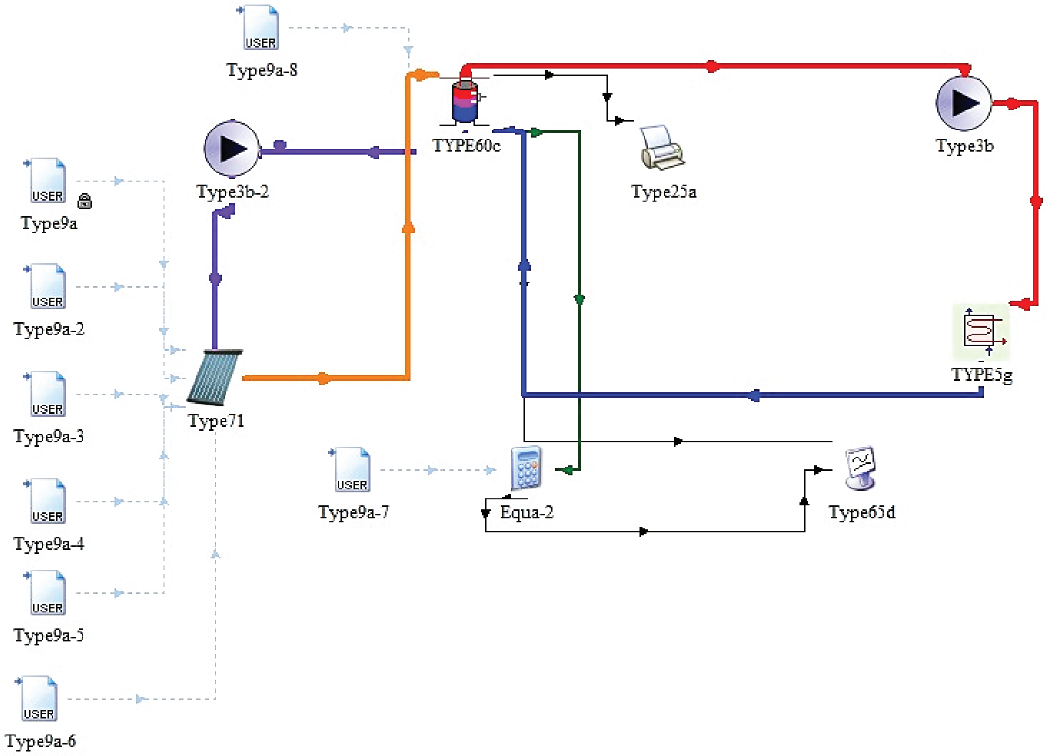


Figure 4. TRSNYS model of the proposed thermal system design for space heating.

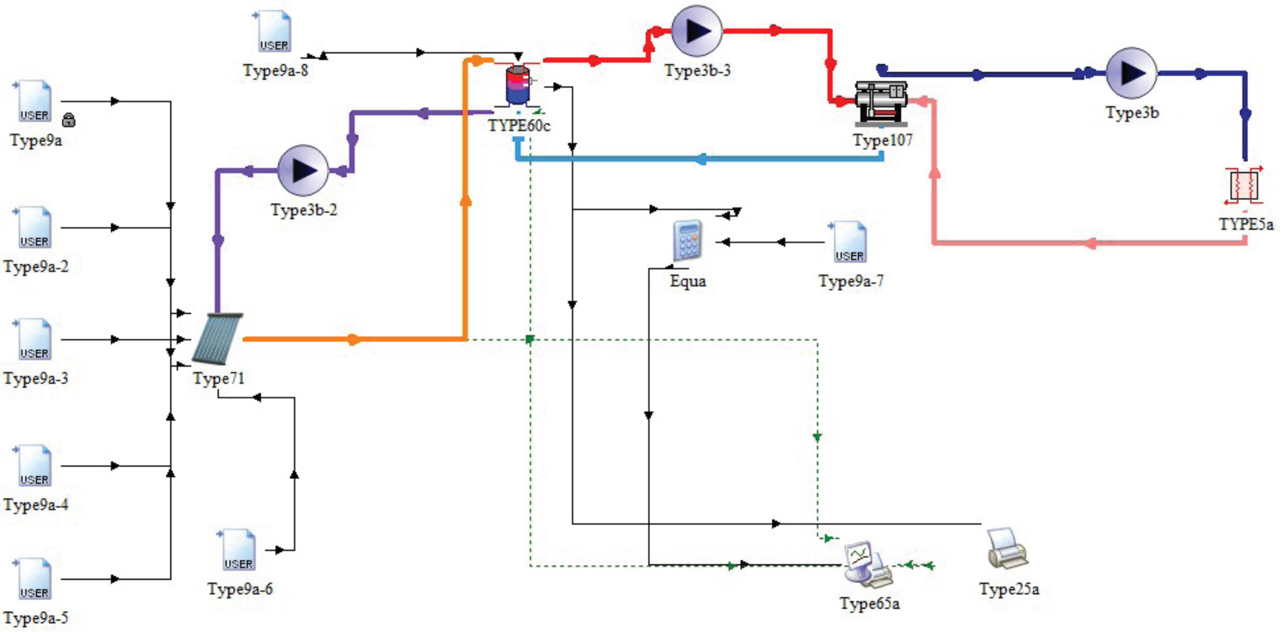


Figure 5. TRSNYS model of the proposed thermal system design for space cooling.

Table 2. Proposed system design parameters

Parameter		Units
ETSC gross area	3.476	m^2
Number of ETSC collectors	4	-
ETSC fluid specific heat	3.5	KJ/kg. K
ETSC efficiency mode	2	-
ETSC fluid flowrate at test conditions	0.02	kg/ms^2
ETSC intercept efficiency (a0)	0.744	0.744
ETSC a1	3.72	W/m. K
ETSC a2	0.013	W/m^{2}K
Collector tilt angle	30	°C
Collector azimuth angle	0	°C
Storage tank fluid density	1000	Kg/m^3
Storage tank loss coefficient	0.833	W/m^2 k
Storage tank fluid thermal conductivity	0.388	W/m K
Storage tank fluid auxiliary heater mode	2	-
Storage tank Gas heater	0	-
Storage tank fluid gas flue temperature	0	-
Pump 1 maximum fluid flowrate	30	Kg/h
Pump 1 fluid specific heat	2.12	kJ/kg K
Pump 2 maximum fluid flowrate	30	Kg/h
Pump 2 fluid flowrate	4.190	kJ/kg K
Heat exchanger specific heat of water	4.190	kJ/kg K
Specific heat of air	1.003	kJ/kg K
Absorption chiller rated capacity	10.5	kW
Absorption chiller COP	0.8	-

Table 3. Feedstock caloric values

Ref	Biodiesel type	Calorific Value kJ/kg	Ref	Biodiesel type	Calorific value kJ/kg
[26]	Algal	40,666	[27]	Rapeseed	39,458
[27]	ethyl palmitate	41,011	[27]	Crambe	40,564
[27]	ethyl oleate	40,450	[28]	Cottonseed oil	42,100
[27]	ethyl stearate	41,548	[29]	Castor oil	38,600
[27]	Soybean	39,480	[27]	Jatropha	39,455

temperature distribution within the tank. Type 107 in **Figure 5** models a single-effect hot-water fired absorption chiller and a capacity of 10.5kW was chosen for this chiller after considering the cooling requirements of a typical residential building in Cyprus. An indoor set point of 26°C was considered in accordance with Kim et al. [25], whose study reported that 75% of occupants preferred indoor set points between 26 and 26.3 for heating seasons.Thermal energy to drive the chiller was supplied by the TES tank. Type 9a, is a data reading component, selected to read weather data files such as ambient temperature and direct normal irradiation. This component was also used to read the demand data obtained from the survey.

Equation (3) was added to the equation box shown in **Figure 4** and **Figure 5** to calculate the energy deficiency.

$$\text{Energy Deficiency} = \text{Energy Demand} - \text{Energy Supplied} \quad (3)$$

Equation (4) calculates the amount of biodiesel required to supplement the energy deficiency using biodiesel caloric values in **Table 3**. Type 9a containing the hourly energy demand values was connected to the equation.

$$Biodiesel\ amount\ (kg) = \frac{Energy\ Deficiency(kJ)}{Biodiesel\ Calorific\ Value\ (\frac{kJ}{kg})} \quad (4)$$

Cost Assessment

The cost analysis assessed the financial viability of the proposed thermal system and compared it against a convectional air conditioner. The parameters, costs and price sources of the components are presented in **Table 4**. The cost of biodiesel varies depending on various factors such as the location, policies on biofuels and feedstock type. Due to lack of information on the price of biodiesel in Cyprus and outdated biodiesel price data in Turkey, the European highest price of 2 $/kg was used to perform the cost analysis of the proposed system in Cyprus. The estimated total cost of the system amounted to $19,000. The following assumptions were made in the Life Cycle Cost Assessment (LCCA):

- Electricity price (2024) was estimated at 0.15$/kWh according to TRNC KibTech tariffs. Fluctuations in electricity prices are often affected by a change in minimum wage [22].
- Due to unavailability of price data in TRNC, biodiesel prices were estimated using the highest biodiesel price of $2/kg in United State of America.

Table 4. Proposed system's cost parameters

Parameter	Units	Proposed system	Electric AC	Source
Estimated useful life	years	20	20	-
O and M	$	190	40	York
Inflation rate	%	3.1	3.1	Congressional Budget Office
Discount Rate	%	3.3	3.1	(CB-TRNC)
Cost of biodiesel	$/kg	2	0	IEA
Biodiesel demand	kg	123.3	-	-
Cost of electricity	$/kWh	0.15	0.15	Local Authority (KIBTECH)
Cost of 10.5kW AC unit	$	-	4000	Makro Cyprus, LG Cyprus
ETSC with Pumps	$	1500	-	Unihot, Solartwin,
TES tank	$	6,000	-	Storathem, Heatex
Indoor HE (radiators)	$	2,000	-	Heatmiser, Stelrad, Vailant
Boiler	$	2,500	-	CleanBurn, Bioheat,
Absorption chiller	$	7,000	-	Trotec, Cryo-Abco
Electricity consumption	kWh	2275	22570	

- Inflation and discount rates were estimated using average rates for 2024.
- A yearly inflation rate of 3.10% was assumed on electricity and O&M costs [30].
- A nominal discount rate of 3.33% was applied on all cash flows [30].

The methodology for assessing the financial feasibility of installing, maintaining and operating the proposed thermal system over a period of 20 years follows 3 common criteria, Pay Back Period (PBP), Return on Investment (ROI) and a Life-Cycle Cost Analysis (LCCA) The LCCA compares the system's costs of providing energy against the costs of installing and operating an electric air conditioner to provide the same amount of energy. Equation (5) calculates energy savings and Equation (6) calculates the payback period where O and M represents the operation and maintenance costs [31].

$$Savings\ (\$) = (\text{Total AC costs at PV}) - (\text{Total proposed system costs at PV}) \quad (5)$$

$$Simple\ Payback\ Period = \frac{Investment\ Costs - Incentives}{Average\ Savings\ per\ year} \quad (6)$$

Return on Investment (ROI) is determined by dividing the annual energy savings by the total investment costs. This metric measures the cost performance of the proposed system. A positive ROI means the investment is profitable. However, this cost evaluation method does consider the time value of money. Return on Investment per year, expressed as a percentage is calculated using Equation (7) [32].

$$Return\ on\ Investment = \frac{Savings - Investment\ Cost}{Investment\ Cost} \times 100 \quad (7)$$

The cost of installing and operating an electric air conditioner is considered and compared to the cost of the proposed system. LCCA considers the capital expenditure, inflation rate, discount rate, biodiesel costs, operation and maintenance costs and lifetime of the system.

Uncertainty Analysis

Uncertainty analysis is necessary to determine the accuracy of the model and acknowledge the limitations of the study. The main sources of uncertainty associated with this study stems from model simplification, cost assumptions, and data recording errors (**Table 5**). The overall uncertainty was calculated using Equation (8) [33].

$$Uncertainty = \sqrt{\sum (Specific\ Uncertainity)^2} = \pm 5.1\% \quad (8)$$

Table 5. Uncertainty of the study

Parameter	Uncertainty (%)
Data	3.0
Simulation	2.2
Biodiesel calorific Value	3.5
Cost	0.1
Emission	0.1
Uncertainty	5.1

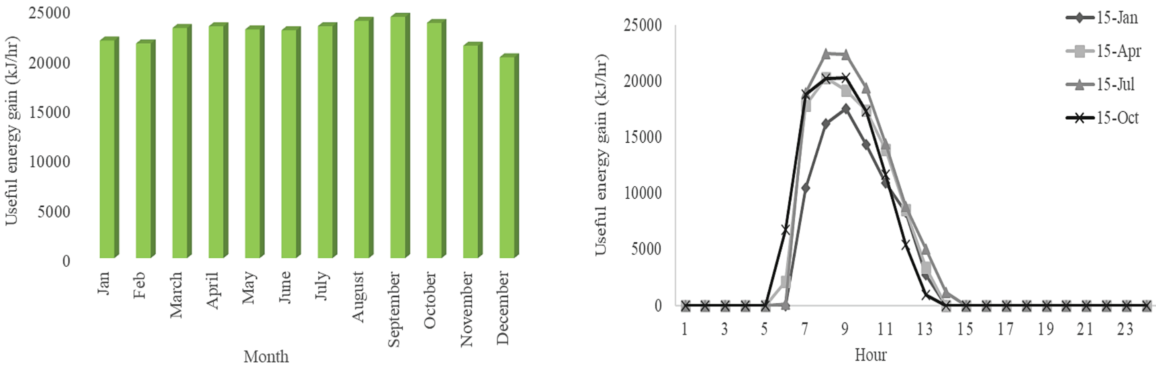
RESULTS AND DISCUSSION

A hybrid solar-biodiesel thermal system was proposed to meet space heating and cooling energy demand for a typical family residential building in Cyprus. Although there is very limited research and data on Cyprus' heating and cooling energy demand, similar research has been performed from various locations under the Mediterranean climate. While a cooling energy consumption of 60,480MJ, and heating energy consumption of 38,700MJ with hourly load of 37.8MJ was obtained from this study, a similar study conducted by Florides et al. [34], modelled a typical Cyprus family house that requires 78,235MJ of cooling energy with a maximum hourly load of 40 MJ and 12,582MJ of heating energy with a maximum hourly load of 51.6 MJ in a year. The load was calculated from type 19 TRNSYS component.

Most researchers have modelled the heating and cooling energy demand from observing the internal gains of the modelled building component in TRNSYS which uses the ASHRAE standards, however, this study considered the freedom that occupants have over their air conditioning system. Occupants use air conditioning systems according to their preferences, freedom and ability to afford electrical energy, even if their thermal comfort levels might deviate from ASHRAE's standards [35, 36]. The findings highlight the willingness of participants to sacrifice their thermal comfort for less electric payments. Regardless, some participants still use their air conditioning systems to cater for their thermal comfort needs. Participants' freedom of choice in using their air conditioners might result in higher energy usage and increased carbon footprint, compared to adhering to ASHRAE's thermal comfort standards. However, the aim of this study is to design a system that effectively meets the space heating and cooling energy demand in residential buildings according to occupants' preferences while considering their actual energy consumption patterns. The scope is to develop a sustainable, responsive and energy efficient solution that not only focuses on improving occupants' thermal comfort, but also caters for the real-world energy needs of residential buildings with similar energy consumption conditions, thereby encouraging a sustainable, user-oriented approach to space conditioning.

Evacuated Tube Solar Collector

The results show that the ETSC had the lowest useful energy gain in December and the highest useful energy gain was achieved in September. **Figure 6** (a) shows the monthly maximum useful energy gained by the solar collector fluid in kJ/hr and **Figure 6** (b) shows the useful energy gain



(a) (b)

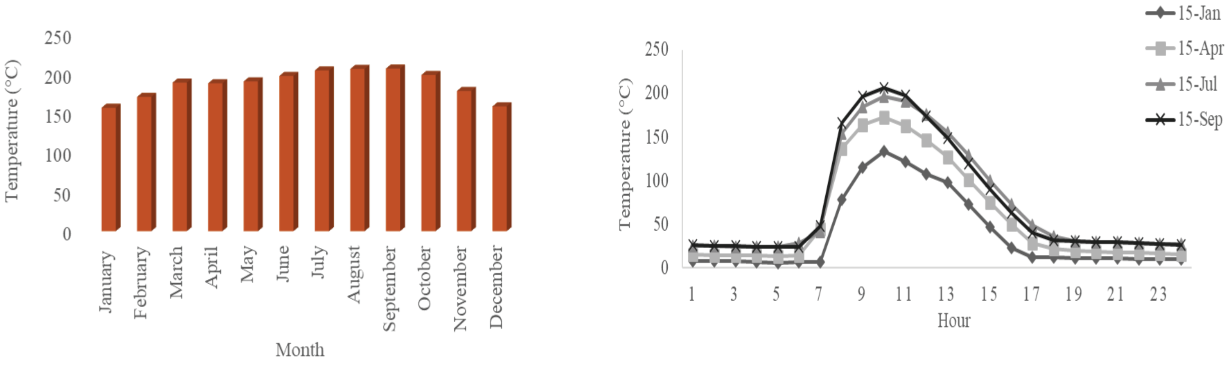
Figure 6. Collector useful energy gain. (a) monthly maximum useful energy gain and (b) hourly useful energy gained on 15 January, 15 April, 15 July and 15 October.

of the collector on the 15th day of January, April, July and October. The results for December, January and February are expected because of the winter season which has low ambient temperatures, high wind speeds and cloudy days. This lowers the temperatures within the tubes, reducing the thermal performance of the collector.

Although July is the peak summer month, September achieved the maximum useful energy gain, reaching 24,200kJ/hr as shown in **Figure 6** (a). This is due to very high ambient temperatures reaching 38°C in July. Very high ambient conditions are not optimal for ETSC efficiency and factors such as overheating, and increased system degradation are for concern. Factors including solar irradiation, inlet and outlet temperatures significantly influence the useful energy gain. A higher temperature difference between the collector outlet and inlet increases the useful energy gain. The unavailability of thermal energy during night times affects the overall thermal efficiency during winter seasons due to longer nights and shorter days.

The outlet temperatures of the working fluid were highest during the summer-fall seasons as illustrated in **Figure 7**. As expected, the highest collector outlet temperatures were attained with maximum monthly temperatures of 204°C, 206°C and 206°C in July, August and September, respectively. According to Kate et al. [37], ETSC can achieve temperatures above 200°C. The highest collector outlet temperatures for the winter season (December and January) achieved were 158°C and 156°C respectively. Winter season has shorter days, reducing the efficiency of ETSC. However, the ETSC temperatures are substantially high for space heating purposes during winter seasons.

In this case, the ETSC is highly efficient and suitable for the Mediterranean climate. The results are consistent with Hayek et al. [38], who experimentally analysed the performance of ETSCs in Lebanon. However, there is a contrast



(a) (b)

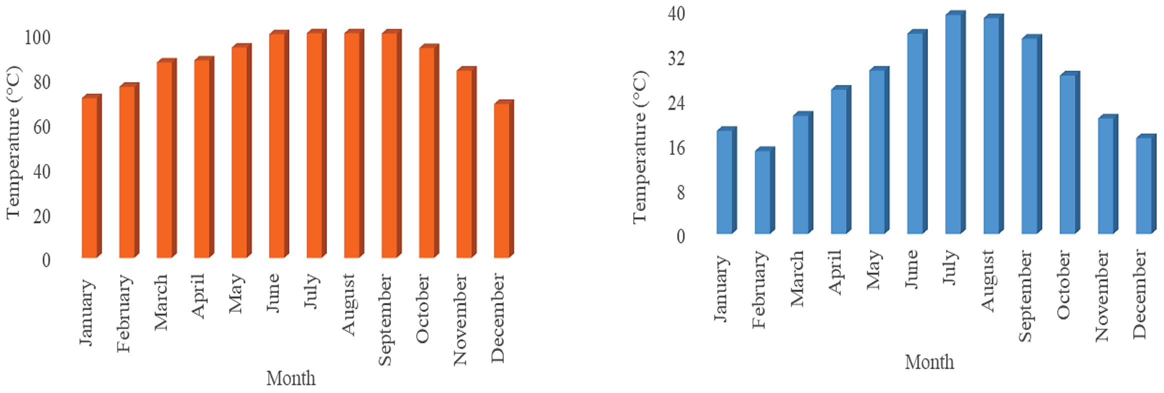
Figure 7. Collector outlet temperatures. (a) highest reached monthly temperatures and (b) hourly temperatures on the 15th day of January, April, July and September

with Adriana et al. [39], whose results suggested that ETSC can only perform well under cold weather conditions. The choice of HTF plays a significant role in improving thermal performance of ETSCs. The lowest fluid outlet temperature obtained was 2°C in January. To maintain the HTF from freezing, glycol oil is recommended due to its thermal properties. According to MEGlobal, thermal oil has lower freezing temperatures of below −10°C and high boiling temperatures above 120°C [40]. Most importantly, the position and orientation of ETSC matter for maximum radiation absorption and to avoid shading of the collectors with buildings or even self-shedding within the collector array.

Thermal Energy Storage Tank

Maximum tank temperatures reaching 100°C were achieved during the summer seasons as illustrated in **Figure 8** (a). July and August had maximum storage temperatures of 100°C while January and December had maximum storage temperatures of 68°C and 71°C respectively. It is evident from **Figure 8** (b) that minimum storage temperatures for the summer seasons are higher compared to those for winter season. This is due to the flow of energy from a higher temperature source (storage tank) to a lower temperature source (surroundings). The winter ambient temperatures are lower compared to the summer ambient temperatures**.**

The temperatures drop drastically during predawn hours as shown by the daily temperature patterns in **Figure 9**. There is a uniform trend which shows that the energy storage tank stores the lowest energy during the early morning hours of the day (4th - 6th hour). This is due to the absence of solar energy to supply thermal energy to the



(a) (b)

Figure 8. Monthly temperatures of the water in the thermal energy storage tank. (a) highest reached temperatures and (b) lowest temperatures reached.

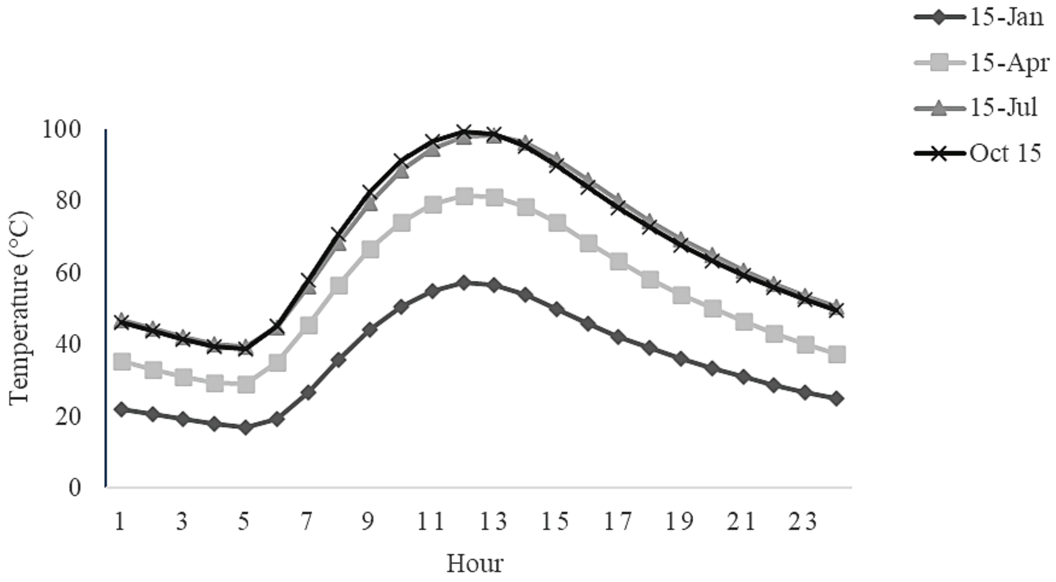
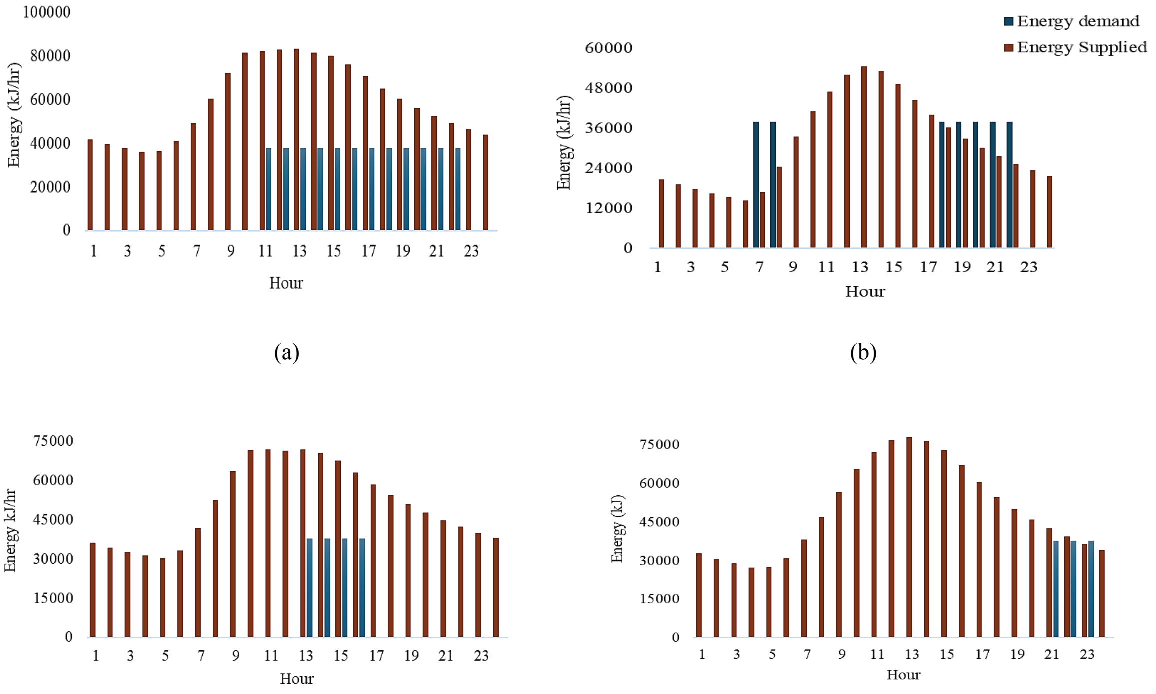


Figure 9. Hourly thermal energy storage temperature on the 15th of January, April, July and October.

storage tank, while the tank continuously discharges energy to the surroundings. The maximum amount of energy is stored during peak hours, 12 pm to 3 pm. The trend shows a decline in the energy stored as the sun sets. The winter season has the lowest energy stored due to less energy input from the ETSC. Considering the estimated demand these results show that the energy stored is sufficient to meet three quarters of the energy demand.

This study judges the thermal performance of the proposed system to meet the estimated demand. **Figure 10** (b) shows an energy deficiency, concluding that the total demand cannot be entirely satisfied using solar energy. The heating hours are during sunrise time and evening hours, after sunset, where solar energy is unavailable. The energy stored in the energy storage tank is insufficient to meet the total demand. Since the spring season requires less heating energy, the solar thermal system almost met all of the demand as illustrated in **Figure 10** (d). However, there is a small deficiency caused by lack of solar energy at nighttime. Although the winter and spring seasons suffered a deficiency, there were periods with excess energy during these seasons. **Figure 10** (b) and (c) illustrates the ability of the solar thermal system with energy storage to meet the entire cooling demand required for the summer and fall seasons. This is facilitated by the availability of abundant solar energy during the summer period. According to Kaushik et al. [41], cooling demand peaks at times of abundant solar radiation, making it possible to meet the entire cooling demand during the day. Temperatures often dip during nighttime, reducing the need for cooling energy when solar energy is unavailable. The cooling demand is higher than the heating demand, therefore, the system's ability to meet all of the cooling energy demand is of major importance. In addition, **Figure 10** indicates a substantial amount of excess energy that can be used for other domestic purposes requiring hot water or can be shared with neighboring households.

Although temperatures of the working fluid in the storage tank reached 100°C during the summer season, the highest thermal losses also occurred during the summer season, with the highest losses reaching 5,326kJ/hr as shown in **Table 6**. There is a substantial amount of thermal losses incurred for the summer seasons (July and August) when the water temperature reaches close to and beyond 100 °C. This means that some vapor starts to evaporate, thereby causing a mass loss from the buffer tank. TRNSYS 16 allows the use of a pressure relief valve to account for the boiling effects of the water when the user-specified fluid boiling temperature is reached. The pressure valve opens to release sufficient energy and maintain the tank at boiling temperature. Various boiler mountings and certain accessories including safety valves, stop valves, pressure gauges,



(a) (b)

(c) (d)

Figure 10. Energy demand and energy supplied by the proposed thermal system on (a) 15 July, (b) 15 January, (c) 15 October and (d) 15 April.

Table 6. Effect of storage temperature difference on thermal energy (21 July)

Hour	Tank temperature (°C)	Ambient Temperature (°C)	Delta T (°C)	Thermal Energy (kJ)	Thermal Losses (kJ)
1	51.9	27.5	24.4	32,636.65	178.15
2	49.2	26.9	22.3	30,944.52	162.00
3	46.8	26.6	20.2	29,416.67	146.65
4	44.6	26.3	18.3	28,040.27	132.67
5	42.7	26.1	16.6	26,857.29	119.11
6	42.0	26.3	15.7	26,377.34	107.84
7	47.7	27.7	20.0	29,968.50	138.92
8	59.7	29.1	30.6	37,500.35	214.81
9	72.4	30.6	41.8	45,533.50	296.81
10	83.9	31.9	52.0	52,749.75	370.53
11	92.9	33.1	59.8	58,413.42	427.89
12	98.8	34	64.8	62,104.74	3544.53
13	100.0	34.7	65.3	62,850.00	5326.55
14	99.8	35.1	64.7	62,729.39	465.83
15	97.9	35.2	62.7	61,520.28	452.69
16	93.4	34.9	58.5	58,678.91	423.36
17	87.5	34.3	53.2	55,018.21	386.80
18	81.6	33.4	48.2	51,316.97	351.58
19	76.2	32.3	43.9	47,880.56	319.03
20	71.2	31.5	39.7	44,773.11	288.82
21	66.8	30.8	36.0	41,964.93	262.03
22	62.7	30	32.7	39,421.55	238.64
23	59.1	29.2	29.9	37,113.71	217.59
24	55.7	28.5	27.2	35,021.45	197.93

flame loss detectors and water level indicators are important to maintain safety and reduce failure from high pressure issues [42]. According to Agarwal et al. [42], safety valves can be mounted on boilers to allow the escape of excess steam from the boiler and ensure normal pressure within the boiler. In addition, location of valves must be optimized and all mountings should be properly arranged. Safety valves protect the energy storage tank by opening and allowing the flow of steam, relieving the tank from build-up pressure [43]. High temperatures achieved during the summer causes the HTF to evaporate, therefore, fluid refilling is necessary during maintenance

However, thermal losses are relatively less as shown in **Figure 11**, except for summertime which is due to increased temperature difference between the tank and the ambient temperature. These results are consistent with Martyna et al. [44], who recorded the highest thermal energy losses during the summer months, August and July for a study conducted in Poland. A storage tank at high temperature loses more energy than a storage tank closer to ambient temperature [45]. This is because of a larger temperature difference between the tank temperature and the temperature of the surroundings/ambient temperatures. As the second law of thermodynamics states, heat energy flows from a high energy source to a low energy source, increasing thermal energy losses. In addition, factors such as radiation play a role to a lesser extent. The tank radiates more energy during the summer season compared to winter seasons.

System's Thermal Performance

The results demonstrated the ability of the solar thermal system with an integrated TES tank to meet 100% of the cooling load and 87.7% of the heating load. Out of 425,750MJ stored by the storage tank, 268,700MJ was in excess and could be used for other purposes such as heating water for domestic use. The results align with Salameh et al, who optimized a 10kW solar assisted cooling system for a house under the Mediterranean climate. Their results showed the ability of an ETSC to meet the cooling demand at worst cooling days. In contrast, Figaj et al. [46] modelled a solar thermal driven absorption chiller which satisfied only 18% of the space cooling demand for a single floor residential building in Poland. Cyprus benefits from the sunny mediterranean climate compared to Poland with low solar radiation. Moreover, the system offered less economic benefits compared to a convectional system due to cheaper gas

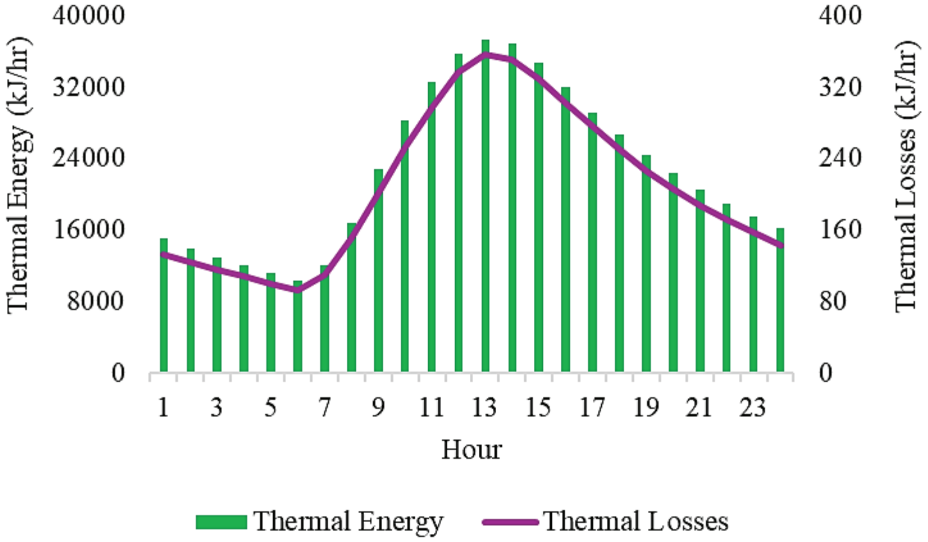


Figure 11. Hourly thermal energy and corresponding thermal losses on January 15.

and electricity prices in Poland. Therefore, the proposed system is well suited for Mediterranean climates.

The prospect of distributing this excess energy to adjacent residential buildings is an additional option to mitigate energy wastage. With the exception of space as a limiting factor, the system is scalable for larger buildings when designed properly [47]. The heating season suffered an energy deficiency of 4,758MJ, which is supplemented by a biodiesel boiler, using pure biodiesel (B100). The amount of biodiesel required was calculated according to the feedstock in **Table 3** and the resulting **Table 7** shows the amount of biodiesel required in kgs. In addition, the amount of natural gas required to meet the yearly energy deficiency is 95.2kg, which is the least amount of fuel required among the other biodiesel fuels. Castor oil has the highest mass required to meet the energy deficiency and this translates to higher fuel costs. Jatropha and rapeseeds have the second highest amount required while cotton seed oil has the least mass among the biodiesel feedstock types mentioned.

Cost Analysis

According to the LCCA performed, the Present value (PV) of the proposed hybrid solar-biodiesel thermal system amounting to $34,000 is significantly lower than $71,200 of the convectional air conditioner. The Payback period reflected that it takes 7.3 years to recover the initial money invested in installing the proposed system. The ROI had a value of 9% while the total savings amounted to $ 37,200. The cost of meeting the total energy demand for the first whole year while using an electric air conditioner and buying electricity from the grid amounted to $3,400. The proposed system consumes biodiesel worth $309 and an additional $341 for running the absorption chiller per year. During the first 10 years of operation, the proposed thermal system has higher costs compared to an electric air conditioner, however, the electric air conditioner becomes expensive from the 11th year.

Domestic solar systems require minimal maintenance compared to large scale solar system. Regular maintenance includes periodic cleaning to remove accumulated dust and dirt particles and replacement of malfunctioning components [47]. The absorption chiller requires maintenance over a period of time due to the corrosive nature of lithium bromide [46]. Boiler tubes can benefit from regular maintenance since they are susceptible to prolonged overheating [41]. Periodic Maintenance of pumps, fuel tanks and boiler

Table 7. Supplementary biodiesel required according to feedstock type

Biodiesel-Feedstock Type	Mass of Biodiesel kg	Biodiesel-Feedstock Type	Mass of Biodiesel kg
Algal	117.0	Rapeseed	120.6
Ethyl palmitate	116.0	Crambe	117.3
Ethyl oleate	117.6	Cotton seed oil	113.0
Ethyl stearate	114.5	Castor oil	123.3
Soybean	120.5	Jatropha	120.6
Natural gas	95.2		

water treatment is necessary to improve system's performance. The thermal energy storage tank must be checked for leakages during maintenance [42].

The suitability of a space conditioning thermal system investment is affected by 2 factors, time and risk [31]. Weather conditions and deflation/inflation in electricity prices are the main risk factors associated with this investment. Weather conditions influence the demand patterns while the inflation of electricity prices benefits the investor as he is exempted from paying electric bills. However, the inflation of electricity prices might affect the cost of biodiesel, posing as a risk to the investor. An electric air conditioner is associated with monthly electricity bills throughout the life of the air conditioner while the proposed system has high investment costs and considerable operating and maintenance costs.

Biodiesel Environmental Analysis

The proposed system prevents the use of fossil fuel based auxiliary energy systems. The results show that using biodiesel as an auxiliary fuel eliminates the emission of 5.3 tons of CO_2 per household over 20 years. This study conclusively demonstrates the environmental benefits of using biofuels instead of burning natural gas. Biodiesel is considered as renewable biodiesel due to its carbon neutrality [6]. However, biodiesel is still considered a niche energy source rather than main source and cannot compete with other fossil fuels on the market. Land competition is a possible challenge as land for energy crops is limited, hence it is difficult to secure continuous supply for biodiesel. If poorly controlled, the use of land for energy can lead to deforestation, increased water demand and other environmental issues. In that case, natural gas becomes more advantageous than biodiesel. However, the environmental issues can be mitigated by sustainable agricultural practices including but not limited to soil conservation, waste management, waste recycling and environmental impact assessments. The overall benefits of GHG reduction should not come at the detriment of environmental damage due to deforestation. According to Bart and Cavallaro, the topic of biofuel is a dilemma between energy and climate [48]. The EU approved certain biofuel feedstocks to promote the sustainability of biofuels by encouraging advanced biofuels which are processed from lignocellulosic materials such as forest waste and agricultural residues. This control strategy eliminates first generation biofuels and prioritizes food security [49].

CONCLUSION

This work presents a techno-economic analysis of a proposed hybrid solar-biodiesel thermal system to meet space heating and cooling energy demand for a typical family residential building in North Cyprus. Auxiliary systems of small-scale renewable energy systems are often overlooked. Therefore, the study addressed the use of biodiesel in fueling an auxiliary heating and cooling thermal energy system. The results indicated that evacuated tube solar collectors have a high thermal performance with outlet temperatures reaching 200°C during summer seasons and are pertinent for regions under the Mediterranean climate. The cooling and heating energy demand was estimated from the survey to be 60,480MJ and 38,700MJ respectively, with an hourly load of 37.8MJ. Although high thermal losses occurred during summer seasons, the thermal energy storage tank was efficient enough to supply 100% of the cooling demand and 87% of the heating demand. Heating energy deficiency of 4,757MJ was met using 123.3 kg of biodiesel instead of 95.2kg of natural gas. A lifecycle cost analysis revealed that despite the high cost of biodiesel, the proposed system is cost efficient compared to a convectional air conditioner starting from year 16. The proposed system had a Return On Investment of 9%, Payback Period of 7.3 years and total savings of $ 37,200 for a lifetime of 20 years. These findings support energy transition in residential buildings. However, biodiesel is still considered a niche energy source rather than main source and cannot compete with other fuels on the market. Further research could explore the potential of biodiesel homebrewing in Cyprus, to promote sustainable utilization of resources and minimize dependency on fossil fuels. In conclusion, this research aligns with the goals of sustainable energy practices and transition, and significantly contributes to the 2050 climate goals.

NOMENCLATURE

Abbreviations

ASHRAE	American Society of Heating, Refrigeration and Air Conditioning Engineers
B100	Pure biodiesel
CO_2	Carbon Dioxide
COP	Coefficient of Performance
ETSC	Evacuated Tube Solar Collector
GHG	Green House Gas
HTF	Heat Transfer Fluid
IEA	International Energy Agency
LCCA	Life Cycle Cost Assessment
Li-Br	Lithium Bromide
O&M	Operation and Maintenance
PBP	Pay Back Period
PCM	Phase Change Material
PV	Photovoltaic
ROI	Return On Investment
TES	Thermal Energy Storage
TMY	Typical Meteorological Year

Special Characters

E	Error margin
S	Standard deviation
T	Temperature, °C
T_c	Critical Value
n	Sample size

n-1	Degree of freedom
$\bar{x}$	Sample mean

Greek Letters

μ	population mean

Subscripts

c	Score, t score

AUTHORSHIP CONTRIBUTIONS

Nyasha Netsai Bema: Methodology, Software, Data curation, Writing (Original draft)

Kemal Masera: Conceptualization, Supervision, Writing (review and editing)

DATA AVAILABILITY

[dataset] National Renewable Energy Laboratory (NREL). (2022). Typical Meteorological Year (TMY) Data. NREL Data Repository. https://data.nrel.gov/submissions/69. Accessed on: March, 2023.

CONFLICT OF INTEREST

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

ETHICS

There are no ethical issues with the publication of this manuscript.

STATEMENT ON THE USE OF ARTIFICIAL INTELLIGENCE

Artificial intelligence was not used in the preparation of the article.

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