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Research Article

Development and Evaluation of a Solar-Powered Cooling System Integrated with Energy Storage

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Abstract

Energy study is conducted on the design of a cooling system powered by solar PV system and used to perform the cooling process of a convenience store according to local environmental conditions. The overall volume of the space is 1000 m^3 with 10 m in width, 25 m in length and 4 m in height. The main object of the study is to optimize the characteristic design parameters of the air conditioning system using solar energy as an alternative to generate electric energy. Energy and mass balances are established to determine the heat gain in the building and the cooling load required to maintain a constant inside air temperature of 22°C. The total daily heat gain of the cooled space is found to be 383915.52 Wh. An air conditioning cycle with return air is considered to provide the required cooling capacity of 33192.5 W. The designed refrigeration unit is mainly constituted by a compressor of 12.8 kW of power, a condensr of 55.2 kW of capacity two evaporator of signle capacity of 20 kW. Rechargeable storage system (battery) is defined to cover the no sunshine period. Technical research is included to design the PV panels field, which combines 88 units of maximum single output power of 385 V. The PV panels are arranged into 8 rows. Each row is mounted with a DC/DC charge controller and 24 storage battery cells with a total voltage of 48 V and a DC/AC inverter.

Keywords

Cooling system, Solar PV system, heat gain, Heat transfer, Air conditioning, Electrical energy storage

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1. Introduction

Energy efficiency is one of the most crucial topics nowadays regarding the excessive usage of heating ventilation and air conditioning (HVAC) systems. These systemes are known for their immense energy amounts required to obtain suitable conditions for the desired purposes. Furthermore, the dissipative thermal energy is usually important and may negatively affect the environment, (Çengel & Boles, 2010).

Heating and cooling account for about half of the global final energy consumption. They are the largest source of energy end use, ahead of power plants (20%) and transport (30%) and are responsible for more than 40% of global energy-related carbon dioxide emissions. The majority of heat generation comes from fossil fuels (coal, oil and natural gas), with some from the unsustainable use of biomass. The conversion of fossil fuels in heat generation has, nevertheless, been declining (from 91% in 2010 to 75% in 2021), (IEA, 2022a). Meanwhile, the buildings (residential and commercial) and industrial sectors account for approximately 95% of global heating demand, (Irena, 2023).

In response to growing environmental concerns and the depletion of natural resources driven by population growth, the demand for renewable energy sources has increased significantly. The environmental impact of fossil fuels, due to emissions and their finite nature, has reduced their importance, leading to a shift toward a world order that favors non-reliance on fossil fuels. As such, renewable energy sources have emerged as a crucial alternative for clean, sustainable energy production. To effectively navigate this shift, it has become essential for countries and regions to invest in renewable energy. One of the primary challenges in this process is selecting the most appropriate renewable energy sources based on regional characteristics and specific factors. Yontar (2022), has conducted a study that highlights the importance of defining the criteria that guide these investment decisions. By reviewing existing literature and incorporating expert opinions, the study identified key factors influencing the selection of renewable energy sources and categorized them under cost, environmental, technical, social, and risk dimensions. These findings provide valuable insights into site selection, resource choice, and investment region decisions for renewable energy projects.

The global transition from fossil fuels to renewable energy sources has been expedited by a multitude of significant events and discoveries. These factors include a growing concern about energy security and climate change. Political and social pressures are particularly observed to minimize greenhouse gas emissions by rising and fluctuating petroleum costs and encouraging independency on foreign energy resources, (Coral Innovative, 2023).

Solar cooling technology plays a significant role in regions with abundant solar energy sources. It is evident that regions with intense solar radiation have a heightened demand for solar cooling solutions, (Rashid et al., 2023). Many developing nations situated in high solar intensity latitudes necessitate cooling systems, including air conditioning and industrial refrigeration to preserve food and medical supplies and to ensure optimal conditions for productivity in work environments, (Sayigh & Mcveigh, 1992).

The growing demand for electricity has prompted countries to seek reliable, cost-effective, and clean energy solutions. Among the emerging energy sources, photovoltaic (PV) power systems have gained significant attention in recent years. In Turkey, which boasts a high solar energy potential, investments in PV power plants have surged, particularly with the support of government incentives. A critical aspect of establishing these plants is conducting feasibility studies for site selection and designing systems that ensure economic viability. One essential step in this process is calculating the electrical energy that can be generated based on solar radiation. In this context, machine learning models have been employed to predict PV power output. A study conducted by Oral et al. (2019) in Turkey aimed to forecast the electricity generated by PV plants in 125 different regions using machine learning techniques such as artificial neural networks (ANN), multiple linear regression (MLR), and k-nearest neighbors' regression (KNNR). The experimental results demonstrated that the machine learning models could effectively predict PV-generated electrical power using various input variables, offering valuable insights for optimizing PV system performance.

A study by Arslan & Yaman (2017) focused on determining the optimum dimensions of Solar Domestic Hot Water Systems (SDHWS) by considering initial capital costs and energy consumption costs across various locations in Turkey. Using Typical Meteorological Year (TMY) data from 12 different regions representing Turkey's climatic diversity, the analysis was carried out with the Particle Swarm Optimization / Hooke-Jeeves (PSO/HJ) hybrid algorithm, a component of the EnergyPlus®-GenOpt® programs. The study aimed to find the ideal number of solar collectors and the appropriate hot water storage tank volume for each location. The results showed that, for Gaziantep, both initial investment and energy consumption costs decreased by 6.1%, while the solar fraction for Ankara increased by 42.8%. On average, the study reported a 4.5% reduction in initial costs and energy consumption, alongside a 35.4% increase in solar fraction.

Several research works are conducted on the integration of solar energy in refrigeration and air conditioning systems for economic and environmental considerations.

Ruiz et al. (2024) conducted an analytical modeling and optimization of a solar-driven system enhanced with a photovoltaic evaporative chimney. The analysis study was based on the grid energy efficiency as key performance indicator. The condenser water flow rate is considered as key parameter for the analysis. The effects of the environnemental parameters such as the ambient temeperature and the relative humidty on the overall system's performance are analysed. Obtained results showed that these parameters affect both the panels' effeciency and the chiller perfromance. Their influence may lead to a reduction of about 10.86 % in the energy required for cooling load. Authors noticed that the use of solar chimney and water-water heat pump increaes the overall system performances of by about 53 % for the chiller and 10 % for the PV panels.

Alghool et al. (2024) perfromed an optimization of solar-assited cooling systems. Two solar cooling systems are investigated considering economic and environmental criteria. The first one was a solar thermal and PV electrical solar system. The second was a hybrid solar cooling system engendering a compression chiller and an absorption chiller to improve the efficiency. In the first step new mixed-integer linear programming models are proposed to generate design and operating effectivity for each system. In the second step the technique for order preference by similarity to ideal solution is adopted to evaluate the actual systems and benchmark them against conventional cooling systems analysed in previous works. Athors proposed decisions makers to assess the potential of the considered systems according to three criteria: the cost, the carbon dioxide emissions and the noise levels. Obtained results showed that the integration of solar energy into conventional cooling system can significantly reduce the annual total net cost by about 61 %, CO2 emission by 60 % and noise levels by 53%. In addition, comparison results showed that the zero-carbon dioxide emission of the solar cooling system reached the highest overall performance score when all criteria are considered together.

Eanes & Smith (2024) conducted an optimization of the solar capacity for commercial PV systems considering an empirical cost-benefit framework for all stakeholders. Through analyzing several sets of interval data, authors found that solar energy permitted to reduce monthly peak demand by an avarage of about 22.9 %.

Fu et al. (2022) developed a review on the strategies applied for commercial heating, ventilating, and air conditioning systems to provide grid services. These strategies are based on numerical and experimental studies. Specific algorithms, such as heuristic rule-based control and model-based control, have been established in the purpose to provide automatic control delivery of grid services. The advantages and disadvantages of the different strategies are analyzed. Main research trends are identified taking into consideration the average thermal comfort determined according to occupant activities and behaviors. The effect of the different control manners of the building and different demand flexibility modes are also taken into consideration.

Yang et al. (2022) conducted a study on the optimization of the energy required for the commercial central air conditioning of a building in Shenzhen based on data mining algorithm. The study strategy was based on 2019 data as the main research data. The measured parameters are extracted such as cooling factor, delivery factor etc. The load factor based on specific analysis, and the K-Means algorithm was used as input parameters for pattern recognition of the central air conditioning system. Then, according to the results of pattern recognition, C5.0 and the CHAID decision tree algorithm are used to obtain the energy-saving strategy model. Then the 2020 operating parameters of the building's central air conditioning system was used to validate data set for energy efficiency verification. Obtained results showed that the energy-saving strategy based on the C5.0 decision tree algorithm was applied to save 78,183 kWh. That constituted about 32.4 % of the total energy consumption. Furthermore, the energy-saving strategy based on the CHDIA decision tree algorithm was applied to save 73,182 kWh. That represented about 30.3 % of the total energy consumption.

Khezri et al. (2022) have presented a comprehensive and critical review on the main parameters affecting the optimal planning process of solar PV and battery storage system for grid-connected residential sector. The considered key parameters are economic and technical data, objective functions, energy management systems, design constraints, optimization algorithms, and electricity pricing programs. The most recent studies on the optimal design of PV systems with batteries are presented. Challenges, strategic directions and recent developments in this field are discussed. Subsequently, the most suitable ways to carry out future investigations are developed. Authors suggested that new guidelines should be established for the customers taking into consideration a variety of electricity rates and demand response programs. Furthermore, numerous design considerations require additional analysis such as grid dependency in the purpose to conduct optimal arrangement of PV-battery systems.

Bin Arif et al. (2024) developed an optimization study of a hybrid energy system constituted by PV array, diesel generator and battery. The system was designed to provide the required power used to supply a residential area being fed with diesel generators during outrage hours. The proposed system was used to generate power from the standalone PV system along with diesel generator in the aim to replace partially the requirement of diesel by solar energy. The optimization of the proposed hybrid system was obtained using hourly measured solar radiation data and per liter cost of diesel for the selected location along with other required components. Performance analysis was performed using Hybrid Optimization Multiple Energy Resources code (HOMER). A comparative study based on percentage renewable penetration, total net present cost (TNPC), cost of energy (COE) and emitted pollutants has been carried out. Obtained results showed that the system constituted by three generators of 50 kW, 50 kW and 10 kW along with a PV array of 64 kW and battery of 53 kW is the optimal solution for the selected site. Sensitivity analysis shows that the proposed system, for a diesel price of 1 $/liter and with solar penetration of 34 %, is more economical and environmentally friendly with the COE and TNPC of 0.392 $/kWh and $ 1,042,824 respectively.

On the other hand, several research works are conducted on the solar refrigeration system optimization.

Su et al. (2020) conducted a study on the effect of a variable speed refrigerator compressor directly connected to the photovoltaic current (DC), without batteries and inverter, on the refrigeration system performances. The DC compressor speed is modified according to the radiation intensity. A dynamic model is established to simulate the behavior of the refrigeration system. Different prototype experiments are carried out to validate the proposed model. The effect of the operating parameter such as the compressor speed, the ambient temperature and the radiation intensity are analyzed. Obtained results showed that, compared with the fixed speed mode, the cooling capacity of the variable speed mode increases by 32.76% and the average PV system efficiency increases by 45.69%. The increase of the ambient temperature leads to a sensibly decrease of the average cooling capacity. But the ambient temperature has less influence on the power consumption. The cooling capacity increases significantly with the solar radiation.

Yıldız et al. (2022) developed an optimization study the performance of a vapor compression refrigeration system powered by PV module and Thermal module, separately and their hybrid. Energy and exergy analyses are conducted in order to determine the system performances, and observe the differences between conventional and modified hybrid systems. The average PV module surface temperature in PV module and the hybrid PV-Thermal are 56.16 °C and 40.93 °C, respectively. That leads to a direct increment in PV module electrical efficiency. The average electrical efficiency in PV module, and in the hybrid module PV/T-VCRS are calculated to be 13.49% and 14.69% respectively. The obtained average COP values are 5.23 for PV assisted vapor compressor refrigeration system, and 5.68 for the hybrid PV-Thermal assisted vapor compressor refrigeration system. The total exergy destruction of the PV assisted refrigeration system is about 175.86 W with an exergy effeciency of about 50.79%. While for the hybrid PV-Thermal system is about 443 W with an exergy effeciency of about 60.73 %. According to obtained results the hybrid PV-Thermal refrigeration system presented promising results in electrical efficiency, COP, energy, and exergy performances compared to those of the conventional system.

Ikram et al. (2021) conducted a conceptual study of a cold storage facility based on the conventional vapor compression refrigeration system used for banana fruit solar preservation and powered by PV field. According to an established mathematical model the condenser is found to be oversized, while the evaporator was undersized. In addition, the air-conditioning compressor was also found to be oversized by approximately 12 kW. The solar field sizing, and performance optimization of the proposed PV assisted refrigeration system was developed using PV*SOL tool. Obtained simulation results showed that with a 170 m2 solar field, an optimized PV hybrid refrigeration system can achieve 58.1% solar fraction at a performance ratio of 59.2%, under given climatic conditions.

Liang et al. (2019) investigated an experimental study on the combination of solar heat pump and a PV system with tri-generation (heating, cooling, and electricity) in the purpose to provide the building's refrigeration capacity requirement. The experimental unit is mainly constituted by 4 roll-bond PV thermal units, 1 horsepower heat pump unit and 600 liters ice storage tank. The performance evaluation method and uncertainty analysis of the system was proposed and the refrigeration performance and operating characteristics of the system are analyzed. Obtained results shown that the proposed photovoltaic thermal heat pump system, can provide the refrigeration capacity required for building cooling in summer with high performance and long-term stable operation.

Gao et al. (2021) are proposed a dynamic model of the PV direct-driven refrigeration system. This model is validated with experimental data. This model engenders a PV-compressor coupling, giving a relationship among solar radiation, compressor load and compressor speed. Two control methods for the PV direct-driven refrigeration system are compared. These methods are the Maximum Power Point Tracking (MPPT) and the Compressor Speed Prediction (CSP). The obtained results showed that the MPPT method is more efficient than the CSP method. The difference between the two control methods can be reduced if the control model in CSP mode matches well with the system. Also, the decrease of the solar radiation leads to the decreases of daily operation time and total cooling capacity in both MPPT mode and CSP mode. Authors suggested that the MPPT method is more adaptive to the variations of ambient temperature and water temperature. Taking into consideration the total emissions, including electrical energy from the power grid and the increased weight due to the PV system, about 33-47 % reduction is obtained, corresponding to 1–5 gCO2/km. The PV panels can provide up to 19 % of the total energy requirements. In economical point of view, the proposed system allows a cost-saving between 0.1 and 0.3 c€/km. Due to the low complexity and promising results authors suggested that the hybrid PV solution is a suitable way for refrigerated transport decarburization.

Maiorino et al. (2024) conducted a study on the energy performances and environmental benefits of a PV system used to power a vapor compression refrigeration (VCR) system serving a light-duty commercial refrigerated van. An energy model is established to analyze thermal, electrical performances. Also, a battery sub-models simulating the system's dynamic behavior is calibrated with real-world data referring to an urban single-delivery mission. The potential benefits are estimated for a long-distance single-delivery mission. The obtained results shown that the system can reduce fuel consumption for refrigeration by more than 88 % during summer months and allows neutral refrigeration during winter months, leading to on-wheel emission savings between 4 and 8 gCO2/km.

Zhang et al. (2024) conducted a study on a solar PV refrigeration system coupled with a flexible, cost-effective and high-energy-density chemisorption cold energy storage module. The main purpose of this study is to reduce the environmental pollution and high costs associated with lead-acid batteries. The proposed system engenders daytime solar PV refrigeration/cold energy charging mode and nighttime cold energy discharging mode. In order to enhance the heat and mass transfer performances, a novel composite sorbent SrCl2 is developed using expanded natural graphite as matrix and carbon coated aluminum as additive. A test unit is designed to determine the sorbent performance. Results showed that the cold energy storage density reached 503.6 kJ/kg, at an evaporating temperature of -15 °C. That represents 1.5 times of the ice storage capacity. Compression-assisted desorption is used to regulate the desorption temperature. With this process water heated by low-cost solar collectors at 75 to 90 °C can be utilized to drive heat source. For an evaporating temperature of -10 °C and a solar hot water temperature of 90 °C, the COP of the cold energy storage unit reached 3.72. That represented an improvement of about 33 % compared to conventional solar PV refrigeration systems. The characteristics of the proposed system such as low cost, high efficiency and eco-friendliness may constitute a promising solution for solar refrigeration.

The current study focuses on energy optimization of the design characteristics of a cooling system powered by solar PV system and used to provide the required refrigeration capacity for a convenience store taking into consideration the local environmental conditions. The main objective of this study is to define the conceptual characteristics of the PV solar system to provide the electrical energy required for the the air-conditioned space operation and thus contribute to reduction of energy costs and preservation of the environment. The novelty of this study is to provide an electrical energy storage system using batteries to cover electricity needs for a period of two days. Similarly, the use of an air conditioning cycle with return air and mixing reduces the cooling capacity of the evaporator and therefore optimizes the investment cost of the proposed system. The store heat gain calculation procedure will be presented as well as the air conditioning cycle and refrigeration equipment. The equations governing the PV field design method will be established. The selected equipment will be presented and the obtained results will be analyzed.

Nomenclature

q_{cond}	Heat Conduction Rate	W
λ	Thermal Conductivity of The Wall	W/mK
A	Wall's Surface Area	m^2
q_{conv}	Heat Convection Rate	W
α	Convection Heat Transfer Coefficient	W/m^2K
A_s	Convection/Radiation Surface Area	m^2
T_s	Convection/Radiation Surface's Temperature	K
T_∞	Convection Fluid's Temperature	K
q_{rad}	Heat Radiation Rate	W
ε	Emissivity	$-$
σ	Stefan-Boltzmann Constant	W/m^2K^4
T_{sur}	Surrounding's Temperature	K
$q_{cooling}$	Cooling Load	W
U	Overall Heat Transfer Coefficient	W/m^2K
R_{total}	Total Thermal Resistance Through a Composite Wall	K/W
$q_{cooling}$	Cooling Load	W
DTD	Design Temperature Difference	K
T_{ev}	Evaporator's Temperature	$°C$
T_{cond}	Condenser's Temperature	$°C$
T_m	Air Mixture Temperature	$°C$
T_{sup}	Supply Air Temperature	$°C$
ΔT_{sh}	Superheating Temperature	K
ΔT_{sc}	Subcooling Temperature	K
HP	High Pressure	bar
HL	Low Pressure	bar
q_{ev}	Evaporator's Capacity	W
W_{comp}	Compressor's Net Work	W
$\dot{m}_{ref}$	Refrigerant's Mass Flow Rate	kg/s

$\dot{m}_{air}$	Air's Mass Flow Rate	kg/s
$\dot{\mathcal{V}}_{ref}$	Refrigerant's Volume Flow Rate	m^3/s
$\dot{\mathcal{V}}_{air}$	Air's Volume Flow Rate	m^3/s
h	Fluid's Enthalpy	kJ/kg
$P_{peak,min}$	Minimum Peak Power	W
E_T	Overall Consumed Energy per Day	Wh
$\eta_{overall}$	Overall Efficiency of The Installation	%
$U_{mpp\_row\_STC}$	Nominal Voltage That Can Be Delivered Through a Single Row of PV Panels	V
$U_{max\_row\_STC}$	Maximum Voltage That Can Be Delivered Through a Single Row of PV Panels	V
$U_{min\_row\_STC}$	Minimum Voltage That Can Be Delivered Through a Single Row of PV Panels	V
N_p	Number of PV Panels per Row	$-$
N_s	Number of Rows	$-$
V_{mpp_STC}	Maximum Voltage in a PV Panel at Standard Test Conditions	V
V_{oc_STC}	Voltage at Open Circuit at Standard Test Conditions	V
K_p	Voltage Temperature Coefficient	$\%/°C$
T_{max}	Maximum Operating Temperature of PV Panel	℃
T_{STC}	Temperature at Standard Test Conditions	℃
$I_{sc}(T_{max})$	Maximum Current That Runs Through The Circuit of a Single Row of PV Panels	I
I_{sc_STC}	Current at Short Circuit at Standard Test Conditions	I
K_c	Current Temperature Coefficient	$\%/°C$
P_{mpp_field}	Maximum Power Output by a Single Row of PV Panels	W
C	Capacity of The Battery Bank	Ah
U_{batt}	Battery's Voltage	V
η_{batt}	Battery's Efficiency	%
$\eta_{Cabling}$	Cabling's Efficiency	%
$Coef_{discharge}$	Coefficient of Discharge	$-$
$U_{max\ \_controller}$	Maximum Voltage of The Charge Controller	V
$U_{min\ \_controller}$	Minimum Voltage of The Charge Controller	V
$I_{DCmax\ \_controller}$	Maximum DC Current of The Charge Controller	I
$P_{max\ \_controller}$	Maximum Power of The Charge Controller	W

2. Heat Gain Calculation

The convenience store is situated in the city of Ankara and has a total size of 250 m^2, 10 m in width, 25 m in length and 4 m in height. One long wall faces the south, and one short wall faces the east. The other two walls are both common with the neighboring building. An enter door, an exit door and a window are situated in the wall facing the south. Both doors are 1 m in width and 3 m in height. The window's size is 22.4 m x 3.4 m.

The type of the building is specified as a work and service building and the gross volume is set as 1000 m^3. That permits to calculate the overall heat transfer coefficient U. The construction and insulation material types are selected with the desired thicknesses for each element of the building.

Under steady-state conditions and for linear distribution of the tempreture, the heat rate transferred by conduction q_{cond}, by convection q_{conv} and by radiation q_{rad} are respectively expressed by the following equations, (Kreider, 2001).

$$q_{cond} = \lambda \times A \times \frac{(T_1 - T_2)}{L} \quad (1)$$

$$q_{conv} = \alpha \times A_s \times (T_s - T_\infty) \quad (2)$$

$$q_{rad} = \varepsilon \times \sigma \times A_s \times (T_s^4 - T_{sur}^4) \quad (3)$$

The heat gain is calculated by:

$$q = U \times A \times \Delta T \quad (4)$$

Where U is the overall heat transfer coefficient expressed as:

$$U = \frac{1}{R_{total}} = \frac{1}{\frac{1}{\alpha_{out}} + \frac{d_1}{\lambda_1} + \frac{d_2}{\lambda_2} + \dots + \frac{d_n}{\lambda_n} + \frac{1}{\alpha_{in}}} \quad (5)$$

R_{total} is the total thermal resistance through the composite wall, (Vedat et al., 2000).

According to the Turkish State Meteorological Service, the maximum measured temperature in the city of Ankara is in July and it reached 41°C, (Turkish State Meteorological Service, 2024). To ensure customer comfort, the inside air temperature is set at 22°C.

The heat gain is determined using the İZODER TS825 Calculating program (2024). The total specific heat gain by conduction and convection are calculated taking into consideration the measurements of the building walls, its type and its location. The calculations are carried out under the standard TS825 of Thermal Insulation Rules in buildings. The simulation allows to specify the composition of different elements of the building, from the outer walls to the roof and the floor. The program allows to calculate the overall heat transfer coefficient of each element of the building as well as the specific heat gain by conduction and convection. Also, the heat gained by radiation is calculated according to the surface temperatures.

The obtained total heat gain by conduction and convection is 15142.62 W, as well as the total heat gain by radiation turns out to be 3187.85 W.

Other various heat sources are taken into consideration to calculate the total heat gain in the building. Besides heat transfer ways, heat can be dissipated from other sources such as people, lighting, machines, etc. The heat gains of these sources are determined using avalable data for standard thermal engineering applications, (ASHRAE Handbook, 2007). The values of the heat gain from the different sources are given on table 1.

Table 1. Calculation of Daily Total HeatbDissipative Heat Sources, (ASHRAE Handbook, 2007)

Heat Sources		Heat gain Wh/day
People: Sensible Heat Gain + Latent Heat Gain = 70 persons x 130 W/person x 3 h/day		27300
Aeration:	Sensible: 4 x 70 persons x 20 m^3/h x 3 h/day	16800
	Latent: 3 x 70 persons x 20 m^3/h x 3 h/day	12600
Lighting: (1900 W x 0.08) x 12 h/day (using economic LED light bulb)		1824
Machines:	Freezers: 540 W x 2 units x 20 h/day	21600
	Refrigerators: 310 W x 4 units x 16 h/day	19840
Total Heat Gain by Conduction and Convection:15142.62 W x 12 h/day		181711.44
Total Heat Gain by Radiation:3187.85 Wx 12 h/day		38254.2
Total Heat Gain		319929.6
Add 20 % for various unknown and unexpected heat gains		63985.92
Total Daily Heat Gain		383915.52
Hourly Cooling Load: 383915.52 W / 12 h		**31992.96 W**

For 12 hours of operating period, the hourly load to be taken as basis in the selection of cooling system equipment is determined by Markvart & Castanier (2003):

$$q_{cooling} = \frac{Daily\ heat\ gain}{Daily\ working\ hours}$$

The total cooling load needed for the convenience store is taken as $q_{cooling} \approx 32$kW

3. Cooling Load Calculation

For economic and energy recovering consideration, an air conditioning cycle with return air is used as shown in Figure 1. This air conditioning system makes it possible to recycle used air and adjust the flow of fresh air according to the store's occupancy conditions using dampers. The cold supply air is distributed to different locations for better homogenization of the internal environment.

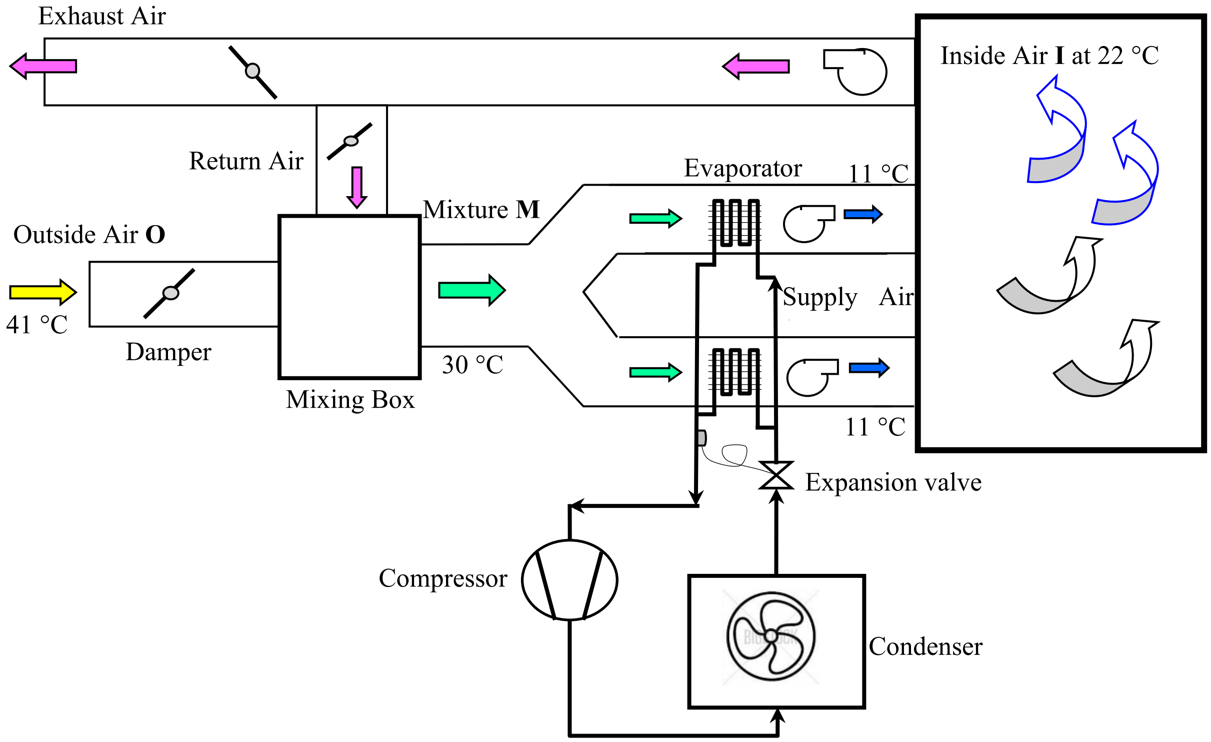

Figure 1. Air Conditioning Cycle with Return Air

The inside air is supplied by a fan from the evaporator at temperature 11°C to unsure an environment space at inside temperature of 22°C. A partial amount of the air discharged from the building called return air is transfered to a mixing box (chamber), while the remaining is emitted as exhaust air. In the mixing box, an air flow created from both outside and return air is delivered to the evaporator. The air mixing tends to minimize the evaporator inlet temperature in order to reduce its capacity, (McQuiston et al., 2001). The refrigerant used in the refrigeration system is R-404a, which is a blended hydrofluorocarbon (HFC) refrigerant comprised of R-125, R-134a, and R-143a.

The Design Temperature Difference DTD of the evaporator is given by, (Trott & Welch, 2000):

$$DTD = T_{sup} - T_{ev} \tag{6}$$

The DTD is taken equal to 8 K.

The operating parameters of the refrigeration cycle are indicated on Table 2.

Table 2. Operating Parameters of the Refrigeration Cycle

Evaporator Temperature T_{ev}	(°C)	3
Condenser Temperature T_{cond}	(°C)	50
Air Mixture Temperature T_m	(°C)	30
Design Temperature Difference DTD	(K)	8
Supply Air Temperature T_{sup}	(°C)	11
Superheating Temperature ΔT_{sh}	(K)	10
Subcooling Temperature ΔT_{sc}	(K)	5

The high pressure and low pressure are determined according to the condensing and the evaporation temperature respectively, given: High Pressure HP is equal 23.75 bars and Low Pressure LP is equal 7 bars.

The refrigeration cycle is drawn on the P-h diagram of refrigerant R404s as shown in Figure 2, (Danfoss, 2018). That permits to determine the refrigerant properties at the different states of the cycle as reported on table 3.

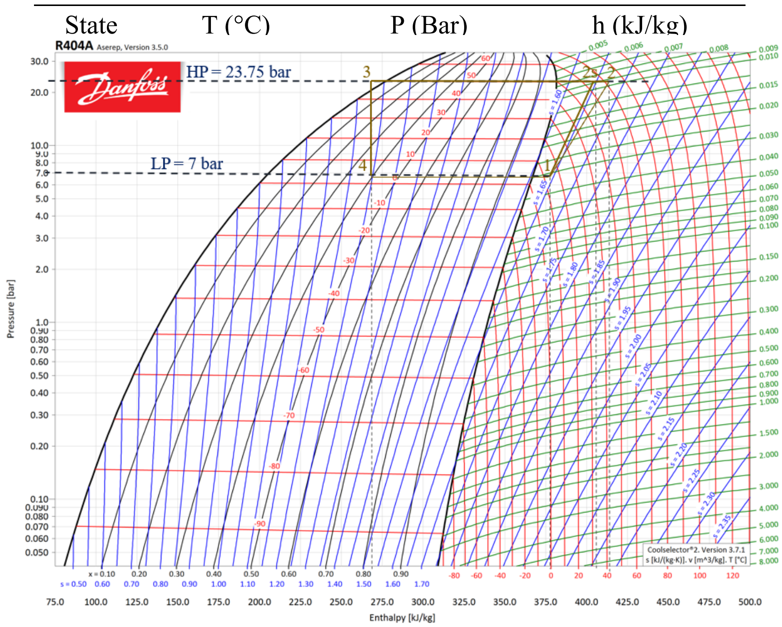

Figure 2. The Refrigeration Cycle on P-h Diagram of R404a, (Danfoss, 2018).

Table 3. R404a Properties in the Different States

State	T (°C)	P (Bar)	h (kJ/kg)
1	13	7	378.36
2is	64.68	23.75	403.54
2	70	23.75	411.93
3	45	23.75	268.18
4	45	7	268.18

Taken into consideration the evaporator efficiency, the cooling load is determined as follows, (Trott & Welch, 2000):

$$q_{cooling} = 0.8 \times q_{evaporator}$$

Consequently, seeing the total cooling load needed for the convenience store, the evaporator capacity is given as follows:

The refrigerant mass flow rate is determined by:

$$q_{evaporator} = \dot{m}_{ref} \times (h_1 - h_4) \tag{7}$$

The compressor net work is calculated as follows:

$$W_{compressor} = \dot{m}_{ref} \times (h_2 - h_1) \tag{8}$$

From the diagram we obtain the specific volume in state 1, $v_1 = 0.030 \frac{m^3}{kg}$.

Consequently, the volume flow rate of the refrigerant is given by:

$$\dot{V}_{ref} = \dot{m}_{ref} \times v_1 \tag{9}$$

The air mass flow rate is determined as follows:

$$q_{air} = \dot{m}_{air} \times c_{pair} \times (T_{in} - T_{out}) \tag{10}$$

With $q_{air} = q_{cooling}$

For the air density of $\rho_{air} = 1.2041 \, \frac{kg}{m^3}$;

The air volume flow rate is given by:

$$\dot{V}_{air} = \dot{m}_{air} \times \frac{1}{\rho_{air}} \tag{11}$$

The air handling process is drown on the psycrhrometric chart as presented in Figure 4, (Kreider, 2001). Outiside air O at 41 °C is mixed with inside air I at 22 °C to obtain the mixture M at about 30 °C. The the air mixture is cooled and dehyumidified through the evaporator with a contact factor of 80 % to reach the supply condition S at 11 °C .

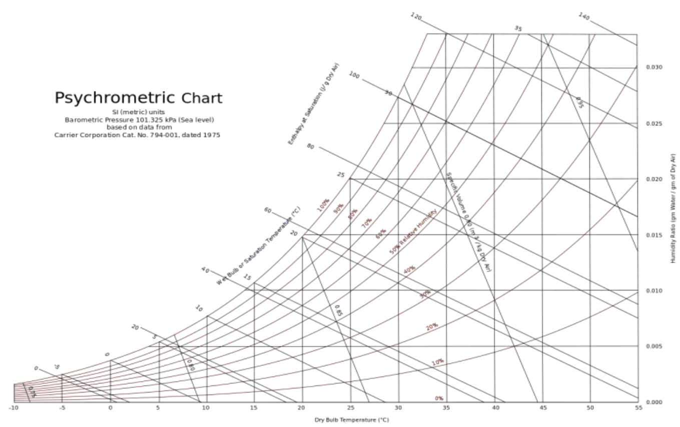

Figure 3. Air Handling Process

The calculated capacities, mass flow rates and volume flow rates are given in table 4.

Table 4. Cooling System' s Information

Parameters	Values
Evaporator's Capacity q_{ev}	40 kW
Compressor's Net Work W_{comp}	12.18 kW
Refrigerant's Mass Flow Rate $\dot{m}_{ref}$	0.3630 kg/s
Air's Mass Flow Rate $\dot{m}_{air}$	1.6758 kg/s
Refrigerant's Volume Flow Rate $\dot{V}_{ref}$	0.01089 m^3/s
Air's Volume Flow Rate $\dot{V}_{air}$	1.392 m^3/s

For the refrigeration unit the shosen design arrangement is a cycle with signle compressor and two evaporators mainly constituting by:

- 2 evaporators installed through two supply ducts,
- 1 condensing unit (compressor and condenser).

The different components of the refrigeration system are selected from manufactuer catalogs, (Friterm, 2016), (AREA, 2021), (Frigo Block, 2019).

The characteristics of the evaporators, the compressor and the condenser are indicated on tables 5, 6 and 7 respectively.

Table 5. Selected Evaporator's Characteristics

Capacity (kW)	20
Airflow Rate (m^3/h)	9900
Voltage (V)	230 V / 1/50 Hz
Number of Fans	2
Power (W)	606
Defrost (W)	9 x 300

Table 6. Selected Compressor's Characteristics

Displacement (cm^3)	93.1
Maximum Refrigerating Capacity (kW)	12.393
Voltage (V)	220 V / 1/50 Hz
Maximum Power Consumption (kW)	3.354

Table 7. Selected Condenser's Characteristics

Capacity (kW)	55.2
Airflow Rate (m^3/h)	12394
Voltage (V)	230 V / 1/50 Hz
Number of Fans	3
Total Power (kW)	2.49

The required AC powers and the operating period of the different equipment are given on table 8.

Table 8. Electrical Needs of the Cooling System

Equipment	*Usage Time per Day (h)*	*Quantity*	*AC Power (W)*	*Consumed Energy per Day (Wh)*
Evaporator Fans	8	2	606	9696
Evaporator Defrost	2	2	9x300	10800
Compressor	8	1	3354	26832
Condenser Fans	8	1	2490	19920
Total				*67248*

The consumed energy per day is 67248 Wh.

4. Solar PV System Design

Before deciding on the number and characteristics of various elements of the photovoltaic system, the minimum attainable power of the photovoltaic field must be determined, taking into consideration the electrical needs and the environmental conditions. This power is called the minimum peak, and it can be calculated by the following equation, (Markvart & Castanier, 2003):

$$P_{peak,min} = \frac{E_T}{SunshineTime \times \eta_{overall}} \tag{12}$$

The compatibility of photovoltaic system elements is crucial in order to select the right characteristics for each element and to avoid any unwanted defect or failure.

The nominal, maximum and minimum voltage that can be delivered through a single row of PV panels can be determined by the following equations,, (Farj et al., 2023), (Luque & Hegedus, 2003):

$$U_{mpp\_row\_STC} = N_p \times V_{mpp\_STC} \tag{13}$$

$$U_{max\_row\_STC} = N_p \times V_{oc\_STC} \times \left[1 + \left[K_p\% \times (T_{max} - T_{STC})\right]\right] \tag{14}$$

$$U_{min\_row\_STC} = N_p \times V_{mpp\_STC} \times [1 + [K_p\% \times (T_{min} - T_{STC})]] \tag{15}$$

The maximum current that runs through the circuit of a single row of PV panels is calculated as following:

$$I_{sc}(T_{max}) = I_{sc\_STC} \times [1 + [K_c\% \times (T_{max} - T_{STC})]] \tag{16}$$

The maximum power output by a single row of PV panels is expressed as:

$$P_{\mathrm{mpp\_field}} = N_s \times N_p \times P_{mp\_STC} \tag{17}$$

With Ns: The number of row, Ns = 1 for single row
Np: The number of PV panels

The capacity of the battery bank, is determined by:

$$C = \frac{E_T \times Autonomy}{U_{batt} \times \eta_{batt} \times \eta_{cablage} \times Coef_{discharge}} \tag{18}$$

All the equations listed above will be used to select the suitable characteristics of the solar photovoltaic system taking into account the maximum attainable values to ensure the smooth functioning of the system.

4.1. Local Solar Potential

Turkey's Monthly Average Solar Potential is presented on Table 9, according to the Ministry of Energy and Natural Resources of the Republic of Turkey (2020). The maximum monthly total potential energy from the sun is detected in July of 175.38 kWh/m^2-month with a total sunshine time of 365 h/month. However, the designing of the solar photovoltaic field will be based on the minimum peak power required for the purpose of covering all consumption demands in unfavorable conditions such as the lack of sunshine time. Thus, the minimum sunshine time is taken into consideration. It is detected in January and December of 103 h/month.

Table 9. Turkey's Monthly Average Solar Potential (2020)

Months	**Monthly Total Sun Energy**		**Sunshine Time**
	Kcal/cm²-month	KW/m²-month	hour/Month
January	4.46	51.75	103.0
February	5.44	63.27	115.0
March	8.31	96.65	165.0
April	10.51	122.23	197.0
May	13.23	153.80	273.0
June	14.51	168.75	325.0
July	15.08	175.38	365.0
Agust	13.62	158.40	343.0
September	10.60	123.28	280.0
October	7.73	89.90	214.0
November	5.23	60.82	157.0
December	4.03	46.67	103.0
Toplam	112.74	13.11	26.40
Average	308.0 cal/cm²-daily	36 kW/m²-daily	7.2 h/day

4.2. Sizing and design of the solar PV Field

The considered efficiencies of the solar PV system equipment are indicated on Table 10, (Alfa Solar Enerji, 2023).

Table 10. Considered Characteristics of the Solar Photovoltaic System

Minimum efficiency of the charge regulator	94%
Minimum inverter efficiency	94%
Minimum battery efficiency	90%
Minimum efficiency of the DC cabling system	97%
Minimum efficiency of the AC cabling system	99%
Correction Factor	80%

The ovverall efficiency of the installation is given by:

$$\eta_{overall} = Product\ of\ Efficiencies \times Correction\ Factor \tag{19}$$

$$\eta_{overall} = 0.61$$

The minimum peak power of the photovoltaic field is calculated according to equation (12), taking into consideration the total daily energy required for the refrigeration system:

$$P_{peak,min} = 33192.5\ W$$

The selection of the PV panel model is performed using available manufacturer catalogs. The charatерisitics of the selected models are presented on Table 11, (Alfa Solar Enerji, 2023).

Table 11. Characteristics of the Selected PV Panel Model, (Alfa Solar Enerji, 2023).

Electrical Data	
Maximum Power P_{max} (W)	385
Module Efficiency (%)	20.69
Current at Maximum Power Immp (A)	10.75
Voltage at Maximum Power Vmpp (V)	39.86
Current at Short Circuit Isc (A)	11.28
Voltage at Open Circuit Voc (V)	41.5
Temperature Specifications	
Nominal Cell Operating Temperature (°C)	41.2 + 2
Power Temperature Coefficient Pmpp (% / °C)	0,311
Current Temperature Coefficient Isc (% / °C)	+0,040
Voltage Temperature Coefficient Voc (% / °C)	-0,237
Working Conditions	
Maximum System Voltage (V)	DC 1500
Operating temperature (°C)	-40 to 85

Taking into considertion the $P_{peack,min}$, the required number of PV panel is 87 panels. We consider 88 PV panels arranged in 8 rows (chains) with 11 panels per chain. The calculation will be carried out for a single and duplicated for the others rows. This arrangement of the PV solar panels is suitable for their location on the roof of the store with better spacing and correct orientation towards the solar flux. It also allows an optimal choice of controllers and DC/AC inverters. The electrical power supplied can be distributed flexibly and modularly to the different equipment.

5. Electrical Control and Storage System Selection

5.1. Charge Controller

The nominal, maximum and minimal voltages of a single row of PV panels are calculated using the equation (13), (14) and (15) successively. The local maximum and minimum operating temperatures are considered to be 60 °C and -20 °C respectively.

Table 12. Electrical Characteristics of a Single PV Panel Row

Nominal Voltage $U_{mpp\_row\_STC}$	(V)	438.46
Maximum Voltage $U_{max\_row\_STC}$	(V)	485.22
Minimum Voltage $U_{min\_row\_STC}$	(V)	402.09
Maximum Current $I_{max\ \_row\_STC}$	(A)	10.9
Maximum Power Output P_{mpp_field}	(W)	4235

The charge controller must have the following requirements:

$$U_{\max\ \_controller} > U_{max\_row\_STC} \tag{20}$$

$$U_{\min\ \_controller} < U_{min\_row\_STC} \tag{21}$$

$$I_{\mathrm{DCmax}\ \_controller} > I_{\max\ \_row\_STC} \tag{22}$$

$$P_{\mathrm{max\ \_controller}} > P_{\mathrm{mpp\_field}} \tag{23}$$

The selected Charge Regulator presents the characterisitics indicated on table 13, (Vario String, 2023), for wich all the required electrical caracterisitics are verified.

Table 13. Characteristics of Selected Charge Controller

Maximum Solar Power at STC (W)	7000
Maximum Current (A)	13
Maximum Solar Open Circuit voltage (V)	900
Minimum Solar Functional Circuit Voltage (V)	200
Nominal Battery Voltage (V)	48
Maximum Efficiency	>98%

5.2. Battery Bank

Taking into account the technical choice concerning the output of the charge regulators and to minimize losses, we choose the 48V storage system. The autonomy of the battery bank is assumed to be equal to 2 days. The capacity of the battery bank is then calculated according to equation (18), for wich the discharge coefficient is estimated at 0.7, (PowerSafe, 2023).

$$C = 4585.17\ Ah$$

We choose from the available catalog a battery cell with a voltage of 2 V and a nominal capacity of 3170 Ah, (PowerSafe, 2023).
The minimal number of batteries is determined by:

$$N_{batt} = Integer\left(\frac{C_{sys}(Ah)}{C_{element}(Ah)}\right) + 1 \tag{24}$$

$$N_{batt} = 2\ batteries$$

The storage system needs a single 48V battery per chain chosen from the catalog with a charging time of 10 hours. Which gives 48/2 = 24 cells of 2 V. The total bank of battery is constituted by 11 batteries of 48 V that shoulds be place in conditioned room at 25 °C. The set number of batteries is convenient and does not represent a heavy additional investment. Also, the location of the batteries in a temperature-controlled space will be relatively easy.

5.3. DC/AC Inverter

According to the specifications, the inverter must:

- Have a minimum efficiency of 90%,
- Be capable of delivering a 220VAC voltage at a frequency of 50 Hz

The characterisitics of the selected inverter are indicated on table 14, (Xtender 2023).

Table 14. Characteristics of the Selected Inverter

Nominal Battery Voltage (V_{DC})	48
Continuous Power @ 25°C (VA)	7000
Power 30 min. @ 25°C(VA)	8000
Power 3 sec. @25°C(VA)	21000
Maximum Efficiency	96 %

6. Conclusion

Study is conducted to optimize the characteristics design of a solar PV system used to provide the required electrical energy of a refrigeration system. The cooling capacity of this system is used to keep a convenience store of total area of 250 m^{2}at suitable inside air temeperature during summer season. Local environemental parameters as well as the available sunchine potential in Ankara region are taken into consideration to determine the available solar energy rate. The buildings size and characterisitics as well as peoples and inside equipment are taken into consideration to dernime the total daily heat gain of the cooled space by 383915.52 Wh. Air conditioning cycle with return air is designed to provide the required cooling capacity for the store. Refrigeration system of 33192.5 W of capacity is selected according to the necessairy cooling load. It consists of a refrigeration cycle with single compressor of net work of 12.393 kW,two evaporators of 20 kWof capacityand one condenser of capacity of 55.2 kW. Then, the total electrical need of these components was calculated to be *67248* Wh. To satisfy this requirement, a PV panels field is designed with 88 units of maximum single output power of 385 V.The PV panels are arranged into 8 rows. Each row is mounted with a DC/DC charge controller and 24 storage battery cells with a total voltage of 48 V and a DC/AC inverter.The standard characterisitics of refregiration and electrical equipment are selected from available manufacturer catalogs.

We notice the large power input generated by the solar PV system which, in fact confirms the beneficial aspect of solar power as it makes it a compelling choice for sustainable energy generation. Moreover, the renewable nature of solar energy ensures long-term availability. By reducing reliance on centralized grids solar energy also promotes energy independence, empowering communities to generate their own electricity.

Embracing solar power not only fosters environmental management but also promotes economic growth through job creation and technological innovation.

Economic optimization study seems to be necessary to determine the investment and operating costs of the designed system, which constitutes our future investigations.

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