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Original Article

Design and Implementation of a Photovoltaic Solar Powered Ice Cube Making Machine for off Grid Applications

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***Abstract* - *Ice cube making machines are widely useful in beverages, hospitals, healthcare, retail stores, manufacturing, entertainment, seafood, agriculture, horticulture, construction and emergency services. Most of these are grid-connected and work on AC supply. For some of the applications, like mobile food vans, roadside vendors, and military and research stations, will require off-grid ice cube-making machines. Off grid ice cube-making machine works with solar power without any grid connection. Harnessing maximum solar power for an ice cube-making machine is a challenging task. In this paper, an off-grid ice cube-making system has been developed with the help of a solar PV panel, MPPT charge controller, solar battery and inverter. The proposed system has been developed to provide six to eight hours backup even when there is no irradiation during rainy, fog and dark conditions. The hardware results proved that the proposed ice cube-making machine is a novel solution, and it is ideal for off-grid applications.*

***Keywords* - *Inverter, Irradiation, MPPT charge controller, Solar PV panel, Solar battery.*

1. Introduction

An ice cube-making machine, also known as an ice maker, is a specialized appliance designed to produce ice cubes in a controlled and automated manner [1]. It is commonly used in various settings, including homes, restaurants, bars, hotels, and industrial applications. The machine functions by freezing water, typically in cube-shaped molds, and then ejecting the ice cubes into a storage bin or container. Depending on the size and type, ice cube-making machines can produce a range of ice cube sizes and quantities, making them essential for keeping beverages cold, preserving food, and ensuring consistent access to ice in a variety of commercial and residential settings [2]. These machines are available in a wide range of capacities and are a valuable tool for maintaining product quality, hygiene, and convenience in industries and environments that rely on ice. An ice cube-making machine is constructed with key components to produce ice cubes efficiently. It typically begins with a water inlet valve, allowing water from a connected supply to enter a storage tank. Inside the machine, an evaporator plate, cooled by a refrigeration system, forms ice cubes as water is sprayed or poured onto it. These cubes take shape in molds on the plate. Once fully frozen, an ejector mechanism releases the ice cubes into an insulated storage bin [3]. The machine's control system allows users to adjust ice cube size and production rates. Additional components, such as a condenser and fan for heat dissipation, a water pump for circulation, and safety features, ensure efficient and reliable ice production. The size and capacity of these machines can vary, catering to a range of applications from residential to industrial needs. On-grid and off-grid ice cube-making machines differ primarily in their power source and application. On-grid machines are connected to a centralized electrical grid, whereas off-grid machines operate independently of the grid. On-grid ice cube makers are commonly used in urban settings, where reliable electricity is available, while off-grid machines find applications in remote areas or during power outages. Off-grid ice cube makers often rely on alternative power sources like solar PV panels, generators, or propane, making them suitable for situations where grid power is unreliable or unavailable.

The choice between these two types depends on factors such as location, accessibility to electricity, and the need for ice production in various environments, ranging from urban restaurants to rural communities or outdoor events [4].

Off-grid ice cube-making machines come in various types and sizes to cater to different needs and environments. The type of machine depends on factors like the power source, ice production capacity, and the specific application. A variety of off-grid solar-powered ice cube machines are available, such as propane-powered, battery-powered, generator-powered, thermoelectric and solar-powered [5, 6].

Out of all these, solar-powered ice cube-making machines are most widely used for small-scale applications. The main challenge in this research work is selecting the suitable hardware components. Ice cube machine draws high inrush currents around six to eight times of rating currents for a short duration of time (nearly 30 seconds). In order to suppress these currents, the inverter must be selected wisely. Usually, high-rated inverters have to be used; otherwise, it is impossible to harvest the produced ice. The block diagram of the proposed solar-powered ice cube-making machine is shown in Figure 1. Solar panel output is connected to the Maximum Power Point Tracker (MPPT) charge controller, which converts 24 volts DC voltage into 12 volts DC. The output of the solar charge controller is connected to a solar battery, where the battery charges in a safe manner in spite of variations in solar irradiation. The fully charged battery is connected to a single-phase inverter where 12 volts DC gets converted into a 230 volts single phase AC voltage. The output AC voltage is connected to the Ice cube-making machine.

The proposed method of ice-making completely works without the support of the main grid continuously and for six to eight hours when there is no solar irradiation present. This paper is organized into seven sections. Section 1 presents the introduction and system block diagram. The solar PV panel specifications for the proposed ice cube machine are elaborated in Section 2.

Section 3 details the MPPT Solar charge controller, while Battery requirements for the ice cube-making machine are discussed in Section 4. Section 5 explains the inverter capacity requirements. The Ice cube-making machine ratings are elaborated in Section 6. The proposed hardware mathematical modelling and results and comparison are discussed in Section 8, and Section 9 deals with conclusions and future scope.

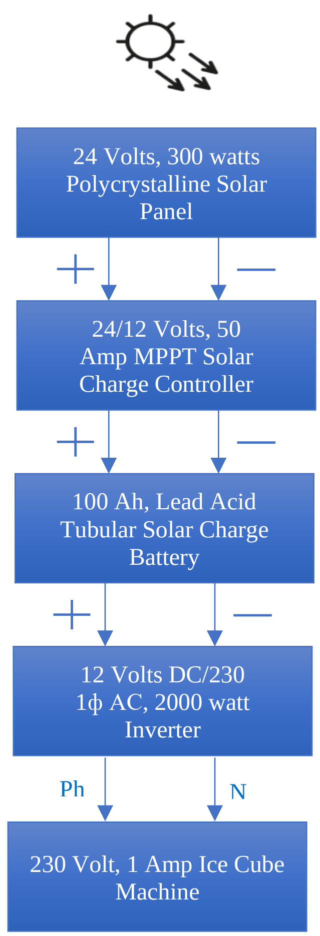

Fig. 1 Block diagram of solar-powered ice cube-making machine

2. Solar Panel Specifications

There are many different kinds of solar panels on the market, including ones that may be used for power generation and heating. Heating panels fall into one of the following categories: Glazed Flat-Plate Collectors. A transparent glass or plastic cover is placed over a dark absorber plate to create these collectors. Heat is produced by the absorber plate, which absorbs solar energy as it passes through the cover [7-9]. The fluid that circulates through the collector after this heat transfer is typically water or a heat transfer fluid. The materials and methods section should contain sufficient detail so that all procedures can be repeated. It may be divided into headed subsections if several methods are described.

Solar pool heating is usually accomplished using unglazed collectors. Because they do not have a translucent cover, sunlight can heat the absorber surface directly. Although they are not as effective as glazed collectors, they work well for some applications. Using curved, reflective troughs, concentrating parabolic trough collector's direct sunlight onto a receiver tube that runs parallel to the focal line. In the tube, concentrated sunlight heats a heat transfer fluid that is subsequently utilized to produce steam for industrial operations or the generation of energy [10-13].

Parabolic dish collectors that focus sunlight onto a receiver at the focal point are made possible by a dish-shaped reflector. This kind of collector is frequently employed in high-temperature industrial settings or for small-scale power generation. Fresnel reflectors that concentrate sunlight onto a receiver work similarly to parabolic troughs by using a series of flat mirrors. They are frequently seen in massive solar thermal power facilities. A heat transfer fluid and an absorber coating are contained in each of the parallel rows of tubes that make up an evacuated tube collector. The tubes are positioned inside a bigger tube that is vacuum-sealed in order to reduce heat loss. Commonly used for space heating and domestic hot water, these collectors work well in cold areas [14, 15].

Air is directly heated by solar air collectors, which absorb sunshine. Applications such as industrial drying or space heating can then make use of the heated air. Solar panels mostly employ Photovoltaic (PV) technology to generate electricity. Solar PV panels use the photovoltaic effect, in which semiconductors absorb photons and release electrons to produce an electric current to convert sunlight into electricity directly. Monocrystalline and polycrystalline solar PV panels are the two primary varieties, though there are other variants as well. Single-crystal silicon is used to make monocrystalline solar panels, which are renowned for their high efficiency and compact design. They are popular for both residential and commercial installations because of their sleek design and consistent black or dark color. Generally speaking, monocrystalline panels are more efficient than polycrystalline ones, which means they can turn a larger proportion of sunlight into electrical power. Multiple silicon crystal structures are used to create polycrystalline solar panels. Although they are inexpensive to manufacture, their efficiency is often marginally lower than that of monocrystalline panels. When space is not an issue, polycrystalline panels are a common option for large-scale solar projects. The same process, known as the photovoltaic effect, is used by both monocrystalline and polycrystalline solar panels to transform sunlight into electricity. Solar cells, which are composed of layers of silicon, phosphorus, and boron, make up solar panels. One of the main distinctions between monocrystalline and polycrystalline solar panels is the silicon content of these solar cells. Figure 2 depicts the solar PV panel that was utilized to conduct the research that was presented. Table 1 provides the specifications. The panel is of the polycrystalline variety. Despite being less efficient than monocrystalline panels, polycrystalline panels are less expensive. From Table 1, the solar panel voltage at maximum power is 37.10 volts; a charge controller must be rated for 24 volts to connect to a battery for safe charging.

Fig. 2 Polycrystalline solar panel

Table 1. Polycrystalline solar panel specifications

Parameter	Value
Maximum Power	300 watts
Open Circuit Voltage	44.45 volts
Circuit Short Current	8.58 Amps
Voltage at Maximum Power	37.10 volts
Current at Maximum Power	8.09 Amps
Maximum System Voltage	1000 volts
Normal operating cell temperature	44.6 ˚C
Temperature coefficient	-1.036 watt/ ˚C

3. MPPT Solar Charge Controller

Solar charge controllers, which manage the voltage and current flowing from solar panels to batteries, are crucial parts of solar power systems. They guarantee that the batteries are charged effectively and avoid overcharging. The two primary categories of solar charge controllers are Maximum Power Point Tracking (MPPT) and Pulse Width Modulation (PWM).

Simple and reasonably priced, PWM charge controllers are perfect for lead-acid batteries and smaller systems with tighter budgets. Compared to MPPT controllers, these are typically less effective, particularly when the voltage from the solar panel is much higher than the voltage from the battery [16]. Through the use of advanced electronics, MPPT controllers maximize power extraction from solar panels by modifying the electrical operating point.

As illustrated in Figure 3, they continuously monitor the maximum power point and modify the operating parameters to correspond with the evolving circumstances with greater efficiency than PWM controllers, especially when there is fluctuating weather and shade, able to manage solar panels with higher voltages and transform surplus voltage into more charging current appropriate for a greater variety of battery types, such as lithium-ion batteries.

Though generally costlier than PWM controllers, their higher efficiency may, in some circumstances, result in a quicker return on investment. In off-grid systems with surplus energy, diversion charge controllers are frequently employed. To avoid overcharging, these controllers redirect extra power to a dump load (such as a water heater or resistive heating element) once the batteries are fully charged [17].

These work well with off-grid systems that have low load demands since they reroute excess electricity to avoid overcharging frequently utilized in hydroelectric and wind power systems. Most commercial MPPT charge controllers use Perturb and Observe (P&O) or Incremental Conductance (INC) due to their balance between accuracy, complexity, and cost.

As illustrated in Figure 4, a 40-amp MPPT charge controller with a voltage rating of 24/12 volts is being employed to carry out this suggested research.

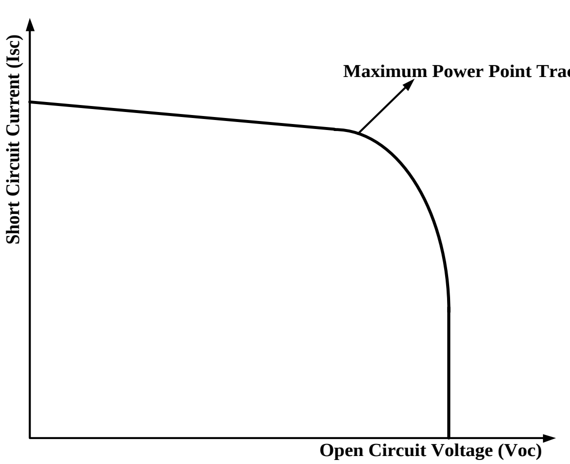

Fig. 3 Maximum power point tracking by the charge controller

Fig. 4 MPPT 24/12-volt, 40 Amp solar charge controller

4. Solar Tubular Lead Acid Battery

In order to capture and store the energy produced by solar panels, solar batteries, also referred to as solar energy storage systems or solar battery storage, are essential. For usage in times of low or no sunlight, these batteries store extra energy generated during sunny spells. Lead-acid batteries, such as flooded lead-acid, sealed lead-acid (AGM or absorbent glass mat), and gel batteries, are frequently utilized in off-grid solar systems. Because of their greater energy density, longer longevity, and reduced weight, these batteries are growing in popularity. Among the variations are Lithium-Ion Manganese Oxide (LMO), Lithium Nickel Manganese Cobalt Oxide (NMC), and lithium iron phosphate ($LiFePO_4$) [18].

The liquid electrolytes used in these batteries are kept in external tanks. Their lengthy cycle life and scalability are well-known. Saltwater Batteries are also referred to as aqueous hybrid ion batteries, these environmentally beneficial batteries employ sodium-ion technology. The amount of electric charge that a solar battery can hold is indicated by its capacity, which is expressed in Ampere-Hours (AH). The capacity needed is determined by the system's or household's energy requirements as well as the degree of independence that is wanted at times when there is no sunlight.

The percentage of a battery's capacity that can be utilized before needing to be recharged is known as the depth of discharge. Because routinely draining a battery to its maximum capacity will shorten its lifespan, the DoD must be considered. A battery's cycle life is the maximum number of charge-discharge cycles it can withstand while still retaining a specific capacity. The cycle life of lithium-ion batteries is often longer than that of lead-acid batteries. Different voltage ratings are available for solar batteries. It is essential to make sure that the battery voltage is compatible with the inverter used in the solar power system and meets the system requirements. Lithium-ion and some lead-acid batteries have BMS integrated to control the charging and discharging procedures, balance cell voltages, and guard against overcharging, over discharging, and overheating. Inverters, which transform the DC electricity stored in solar batteries into AC electricity for usage in residences or commercial buildings, are commonly attached to solar batteries. Verify that the inverter system and the battery are compatible. The durability and functionality of solar batteries depend on proper installation and upkeep. Consistent cleaning, monitoring, and following manufacturer instructions are crucial.

Installation, possible replacement costs, and the initial purchase price are all included in the price of solar batteries. Over time, lithium-ion batteries prove to be more cost-effective due to their longer lifespan and superior performance, even though their initial cost may be greater. As seen in Figure 5, the solar tubular lead acid battery used in this suggested study has a capacity of 100 Ah and a rating of 12 Volts.

Fig. 5 Solar tubular lead acid battery (12V, 100 Ah)

5. Solar Inverters

A vital component of solar power systems is solar inverters, often known as PV inverters or solar inverters. Their main job is to change the Direct Current (DC) electricity produced by solar panels into Alternating Current (AC) electricity so that it may be fed into the electrical grid or used to power equipment and appliances. There are various kinds of solar inverters, and each is made for a particular use. The following are some essential features of solar charge inverters: Solar installations in homes and small businesses frequently use string inverters. They transform the combined DC electricity into AC power by connecting to several solar panels that are wired in series (or strings). Each solar panel has a microinverter installed, which immediately converts DC power to AC power at the panel level. String inverters, on the other hand, connect a single inverter to several panels. Power optimizers are similar to microinverters in that they are positioned at the panel level.

Nevertheless, they optimize each panel's DC output before transferring it to a central string inverter rather than converting it to AC. Systems that combine solar and storage are the ideal applications for hybrid inverters. Both the solar panels and any linked energy storage devices, like batteries, can be controlled by them. Electric grid-connected solar power systems are the target market for grid-tied inverters. The surplus electricity is fed back into the system after they coordinate with it [19]. For independent solar power systems that are not linked to the utility grid, off-grid inverters are utilized. They provide loads with AC power and oversee battery charge. A few factors to consider while choosing a solar inverter include the system size, solar panel type, shading circumstances, budget, and whether or not energy storage is included in the system [20]. In this suggested study, an inverter with a 600 VA capacity that transforms 12 V DC into 230 V single-phase AC is used, as illustrated in Figure 6.

Fig. 6 Solar Charge Inverter (12V DC/230V AC, 1Ø AC 50 Hz, 2000 watt)

6. Ice Cube-Making Machine

A machine made to create ice cubes is called an ice cube-making machine, sometimes referred to as an ice maker or ice machine. Numerous locations, such as residences, restaurants, pubs, hotels, hospitals, and more, make extensive use of these devices. An ice cube maker's primary job is to freeze water into ice cubes, which can then be dispensed or stored for later use [21]. Only ice is produced by modular ice makers, which need a separate storage bin to hold the ice cubes. Undercounter ice maker devices come with an ice maker and a built-in storage bin, and they are made to fit beneath bars or counters.

Numerous ice cube sizes and forms, such as normal cubes, crescent-shaped cubes, nugget ice, gourmet ice, and more, can be produced by ice cube manufacturing machines. The particular needs of the consumer or the kind of business frequently influence the ice cube shape selection. The production capacity of ice makers, expressed in pounds or kilos of ice produced in a 24-hour period, is used to grade them [22]. The storage capacity is important for machines that have built-in storage bins. It establishes the maximum amount of ice that can be kept before having to be used or discharged. A variety of cooling systems, such as air-cooled, water-cooled, and remote-cooled systems, are used in ice cube makers. The machine's efficiency, energy usage, and installation needs can all be impacted by the cooling system selection. Modern ice producers have self-cleaning capabilities to preserve cleanliness and stop the accumulation of mineral deposits and microorganisms. Table 2 displays the specs of the ice cube maker employed in this proposed study, which is depicted in Figure 7.

Fig. 7 Ice cube making machine

Table 2. Ice cube machine specifications

Parameter	Value
Power Supply	220-240/50 Hz
Electrical Safety Class	I
Ice Making Rating	0.7 Amp.
Ice Harvest Rating	01 Amp.
Refrigerant	R600a
Vesicant	C_5H_{10}

7. Mathematical Modelling and Hardware Results

This section will initially explain the mathematical modelling of the ice cube machine, mathematical modelling of solar powered ice cube machine, hardware results and comparison of the proposed system with existing solutions.

Modelling an ice cube machine mathematically involves considering various physical and thermodynamic principles, which include the following.

Identify the Components: Break down the ice cube machine into its essential components, such as the refrigeration system, the ice cube trays, the water supply system, and any controls or sensors.

Define the Processes: Understand the processes involved in making ice cubes. This typically includes cooling water to a temperature below freezing point, pouring the cooled water into ice cube trays, allowing the water to freeze, ejecting the ice cubes from the trays, refilling the trays with water and managing the refrigeration cycle to maintain the desired temperature.

Apply Thermodynamics: Use principles of thermodynamics to model the heat transfer processes involved in cooling water and freezing it into ice cubes. This might involve concepts such as heat conduction, convection, and phase transitions.

Fluid Dynamics: Consider the flow of water through the system, including the rate at which water is poured into the trays, the rate at which ice cubes are ejected, and any circulation of water within the machine.

Refrigeration Cycle: Model the refrigeration cycle that cools the water and maintains the temperature within the ice cube trays. This involves understanding the operation of components such as compressors, condensers, evaporators, and expansion valves.

Control Systems: If the ice cube machine has any control systems or sensors to regulate temperature, water flow, or other parameters, incorporate these into the model.

Numerical Simulation or Analytical Solution: Depending on the complexity of the system, you may use numerical simulation techniques (such as finite element analysis or computational fluid dynamics) or analytical methods (such as mathematical equations) to solve the model and predict the behaviour of the ice cube machine under different conditions.

Validation and Testing: Validate the model by comparing its predictions to experimental data or observations from real ice cube machines. Adjust the model as necessary to improve its accuracy.

Optimization: Once you have a validated model, you can use it to optimize the design or operation of the ice cube machine. This might involve finding ways to improve energy efficiency, production rate, or product quality.

Sensitivity Analysis: Perform sensitivity analysis to understand how changes in various parameters (such as ambient temperature, water flow rate, or refrigerant pressure) affect the performance of the ice cube machine.

7.1. Mathematical Modelling of Ice Cube Machine

The desired capacity of the PV system required is evaluated by using (1).

$$C_p = \frac{EC}{PGF} \tag{1}$$

Where

C_p : Desired capacity of PV system (KWp)
EC : Energy consumption of ice-cube-making machine (kWh)
PGF : Panel Generation Factor (kWh/kWp)

Battery bank capacity is evaluated by using (2).

$$BB = \frac{EG*1000*\eta_B}{V_{nB}*DoD} \tag{2}$$

Where

BB : Battery bank capacity (AH)
EG : Energy generated by solar PV system (kWh)
η_B : Efficiency of the battery (per unit), considered as ‘0.85’
V_{nB} : Battery bank nominal voltage
DoD : Depth of discharge of the battery

Solar charge controller capacity is evaluated by using (3).

$$SCC = \frac{W_A}{V_{nB}} * F_{SC} \quad (3)$$

Where

SCC : Solar charge controller capacity (A)
W_A : PV array wattage (W)
V_{nB} : Battery bank nominal voltage (V)
F_{SC} : Short-circuit factor

7.2. Hardware Results

The steps followed while testing and executing the proposed research are shown in Figure 8.

1. Testing of ice cube machine with charged battery and inverter.
2. Testing of battery charging with solar panel and charge controller.
3. Testing of ice cube machine with solar panel, charge controller, battery and inverter.
4. Analysis of results and comparison.

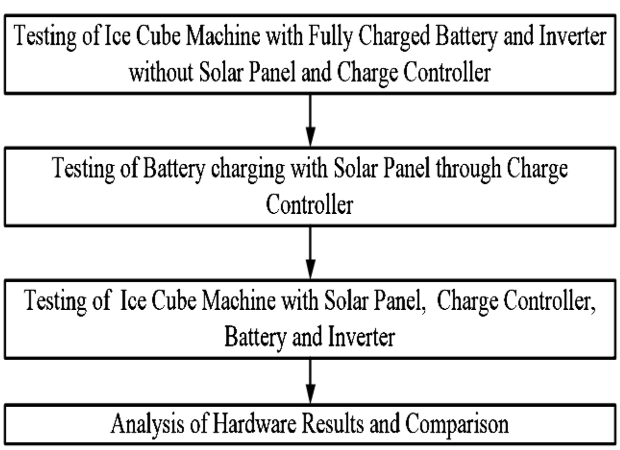

Fig. 8 Steps followed in testing and execution of the proposed project

7.3. Testing of Ice Cube Machine with battery and inverter

Initially, the ice cube-making machine is tested with the fully charged battery and inverter without connecting the solar panel and charge controller, as shown in Figure 9. The time taken by the ice cube-making machine to deliver the first batch of ice cubes is approximately 30 minutes, whereas with the direct grid-connected, the time consumption is 10 minutes. This situation is due to the fact that initially, the ice cube-making machine draws more inrush current for ice harvesting.

In the next phase, the battery is fully discharged and is connected to the solar panel through a charge controller. Under shadow conditions of solar panels, the time to charge the battery is large due to the decreased capacity of the solar panels, whereas, under strong irradiation conditions, the charging time is drastically reduced. The battery charging with solar panel is as shown in Figure 10.

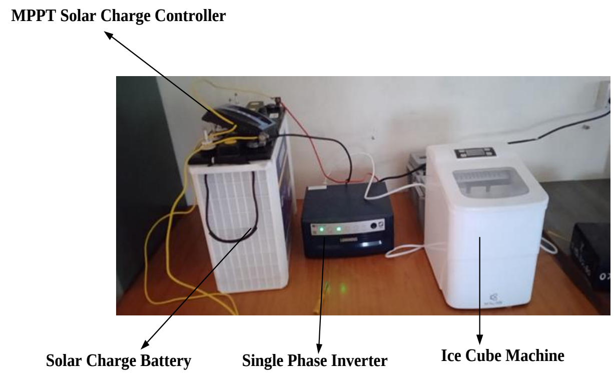

Fig. 9 Testing of ice cube machine with battery and inverter

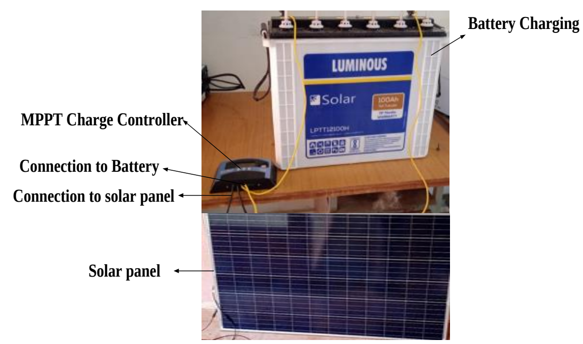

Fig. 10 Battery charging with the solar panel through a charge controller

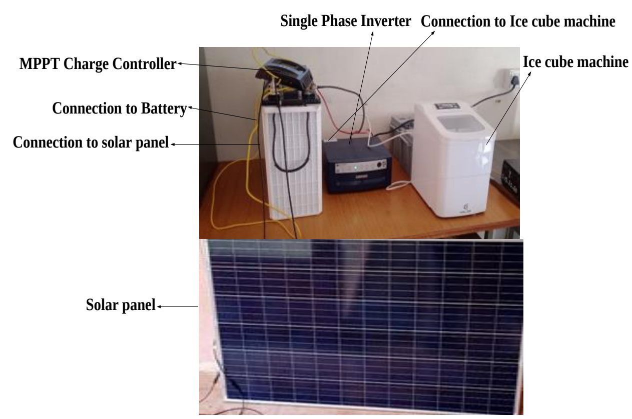

Fig. 11 Testing of ice cube-making machine with complete setup

Fig. 12 Ice cube formation with the proposed setup

Once the battery is reached to a sufficient level of charging, then this setup is connected to the inverter and the output of the inverter is connected to the ice cube-making machine. This complete setup is shown in Figure 11. Though the initial time is more for the first batch of ice cubes, for the remaining batches, the time consuming is less (approximately five minutes for each batch). Figure 12 shows the ice cubes formed by the proposed setup. The components along with the parameters used to implement this proposed research are, as shown in Table 3

Table 3. Hardware components, along with parameters

Component	Specification
Poly Crystalline Solar Panel	24V, 300 Wp
Charge Controller	12 V/24 V – 12 V, 40 Amp, MPPT
Lead Acid Solar Battery	12 V, 100 Ah
Single Phase Inverter	12 V/230 V, 50 Hz, 2000 watt
Ice Cube-Making Machine	230 V, 1 Amp

The comparison of the proposed off-grid ice-making with the on-grid machine is shown in Table 4.

Table 4. Comparison of off-grid and on-grid ice cube machine

On/Off Grid	Initial Cost	efficiency	Reliability	Production	Renewable	Energy Bills	Payback period
On-grid Ice Cube Machine	Less	More	Less	More	No	High	Not Applicable
Proposed Off grid Ice Cube Machine	More	Moderate	More	Moderate	Yes	Zero	Two years

8. Conclusion and Future Scope

8.1. Conclusion

The proposed ice cube machine is very useful for off-grid applications where the main grid is not accessible, like for storing medicines, fish, beverages, juice makers, ice creams etc. Sufficient energy conservation is possible with the proposed ice cube machine since it is fed by solar energy. This solar energy is also renewable, eco-friendly and will not harm nature. This method of ice-making is novel and is not reported anywhere in the literature.

8.2. Future Scope

Large-capacity solar-powered ice cube-making machines can be implemented based on the proposed method to meet the huge community applications. Since the ice cube making machine draws large inrush currents initially, it will usually take more time to produce the first batch of ice cubes with the proposed method. To address this issue, a separate automatic setup can be designed. The space required is more to place this proposed ice cube making machine. The latest energy storage devices like supercapacitors and fuel cells may reduce space requirements.

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