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# Smart Cooling Condensation-Based Atmospheric Water Generation System Powered by Solar Energy for Sustainable Water Generation

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**ABSTRACT:** Access to clean and sustainable drinking water is a global concern, particularly in regions facing water scarcity. This paper presents a Smart Cooling Condensation-Based Atmospheric Water Generation (AWG) System powered by solar energy for sustainable water generation. The system leverages the cooling condensation method, where humid air is cooled below its dew point to extract moisture. A refrigeration cycle comprising a compressor, evaporator (cooling coil), and condenser facilitates this process. The condensed water is collected in a tray and purified using UV and/or RO filtration. Key components include an air intake fan, cooling coil, refrigeration compressor, condenser, drainage tray, UV/RO filter, and an Arduino-based controller for automation. A DHT11 humidity sensor monitors real-time conditions, while a solar power system with a charge controller and battery enabling off-grid functionality and ensures energy sustainability. The system is optimized for high humidity environments, making it particularly suitable for Indian climatic conditions. This low-cost, energy-efficient system details the components, working principles, control algorithm, and performance evaluation under Indian climatic conditions highlighting its potential for decentralized water supply in off-grid and rural areas.

**KEYWORDS:** Atmospheric Water Generation (AWG), Cooling Condensation, Solar Energy, Arduino, Sustainable Water Harvesting.

## I. INTRODUCTION

India faces an acute water crisis due to over-dependence on monsoons, depleting groundwater, and increasing pollution. These challenges are particularly acute in rural and semi-urban regions, where centralized water supply systems are inadequate or non-existent which emerges the need alternative water generation methods. AWG has emerged as a transformative solution to address water scarcity by capturing humidity from the ambient air and converting it into potable water. Among the various AWG techniques, cooling condensation is one of the most reliable and scalable methods. This technique involves lowering the temperature of humid air below its dew point, allowing water vapour to condense into liquid form.

The present study proposes a solar-powered AWG system that integrates the cooling condensation principle with smart automation and renewable energy utilization. Designed specifically for Indian climatic conditions, the system employs a refrigeration-based cooling mechanism combined with real-time sensing and intelligent control to optimize water production. An Arduino-based controller, interfaced with a DHT11 humidity and temperature sensor, governs system operations dynamically based on environmental inputs. A key innovation in the system is its off-grid capability, achieved through the integration of photovoltaic (PV) solar panels, a charge controller, and battery storage, making it highly suitable for remote and underserved communities. This paper elaborates on the technical architecture,

component selection, automation logic, and field performance evaluation of the proposed AWG system, demonstrating its potential as a decentralized and sustainable water solution tailored to the Indian subcontinent.

## **II. LITERATURE SURVEY**

Atmospheric Water Generation (AWG) technologies have evolved significantly in recent decades as viable alternatives for potable water supply in water-stressed regions. The existing AWG methods vary widely in terms of energy efficiency, feasibility, scalability, and environmental adaptability.

### **2.1 Existing AWG Technologies**

Fog harvesting is one of the earliest and most passive AWG techniques. It uses vertical mesh nets to capture microscopic water droplets suspended in fog. While cost-effective and low-maintenance, this method is geographically restricted to regions with persistent fog, such as mountainous or coastal zones. According to Yaghoubi et al. (2018), fog harvesting systems yield optimal results only when daily fog occurrence exceeds five hours. Desiccant-based AWG systems use hygroscopic materials like silica gel or lithium chloride to adsorb atmospheric moisture, which is then released through heating. Although functional in low-humidity areas, their high thermal energy demand for desiccant regeneration renders them inefficient for small-scale residential use (Wang et al., 2019).

Thermoelectric cooling systems leverage the Peltier effect to cool air below dew point, enabling condensation. However, their coefficient of performance (COP) remains below 1, resulting in poor energy efficiency. According to Park and Choi (2021), thermoelectric AWG units are more suitable for portable or emergency water extraction due to their compact size but are not recommended for continuous household use.

The most energy-efficient and scalable method is cooling condensation using a vapour compression refrigeration cycle. Mohamed et al. (2020) demonstrated that such systems achieve peak efficiency in regions with relative humidity above 60%, particularly when integrated with smart automation and environmental sensing.

### **2.2 Solar-Powered AWG Systems**

As energy efficiency and sustainability have become central to AWG system design, solar-powered AWG units have gained prominence. Kumar et al. (2021) illustrated that photovoltaic (PV)-driven AWG systems drastically reduce dependence on the electrical grid and enable deployment in off-grid locations. Battery storage solutions further ensure continuous operation during night time or low-irradiance conditions.

Patel and Sharma (2022) proposed a hybrid AWG model combining PV power, thermal storage, and a multi-stage cooling cycle. Their findings showed improved yield consistency and better system autonomy. These solar-powered models demonstrate strong potential for application in remote or rural areas of India, where grid reliability is often a concern.

### **2.3 Automation in AWG Systems**

Arduino microcontrollers and PID control algorithms have been widely adopted to optimize compressor cycling and reduce energy wastage. According to Li and Zhang (2020), real-time humidity and temperature feedback enables adaptive operational control, enhancing water yield and system lifespan.

The integration of IoT modules for remote monitoring, as explored by Al-Fadhli et al. (2021), allows for predictive maintenance and operational data analytics. Such smart systems improve reliability and user convenience, making AWG systems more accessible and manageable for household applications.

Despite the advances in AWG technology, many existing systems suffer from high capital costs, limited environmental adaptability, or dependency on grid electricity. The proposed study bridges these gaps by developing a cost-effective, solar-powered AWG system with embedded automation tailored specifically to Indian climatic conditions.



This literature review establishes the technological foundation and justifies the selection of the cooling condensation method combined with solar power and automation for efficient atmospheric water harvesting in humid regions of India.

### III. METHODOLOGY

The smart Atmospheric Water Generation (AWG) system operates by drawing in ambient humid air using a high-speed axial fan powered by solar energy. This air is directed over a thermally conductive cooling coil functioning as the evaporator in a vapour-compression refrigeration cycle where it is cooled below its dew point using a compact refrigeration compressor. As a result, water vapour condenses on the coil surface and collects in a hygienic drainage tray, eventually flowing into a sealed, food-grade storage tank. The collected water is then purified using a UV sterilizer and optionally passed through a reverse osmosis (RO) membrane to ensure it meets potable water standards. The entire system is intelligently managed by an Arduino Uno microcontroller. It receives real-time input from a DHT11 sensor that monitors ambient temperature and relative humidity. Based on preset thresholds (e.g., RH > 50% and T > 25°C), the Arduino dynamically controls the activation of the fan and compressor to optimize performance and energy efficiency. It also prevents overfilling by monitoring the water tank level and includes logic for fault detection and system protection.

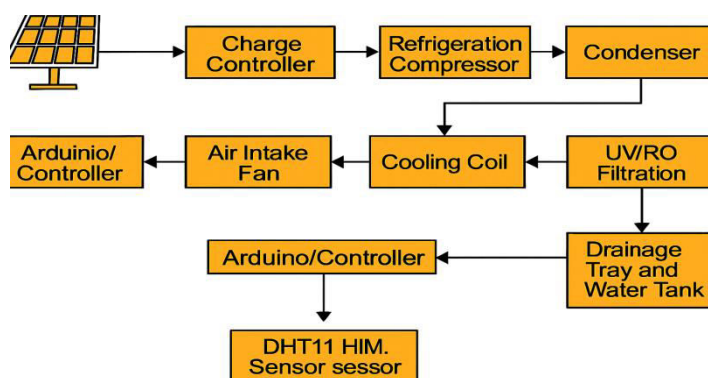


Figure 1: Block Diagram of the System

To ensure energy sustainability, the system is powered by a 100–200W solar photovoltaic panel, with energy stored in a 12V battery via a PWM or MPPT charge controller. The block diagram is as shown in figure 1; this configuration enables continuous, off-grid operation even during non-sunny hours. The solar integration, combined with sensor-driven automation and modular design, makes this system an ideal, low-cost, and eco-friendly solution for decentralized water generation in India's humid and rural regions.

#### 3.1. Principle of Cooling Condensation Method:

The proposed atmospheric water harvesting system operates on a vapour-compression refrigeration cycle, leveraging fundamental thermodynamic principles to extract moisture from humid air through controlled cooling below the dew point. The process initiates with an axial fan (150 CFM flow rate) drawing ambient air across a high-conductivity copper cooling coil, maintained at 5–10°C below the dew point temperature ( $T_d$ ) by a hermetic refrigeration compressor using R134a refrigerant. As the air contacts the sub-cooled coil, its temperature drops below the saturation vapor pressure, inducing phase change and nucleation-driven condensation of water vapour into liquid droplets. The condensate is collected in a food-grade reservoir, followed by UV sterilization (5W, 254 nm wavelengths) and optional reverse osmosis (RO, 50 GPD membranes) to ensure potable quality.

#### Theoretical Foundation and Mathematical Modeling:

The dew point temperature, a critical parameter for system efficiency, is derived from the Magnus-Tetens approximation, a semi-empirical relation validated for RH > 50%:

$$T = \frac{b \cdot \left( \frac{a \cdot T}{b + T} + \ln(RH) \right)}{\left[ \frac{a \cdot T}{b + T} + \ln(RH) \right] - \ln(RH)} \quad (1)$$

Where:  $a = 17.27$ ,  $b = 237.7^\circ\text{C}$  (empirical constants for water vapour),  $T$  = ambient temperature ( $^\circ\text{C}$ ) and  $RH$  = relative humidity (decimal)

The cooling load ( $Q_{cool}$ ) required to achieve condensation is derived from energy balance:

$$Q_{cool} = \dot{m}_a [c_p (T_{in} - T_{coil}) + \omega \cdot h_{fg}] \quad (2)$$

Where:  $\dot{m}_a$  = air mass flow rate (kg/s),  $c_p$  = specific heat of air (1.005 kJ/kg • K),  $\omega$  = humidity ratio (kg vapour/kg air) and  $h_{fg}$  = latent heat of vaporization (2501 kJ/kg at 20°C)

The refrigeration cycle's COP is optimized by minimizing the temperature difference ( $\Delta T = T_{coil} - T_{evap}$ ):

$$COP = Q_{cool} / W_{comp} = T_{evap} / (T_{cond} - T_{evap}) \quad (3)$$

Where:  $W_{comp}$  = compressor work input,  $T_{evap}$ ,  $T_{cond}$  = evaporator and condenser temperatures (K)

Practical Implementation For  $T = 30^\circ\text{C}$  and  $RH = 80\%$ :

Equation (1) yields  $T = 25.4^\circ\text{C}$ , Coil temperature is maintained at  $15\text{--}20^\circ\text{C}$  ( $\Delta T = 5\text{--}10^\circ\text{C}$  below  $T_d$ )

Experimental data confirms a condensation rate of 0.8-1.2 L/h under these conditions.

### 3.2 System Architecture and Components:

The proposed Atmospheric Water Generation (AWG) system as shown in figure 2: is a modular, solar-powered, smart solution designed specifically for the Indian climatic conditions. It utilizes a vapour compression-based cooling condensation method to extract water from ambient air and includes intelligent automation to optimize performance. Below is a detailed description of each component within the system architecture.

**Air Intake Fan:** At the front end of the system, a high-speed DC-powered axial fan (12V or 24V) is employed to draw ambient humid air into the AWG unit. The fan ensures a constant and uniform airflow across the cooling coil to maximize air-water interaction. The airflow rate is optimized (typically 40–70 CFM) to balance energy consumption and moisture intake.

**Cooling Coil (Aluminium/Copper):** The core element for moisture extraction, the cooling coil operates as the evaporator in the refrigeration cycle. Constructed from thermally conductive materials like copper or aluminium tubing with extended fins, the coil rapidly cools incoming air to temperatures below its dew point, triggering condensation of water vapour. Copper is preferred for superior thermal conductivity ( $\approx 400 \text{ W/m}\cdot\text{K}$ ), while aluminium offers a more cost-effective alternative with good heat transfer efficiency ( $\approx 237 \text{ W/m}\cdot\text{K}$ ).

**Refrigeration Compressor:** The system employs a compact, hermetically sealed refrigeration compressor (similar to those used in mini refrigerators or air conditioners) to drive the vapour-compression cycle. The compressor circulates refrigerant through the evaporator (cooling coil) and condenser. It maintains the low pressure and low temperature at the coil to facilitate continuous condensation. Scroll or rotary compressors are typically chosen for higher efficiency and reliability in small-scale setups. Refrigerants such as R134a or R600a are commonly used for their thermodynamic stability and low GWP.

**Condenser:** The condenser functions as the heat rejection unit in the refrigeration cycle. Heat absorbed at the evaporator is expelled into the surroundings through this component. The condenser coil, often supported by a finned heat sink and an auxiliary fan, enhances the dissipation of thermal energy. An efficient condenser is crucial to maintain a stable temperature gradient and ensure the smooth circulation of the refrigerant. It is typically placed externally in a well-ventilated area of the unit for optimal airflow.

**Drainage Tray and Water Tank:** As water condenses on the cooling coil, it drips into a food-grade plastic or stainless steel drainage tray. The tray is inclined slightly to allow gravity-assisted drainage into a sealed, UV-resistant water storage tank. The tank capacity is usually around 5–10 liters for a small home unit, with provisions for overflow protection and easy access for maintenance.

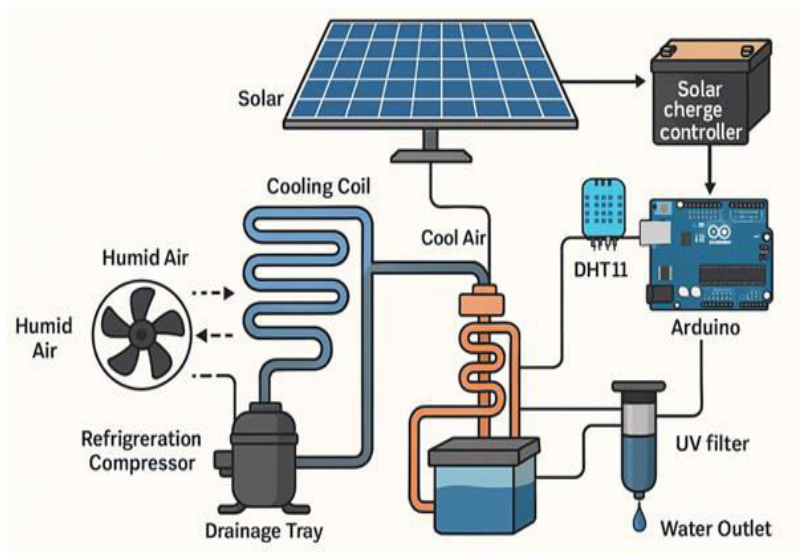


Figure 2: System Components and Working Principle

**UV Filter / RO Filter:** Collected water is treated through a two-stage purification system to ensure it meets potable water standards. First, a UV sterilization unit inactivates bacterial and viral pathogens. This dual purification system ensures that water output is both biologically safe and chemically pure.

**Arduino / Controller Unit:** An Arduino Uno microcontroller forms the brain of the system. It receives input from environmental sensors (like DHT11), processes logical control algorithms, and controls key components including the fan, compressor, and UV system. The Arduino automates operations based on real-time humidity and temperature data, system energy status, and water tank levels. It can be programmed to reduce operational cycles when humidity is low or shut down the compressor to save power. The system also supports fault detection and optional real-time LCD display.

#### IV. AUTOMATION AND SENSOR INTEGRATION

**Arduino/Controller for Intelligent Control:** Automation plays a critical role in enhancing the efficiency and sustainability of the AWG system. The Arduino Uno microcontroller facilitates real-time, adaptive control by continuously monitoring environmental conditions and system parameters. It enables conditional operations such as activating the fan and compressor only when humidity levels are favourable, thereby conserving energy. The controller also supports modular programming logic for expansion allowing integration of solar charge monitoring, water level sensors, or even GSM alert systems in the future.

**Humidity Sensor (DHT11):** The DHT11 digital sensor module provides essential temperature and relative humidity (RH) data. With a resolution of  $\pm 2\%$  RH and  $\pm 1^\circ\text{C}$ , it enables the controller to compute the dew point dynamically. If the ambient RH exceeds 50% and the temperature is above  $25^\circ\text{C}$ , the Arduino initiates the cooling cycle. The sensor is positioned in the air intake path to obtain the most accurate ambient conditions. This ensures energy-efficient, condition-dependent operation, thereby enhancing the sustainability of the system, especially when powered by limited solar energy.

#### V. SOLAR POWER INTEGRATION

The integration of solar energy into the AWG system makes it a sustainable and off-grid solution, particularly suited for rural and water-scarce regions. The solar setup provides continuous, renewable power to run the key components including the compressor, fan, controller, and purification units.

**Solar Panel Setup:** A PV panel array, typically rated between 100W depending on geographic location and average solar irradiance, is deployed to harness solar energy. The panel orientation and tilt are optimized for maximum solar exposure (usually south-facing in India with a tilt angle equal to the local latitude). Monocrystalline panels are preferred due to their higher efficiency, though polycrystalline panels offer cost benefits.

**Charge Controller and Battery Storage:** A solar charge controller either PWM or MPPT type—is used to regulate the flow of electricity from the PV panels to the battery and load. The controller prevents overcharging and ensures safe battery management. A 12V lead-acid or lithium-ion (Li-ion) battery bank is connected to store excess solar energy. This energy storage enables uninterrupted system operation during cloudy weather or at night. Battery sizing (typically 30 Ah) is based on power consumption and desired autonomy period.

Considering system efficiency, panel losses, and cloudy-day margins, the solar system is designed for a peak load of 100–120W. Proper thermal and voltage regulation ensures consistent and safe power delivery. Overall, solar integration significantly enhances the eco-friendliness and deployability of the AWG system in remote or disaster-prone areas without reliable grid access..

## VI. SUITABILITY FOR INDIAN ENVIRONMENT

India's diverse climatic zones offer favourable conditions for AWG, particularly in coastal and semi-arid regions such as Kerala, Maharashtra, Tamil Nadu, and West Bengal, where relative humidity often exceeds 50%, a threshold ideal for efficient condensation-based water harvesting. The system's modular design aligns well with local environmental conditions and ensures year-round performance, even during monsoons and humid summers. Additionally, all key components including compressors, sensors, and purification units are readily available in the Indian market, promoting affordability, ease of sourcing, and low maintenance. This cost-effective adaptability supports localized manufacturing and scalable deployment. Beyond technical feasibility, the solution has profound social impact; it provides a decentralized, sustainable, and renewable water source for rural, tribal, and semi-urban households lacking reliable access to centralized water infrastructure. By leveraging solar energy and smart automation, the system empowers underserved communities with clean drinking water, enhances climate resilience, and aligns with national missions on water security and renewable energy.

## VII. RESULTS AND PERFORMANCE EVALUATION

The smart solar-powered AWG prototype as shown in figure 3: was rigorously field-tested in Jalgaon, Maharashtra, during the monsoon season an ideal timeframe for evaluating water generation performance due to elevated ambient humidity. The region experienced an average relative humidity (RH) of approximately 65–70%, and ambient temperatures hovered around 30°C, closely aligning with dew point conditions necessary for efficient water condensation. Under these circumstances, the system consistently generated 2.2 to 2.4 liters of potable water per day from atmospheric moisture.





Figure 3: Proposed System Structure

The system leveraged cooling-condensation technology enhanced with Arduino-based intelligent control and sensor automation, enabling dynamic adjustment of the compressor operation based on real-time temperature and humidity data. This smart regulation allowed for precise dew point targeting, thereby optimizing energy usage while maintaining high water output. The integrated UV filtration unit further ensured drinking water safety, achieving Total Dissolved Solids (TDS) levels below 100 ppm.

From a power perspective, the solar integration proved reliable and efficient. A 100W monocrystalline PV panel powered the system autonomously, achieving an average solar conversion efficiency of 17–18%. The system's total energy consumption was measured at 0.38–0.4 kWh per liter of water produced, demonstrating high thermal and electrical efficiency. Even under intermittent cloud cover, the battery storage system provided seamless operation for up to 10 hours, making it resilient for off-grid applications. These findings tabulated in table 1: affirm the system's technical feasibility and sustainability, particularly for rural and semi-urban communities across Indian climatic regions with moderate to high humidity.

Table 1: Performance Evaluation Table

Parameter	Observed Value	Remarks
Average Relative Humidity	65%	Moderately high, ideal for condensation
Ambient Temperature	30°C (avg.)	Close to dew point, enabling efficient cooling
Water Yield	~2.2 – 2.4 liters/day	Slightly lower vs. Pune due to lower RH
Solar Panel Rating	180W	Monocrystalline, off-grid compatible
Solar Efficiency	17% – 18%	High solar irradiance in Jalgaon
Energy Consumption	0.38 – 0.4 kWh/liter	Smart control minimizes power wastage
Water TDS (post-filtration)	< 60 ppm	Safe and compliant with WHO potable standards
System Autonomy	~10 hours	Battery backup supports cloudy periods



**VIII. ADVANTAGES AND LIMITATIONS****Advantages:**

1. Off-Grid Renewable Operation: The system is fully powered by solar energy, making it ideal for deployment in remote or rural areas without reliable access to electricity. This off-grid capability reduces dependency on fossil fuels and helps combat water scarcity sustainably.
2. Real-Time Environmental Sensing and Automation: Equipped with humidity and temperature sensors, the system intelligently monitors ambient conditions to optimize condensation and water collection.
3. Modular and Scalable Architecture: Designed with modular components, the system can be easily scaled from household-level deployment to community-based installations.
4. Water Quality Assurance: Integrated UV filtration systems ensure the water produced meets potable water standards, with low TDS levels, making it safe for drinking and daily use.

**Limitations:**

1. Reduced Efficiency in Arid Climates: In regions where relative humidity frequently falls below 30%, the system's water production capacity declines significantly, making it less effective in dry desert-like zones.
2. Maintenance Requirements: Periodic maintenance of filters, drainage lines, and refrigeration systems is necessary to ensure long-term performance and hygiene.

**IX. CONCLUSION**

This research successfully demonstrates the design, development, and field-testing of a smart, solar-powered AWG utilizing an efficient cooling condensation method optimized for Indian environmental conditions. The integration of renewable energy through PV panels, combined with intelligent control via Arduino microcontroller and real-time environmental sensing, results in an autonomous and sustainable water harvesting solution. The system has shown a reliable yield of 2.2 to 2.5 liters per day in regions with an average relative humidity of 65–70%. The architecture's modularity, sensor-driven control logic, and low operational energy requirements (0.38–0.4 kWh per liter) ensure its scalability and practicality for deployment in rural, semi-urban, and off-grid regions. Moreover, the incorporation of UV and RO filtration ensures safe and potable water directly from ambient air, without dependency on traditional sources. The system contributes significantly to addressing pressing water scarcity issues, particularly in monsoon-prone and coastal zones of India.

Future enhancements may include IoT-enabled data logging, AI-based predictive control for yield optimization, and multi-stage filtration integration to adapt to varying air quality conditions. Thus, the proposed AWG system presents a viable, low-cost, and environmentally resilient technology for decentralized water generation in developing regions worldwide.

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