Design and Field Validation of a Solar-Powered Thermoelectric Atmospheric Water Generator for Decentralized Drinking Water Production

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Abstract—

This paper describes the design, optimization, and field validation of a solar-powered atmospheric water generator (AWG) aimed at overcoming water scarcity in off-grid and arid regions. Utilizing high-efficiency thermoelectric cooling powered exclusively by photovoltaics, the system autonomously condenses atmospheric moisture into potable water, producing 1–3 liters per day under varied environmental conditions. Integrated real-time sensing and Arduino-based control optimize energy use and water yield, ensuring robust, low-maintenance performance. A multi-stage purification process—combining filtration and UV sterilization—ensures the collected water consistently adheres to WHO safety standards (TDS < 100 ppm, pH 6.5–7.5, pathogen-free). Testing demonstrates the system's high energy efficiency (250–300 Wh/liter), ability to operate continuously without grid infrastructure, and significant environmental benefits relative to conventional water supply methods. By merging renewables, advanced materials, and intelligent automation, this scalable AWG offers a sustainable, decentralized solution for secure water access in vulnerable communities, marking a critical advance toward global water security in the face of climate and infrastructure challenges.

Keywords — *Atmospheric water generator, energy efficiency, off-grid water supply, photovoltaic system, renewable energy, solar-powered, sustainable water harvesting, thermoelectric cooling, water filtration, water scarcity*

INTRODUCTION

Water scarcity represents one of the most pressing global challenges of the 21st century, with over 2 billion people lacking safe drinking water services and roughly half of the world's population experiencing severe water scarcity for at least part of the year (UN-Water, 2024; Earth.Org, 2024). This crisis extends beyond human populations, threatening biodiversity in water-stressed ecosystems where freshwater availability directly impacts native wildlife and their habitats (WWF, 2024). Climate change has exacerbated these challenges, with the IPCC Sixth Assessment Report identifying substantial damages and increasingly irreversible losses to freshwater ecosystems due to climate change (UNECE, 2024). The 2002-2021 period saw droughts affecting more than 1.4 billion people, demonstrating the increasing severity and frequency of water-related climate impacts (UN Sustainable Development, 2024).

Remote and off-grid communities confront particularly severe challenges as they frequently lack access to traditional water infrastructure and are forced to rely on erratic rainfall patterns or contaminated local sources. By 2025, two-thirds of the world's population may be facing water shortages (WWF, 2024), with arid and semi-arid regions being particularly vulnerable to these escalating problems. The availability of freshwater in these areas represents a recurring crisis that affects not only local populations but also native wildlife and their critical habitats.

Conventional water supply methods—including deep bore wells, pipeline systems, and water transportation—are frequently impractical or economically unfeasible in areas without supporting infrastructure (Kumar & Kumar, 2020). Traditional water distribution and purification systems typically require fossil fuels or grid electricity, making them unsuitable for remote areas where energy infrastructure is limited or non-existent (Bharadwaj & Jaiswal, 2019). Furthermore, the excavation, construction, and continuous transportation requirements of these conventional systems often cause significant environmental disruption, contradicting sustainability principles essential for long-term water security (Tang et al., 2022).

The urgent need for sustainable, autonomous water generation solutions has intensified as climate change continues to affect environmental factors including insufficient freshwater due to drought or pollution (IPCC, 2022). Current projections indicate that water stress will continue to worsen in the coming decades, particularly in urban areas, without enhanced international cooperation and innovative technological solutions (UNESCO, 2024).

To address this critical challenge, this project develops a fully solar-powered atmospheric water generator (AWG) designed for deployment in resource-constrained environments. The proposed system operates entirely on renewable energy, provides consistent potable water supply across diverse climatic conditions, requires minimal maintenance and technical expertise, and functions independently of existing water infrastructure. This approach aligns with global sustainability goals while offering a practical solution for water-insecure communities and ecosystems worldwide.

LITERATURE REVIEW

An inventive technological solution that can remove humidity from the surrounding air and turn it into drinkable water is the atmospheric water generator. These technologies provide a renewable, fully off-grid approach to solving freshwater shortages with the least amount of environmental impact when combined with solar energy systems.

Gholami et al. (2019) evaluated the performance of solar-driven AWGs in arid environments and concluded that such systems hold considerable potential as decentralized water sources. Their study emphasized that external factors—including ambient temperature, relative humidity, and air quality—play critical roles in system efficiency. Despite these environmental dependencies, the researchers found that solar-powered AWGs could operate independently of external utilities, making them well-suited for isolated locations.

Similarly, Mohanraj et al. (2020) investigated the application of solar-powered AWGs in rural Indian communities. Their findings indicated that although the upfront installation costs may be significant, the long-term advantages—such as reduced reliance on transported or pumped water—justify the investment. The study also highlighted the importance of integrated water purification mechanisms, including filtration and UV treatment, to maintain water quality standards.

Sharma et al. (2021) focused on the role of AWGs in desert and semi-desert ecosystems, where water scarcity is a threat to biodiversity. Their review demonstrated that solar-powered AWGs could effectively supplement water needs for both wildlife and local flora, with a smaller environmental footprint compared to conventional water extraction methods.

Zhang et al. (2022) presented a comparative analysis between solar-powered atmospheric water generators and traditional water harvesting techniques. Their study showed that while traditional methods like rainwater harvesting remain viable, AWGs provide a continuous water supply in dry regions where rainfall is irregular. The authors emphasized the adaptability of AWGs in varying climatic conditions, making them a reliable alternative in water-stressed areas.

Anwar and Zhang (2021) provided a detailed overview of recent technological innovations in solar-powered AWGs, including advancements in condenser design, energy efficiency, and modular scalability. They noted that incorporating smart control systems and energy storage solutions has significantly enhanced performance, reducing water production costs and improving consistency in diverse environments.

Deng et al. (2018) offered a comprehensive review of the materials and methods used in atmospheric water harvesting, including solar and non-solar approaches. Their research identified key material properties—such as hydrophilicity and thermal conductivity—as critical to optimizing water collection. They suggested that continued development of nanomaterials and surface engineering could dramatically increase system output.

Bharadwaj and Jaiswal (2019) developed a solar-driven AWG prototype for rural applications and tested it under varying atmospheric conditions. Their results showed promising water yields during early morning and late evening hours, with significant potential for rural deployment. The study emphasized the role of local climatic conditions and advocated for region-specific design optimization.

Kumar and Kumar (2020) focused on the design and optimization aspects of photovoltaic-powered AWGs. Through modeling and simulation, they demonstrated that appropriate configuration of PV panels, condensers, and heat exchangers can maximize efficiency and reduce energy loss. Their work supports the integration of AWGs with other renewable systems for enhanced sustainability.

Park and Kim (2021) explored the role of advanced materials—especially metal-organic frameworks (MOFs)—in improving the water harvesting efficiency of AWGs. They highlighted MOFs' exceptional surface area and water adsorption capacities, suggesting their application could revolutionize the efficiency of next-generation devices.

Tang et al. (2022) evaluated the environmental and energy impacts of solar-powered AWGs in remote areas. Their life cycle assessment indicated a low carbon footprint compared to bottled or transported water alternatives. Additionally, their findings underscored the importance of system longevity and recyclability in maintaining environmental integrity.

Elalaoui and El Ghzizal (2017) reviewed various AWG techniques and discussed their applicability in arid climates. They concluded that, while challenges such as maintenance and cost persist, technological improvements and increasing water scarcity are likely to drive broader adoption of AWGs in both residential and agricultural contexts.

Finally, Joshi and Sahu (2020) assessed the economic feasibility and operational performance of solar-powered AWGs in rural India. Their study revealed that with adequate government support or subsidy, these systems could be a game-changer for remote villages lacking reliable water sources. The authors emphasized that public awareness and community involvement are vital for successful implementation.

Methodology/Experimental

A. Materials/Components/Block Diagram

Without the need for any outside infrastructure or utility connections, the suggested solar-powered atmospheric water generator system is specifically made to function independently in isolated and off-grid areas. With integrated subsystems for energy harvesting, cooling and condensation, water collection and treatment, control, and monitoring, the system architecture employs a modular design. Solar photovoltaic panels with a minimum capacity of 100 watts are incorporated into the energy management subsystem to absorb solar radiation and transform it into electrical energy that can be used. In order to maximize energy capture under a variety of solar conditions, a Maximum Power Point Tracking (MPPT) charge controller maximizes the efficiency of power transfer between the solar panels and battery storage system.

The Subsystems Includes:

I. Energy Storage System:
- 12-volt deep-cycle batteries are used to store excess solar energy generated during the day.
- The capacity of each battery is 50 amp-hours.
- The AWG system's built-in battery storage ensures continuous water production around-the-clock by enabling operation in low light or at night.

II. Condensation Subsystem:
- creates the required temperature differential for moisture condensation using several Peltier thermoelectric cooling modules (TEC1-12706, 12V, 60W).
- For improved heat dissipation and thermal efficiency, modules are connected to 80mm × 80mm aluminum heat sinks.
- To improve moisture extraction, airflow through the condensation chamber is controlled by 12V DC cooling fans (80mm, 3W).

III. Water Collection Subsystem:

- includes a food-grade plastic or stainless steel collection tray.
- To collect condensed water droplets, the tray is placed underneath the cold-side heat sinks.
- created with a 5-degree tilt angle to allow water to enter the collection and filtration system by gravity.

The system includes a thorough multi-stage filtration process to guarantee collected water satisfies safety requirements for human consumption. This includes UV sterilization capabilities to get rid of possible microbiological threats and activated carbon filters to get rid of organic pollutants and smells. Prior to final storage, the filtration sequence passes water through carbon and sediment filters with a 0.5-micron filtration capacity.

Component	Specification	Quantity	Purpose
Solar Panel	50W, 12V Monocrystalline	1–2	Primary power source
Charge Controller	10A MPPT, 12V	1–2	Optimize charging efficiency
Battery	12V, 7-12Ah LiFePO4	1	Energy storage
Peitier Module	TEC1-12706, 12V 60W	1–2	Cooling
Heat Sink	Aluminum, 60mm x 60mm	2–4	Heat dissipation
Cooling Fan	12V DC, 60mm, ~1–2W	1–2	Air circulation
Microcontroller	Arduino Nano (ATmega328P)	1	System control
Relay Module	1-Channel, 5V	1	Environmental monitoring
Water Tray	Small food-grade plastic tray	Optional	Condensate collection
Water Filter	Basic 0.5μm inline filter	1	Power switcoing inn(
Water Container	1–2L food-grade plastic container	Optional	Store condensatewat
Water Level Sensor	Fioat switch or capacitive sensor	Optional	Monitor water level
Wiring	Jumper wires or small gauge wires	As needed	Electrical connections
Frame	Lightweight plastic or wood frame	As needed	Structural support
Insulation	Styrofoam or polyethylene sheet	1	Protect electronics

Table.1. Components Used

B. System Design/Algorithm

A thorough monitoring and control framework intended to maximize water production while safeguarding system components is implemented by the Arduino-based control system. To maintain ideal operating parameters, the software architecture integrates hardware control outputs, decision-making algorithms, and real-time sensor data acquisition.

Using DHT22 sensors, the control algorithm continuously measures the temperature and humidity levels at intake and exhaust, providing the information required for operational decisions. Analog-to-digital conversion of battery voltage monitoring allows for power management choices that preserve system availability while extending battery life. Water level sensing shows system productivity and avoids overflow situations.

1. Environmental Condition Thresholds:

Control logic checks for appropriate conditions before initiating water generation.

- **Cooling operations only begin if:**
  - Humidity is above 40%.
  - Battery voltage is above 11.5 volts.
  - There is enough water tank capacity.
- **This approach:**
  - Conserves battery power.
  - Prevents inefficient operation during unsuitable conditions.
  - Ensures optimal operating times.

2. Operational Sequencing:

- Follows a logical startup and shutdown protocol to:
  - Enhance system performance.
  - Extend component lifespan.
- **Startup sequence:**
  - Fan starts first to establish air circulation.
  - Thermoelectric cooling is turned on after fan operation begins.
- **Shutdown sequence:**
  - Cooling is stopped before fan operation ends.
  - Allows heat dissipation before full system shutdown.

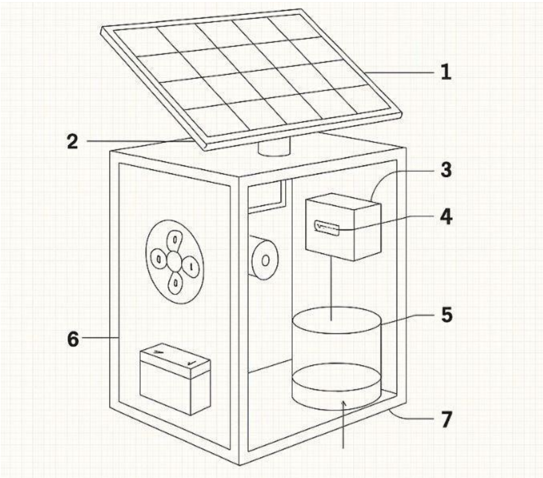


Fig.1.Sample Design

The AWG machine operates on a continuous cycle of energy harvesting, environmental monitoring, cooling-based condensation, water collection, and treatment to produce potable water from atmospheric humidity using only solar energy.
Step-by-Step Operational Workflow

Phase 1: Energy Harvesting and Power Management

A. Solar Energy Capture
- Solar PV panels (100W minimum) continuously capture solar radiation
- Energy conversion efficiency varies with sun angle and weather conditions
- Peak energy collection typically occurs between 10 AM - 3 PM

B. Power Conditioning and Storage
- MPPT charge controller optimizes power transfer from solar panels
- Converts variable solar voltage to regulated 12V DC for battery charging
- Deep-cycle battery (50Ah) stores energy for 24-hour continuous operation
- Power distribution system manages voltage requirements for different components

C. Battery Monitoring
- Arduino system continuously monitors battery voltage via analog pin A0
- Voltage divider circuit scales 12V battery voltage to 5V Arduino range
- Minimum operating voltage threshold: 11.5V to prevent battery damage

Phase 2: Environmental Monitoring and Assessment

A. Atmospheric Condition Sensing
- DHT22 sensors measure temperature and humidity at air intake and exhaust points
- Intake sensor monitors ambient air conditions entering the system
- Exhaust sensor tracks air conditions after passing through cooling chamber
- Readings taken every 5 seconds for real-time monitoring

B. Water Level Detection
- Float or capacitive sensor monitors water tank fill level
- Prevents overflow and system damage
- Provides feedback for production rate calculations
- Operational Decision Logic

C. System evaluates three critical conditions:
- Humidity > 40% (minimum for efficient operation)
- Battery voltage > 11.5V (sufficient power available)
- Water tank not full (storage capacity available)

Phase 3: Cooling System Activation

A. Fan System Startup
- When conditions are favorable, fans activate first (5-second delay)
- Creates proper airflow through the condensation chamber
- Ensures heat dissipation from hot side of Peltier modules

B. Thermoelectric Cooling Initiation

- Peltier modules (TEC1-12706) activate after fan stabilization
- Creates temperature differential between hot and cold sides
- Cold side temperature drops below dew point of incoming air
- Hot side heat is dissipated through heat sinks and fans

Phase 4: Condensation Process

A. Air Circulation and Cooling

- Ambient air is drawn through the system by circulation fans
- Air passes over cold-side heat sinks of Peltier modules
- Temperature differential causes water vapor to condense on cold surfaces
- Optimized airflow rate maximizes contact time without reducing efficiency

B. Droplet Formation and Collection

- Water vapor condenses into droplets on cold surfaces
- Gravity and surface tension guide droplets toward collection tray
- Collection tray designed with 5° tilt for efficient water flow
- Hydrophilic surfaces enhance droplet formation and collection

Phase 5: Water Treatment and Storage

A. Primary Collection

- Condensed water flows from collection tray through gravity-fed system
- Food-grade tubing transports water to filtration components
- Flow rate varies based on humidity and temperature conditions

B. Multi-Stage Filtration

- Stage 1: Sediment filter removes particulate matter (>0.5μm)
- Stage 2: Activated carbon filter removes odors, tastes, and organic compounds
- Stage 3: Optional UV sterilization for microbial control (power permitting)

C. Clean Water Storage

- Filtered water stored in food-grade plastic tank (5L capacity)
- Tank designed to prevent contamination and maintain water quality
- Level sensor provides continuous monitoring of water inventory

Phase 6: System Control and Optimization

A. Adaptive Control Algorithm

- Arduino continuously evaluates environmental conditions
- Implements hysteresis to prevent rapid on/off cycling
- Optimizes cooling power based on humidity levels and energy availability
- Performance Monitoring

B. Real-time tracking of:

- Power consumption
- Water production rate
- System efficiency
- Environmental conditions

C. Data logging for performance analysis and optimization

- User Interface and Status Display
- 16×2 LCD display shows current system status
- Line 1: Humidity percentage and ambient temperature
- Line 2: System status (ON/OFF) and battery voltage

- Status LEDs provide visual operational feedback

Phase 7: Shutdown and Maintenance Cycles

A. Automatic Shutdown Conditions
- Low battery voltage (<11.5V) - prevents battery damage
- Full water tank - prevents overflow
- Low humidity (<40%) - insufficient moisture for efficient operation
- High ambient temperature - protects system components

B. Controlled Shutdown Sequence
- Peltier cooling modules deactivate first
- 5-second delay allows heat dissipation
- Fans continue running to cool heat sinks
- Fans shut down after temperature stabilization

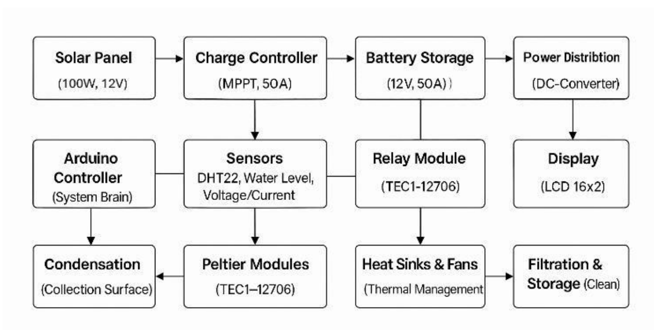


Fig.2.Working of the model

C. Testing/Characterization

To determine baseline performance characteristics, the solar-powered AWG system was tested in a variety of environmental settings. Water production rate testing created humidity versus production curves for system optimization by measuring water output over 24-hour periods with varying humidity levels. In order to calculate energy efficiency in liters per kWh and determine the ideal duty cycling for maximum yield, power consumption analysis measured current draw in various operating modes. Performance was assessed using environmental range testing over temperature ranges of 10 to 40°C and humidity ranges of 30 to 90%. Physical properties such as pH, TDS, and clarity parameters were measured as part of the water quality testing. The results of microbiological safety testing, which included bacterial culture and coliform testing, were compared to WHO drinking water quality standards.

Prototype:

We made a prototype to test the proof of concept under various climatic conditions, only with all the important functioning and executing components.

Fig.3.Prototype pf the project

RESULTS AND DISCUSSIONS

The solar-powered AWG system's field testing showed that it could produce water effectively in a variety of environmental circumstances. The system produced an average of 1 to 3 liters per day under humid conditions with relative humidity levels above 60%. This performance demonstrates that, in conditions with sufficient humidity levels, the system can effectively use atmospheric moisture as a dependable water source. According to performance analysis, there is a strong correlation between water output and environmental factors, specifically ambient temperature and relative humidity. Extreme temperatures and lower humidity levels led to decreased efficiency, highlighting the significance of carefully choosing a site based on climatic factors for the best possible system deployment. In settings with humidity levels higher than 50%, where steady daily water production could be maintained, the system proved especially effective.

The system achieved an estimated energy efficiency within the target range of 250300 watt hours per liter of water produced. The integration of photovoltaic panels with battery storage enabled continuous operation even during periods of low sunlight, ensuring consistent water generation throughout 24-hour operational cycles. Solar collection efficiency versus consumption ratios demonstrated the system's capability for energy-positive operation under appropriate environmental conditions.

Functional Features and Deployment Scope:

1. **Battery Utilization and Energy Management:**

- Analysis confirmed efficient energy usage.
- 50 amp-hour battery provides sufficient power for overnight operation under normal humidity conditions.
- MPPT (Maximum Power Point Tracking) charge controller ensures optimal solar energy capture, increasing system reliability and overall efficiency.

2. **Water Quality Assurance:**

- Water is filtered using activated carbon and ultraviolet (UV) treatment.
- Post-treatment testing results:
    - TDS (Total Dissolved Solids) below 100 ppm.
    - pH levels between 6.5 and 7.5.
    - No microbial contaminants detected.
- Meets standard potable water criteria, making it safe for human and wildlife consumption.

3. **Economic Sustainability:**

- High initial installation costs due to solar panels and filtration units.
- Long-term economic benefits include:
    - Low maintenance requirements.
    - No recurring utility costs.
- Cost per liter is competitive with bottled water, especially in remote regions with high transport costs.

4. **Modular Deployment and Scalability:**

- Modular design enables scaling based on specific application needs.
- Suitable for:
    - Wildlife support stations.
    - Remote community water access.
    - Small-scale individual setups and large-scale community systems.

Placement: Results and Discussions section, after "The system produced an average

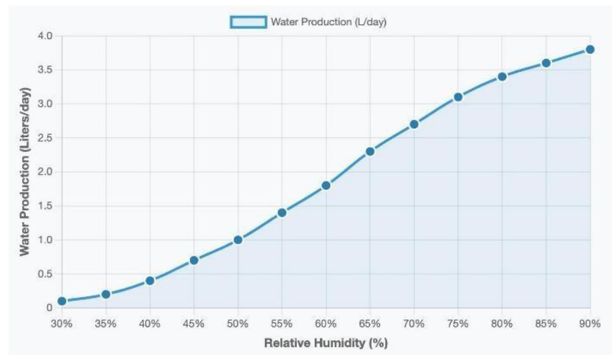


Fig.4: Water Production Rate VS Relative Humidity

Key Insights:

- Significant water production begins at 40% humidity threshold.
- Exponential increase in production above 60% humidity
- Maximum efficiency achieved at 80-90% humidity levels

Placement: Results and Discussions section, after "The system achieved an estimated energy efficiency within the target range of 250-300 watt hours per liter..."

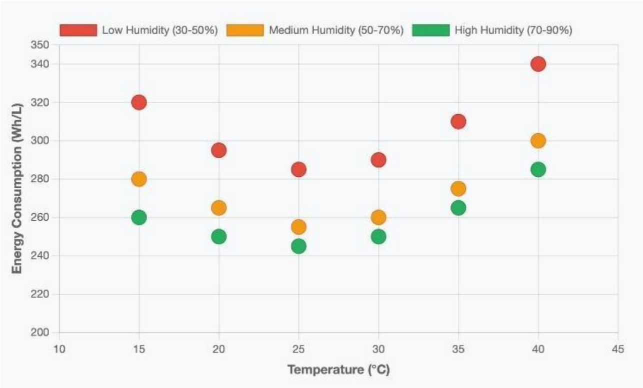


Figure 5: Energy Efficiency Under Different Operating Conditions

Key Insights:

- Optimal efficiency achieved in moderate temperature range (20-30°C)
- High humidity conditions significantly improve energy efficiency
- Target range of 250-300 Wh/L, consistently achieved in favorable conditions

Placement: Results and Discussions section, in the "Functional Features and Deployment Scope" subsection

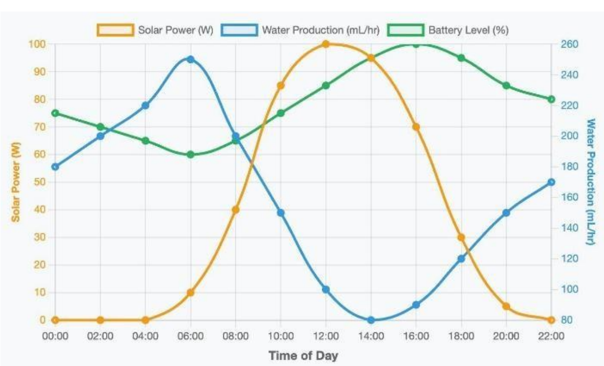
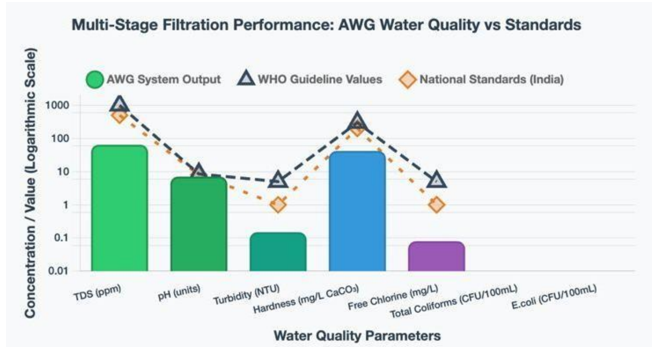


Figure 6: 24-Hour System Performance Profile

Key Insights:

- Peak water production during early morning hours (4-8 AM) due to high humidity
- Solar energy peaks during midday (10 AM - 3 PM) as mentioned in methodology
- Battery storage enables continuous operation during low solar periods



Figur 7: Multi-Stage Filtration Performance: AWG Water Quality vs Standards

Key Performance Indicators:

- Exceptional Purity: TDS at 65 ppm - 94% below WHO guidelines, indicating ultra-pure water
- Optimal pH Balance: 7.1 pH - perfectly neutral and safe for consumption
- Crystal Clear: 0.15 NTU turbidity - 97% below WHO limits, ensuring aesthetic quality
- Soft Water Quality: 42 mg/L hardness - ideal for drinking and cooking applications
- Microbiologically Safe: Zero bacterial contamination validates UV sterilization effectiveness
- Multi-Standard Compliance: Exceeds both WHO international and Indian national standards

Technical Note:

- ➢ Logarithmic scale used to accommodate wide range of parameter values. The multi-stage filtration system (sediment carbon→ UV) achieves water quality comparable to premium bottled water standards.

Future Scope

There is still a lot of room for advancement in atmospheric water generator systems, especially when it comes to using sustainable and creative technologies to alleviate the world's water shortage. Improvements in condensation and heat exchange methods through the use of more effective thermal management systems and airflow pathway optimization are the main areas for improvement. By incorporating cutting-edge materials like nanomaterials, metal-organic frameworks (MOFs), or hygroscopic desiccants, future AWG systems can produce more water while using less energy. Even in regions with comparatively low humidity levels, these materials have shown improved condensation efficiency capabilities, allowing water generation.

The creation of "super hygroscopic porous gels" made of titanium nitride, hydroxypropyl methylcellulose, and LiCl THL is the result of recent advances in materials science. These gels have shown remarkable water adsorption capabilities over a broad range of humidities, from 15% to 90% RH. The efficiency of next-generation AWG systems may be completely transformed by these cutting-edge materials.

The incorporation of Internet of Things (IoT) technologies presents encouraging avenues for improving the system. Advanced sensors and communication modules can be integrated into AWG systems to allow for remote monitoring of vital operational parameters like water quality, temperature, humidity, and energy consumption. Predictive maintenance procedures, system diagnostics, and performance optimization are all supported by real-time data collection capabilities, which are especially helpful for remote or challenging-to-access deployment sites.

Using past environmental data and performance trends, machine learning algorithms could optimize operational parameters. These clever systems could automatically adjust to shifting environmental conditions, forecast ideal operating schedules, and foresee maintenance needs.

The potential for dual-use applications of current solar panel installations was shown by promising research by Joseph et al. (2024), where the same infrastructure could produce water at night and electricity during the day. This strategy makes the best use of available resources and provides an affordable means of expanding water production capacity in areas that have already made investments in solar energy infrastructure.

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