Experimental Study of Solar-Powered Atmospheric Water Generator for Extracting Potable Water from Air

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Supervisor: Dr. Nadia Shahzad

U.S.-Pakistan Centers for Advanced Studies in Energy (USPCAS-E)

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Titled: Experimental Study of Solar-Powered Atmospheric Water Generator for Extracting Potable Water from Air be accepted in partial fulfillment of the requirements for the award of **MS Energy Systems Engineering** degree with (A) grade.

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DEDICATION

I dedicate this thesis to my parents, whom I adore. I sincerely appreciate your consistent support in all my undertakings. There are no words to describe how much I love you both.

₩

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LIST OF SYMBOLS, ABBREVIATIONS AND ACRONYMS

AWG	Atmospheric Water Generator
RH	Relative Humidity
WHO	World Health Organization
DC	Direct Current
m/s	Meter per second
ºC	Celsius
cm	Centimeter
mA	Mili ampere
V	Voltage
W	Watt
TEC	Thermoelectric Cooler
Wh	Watt Hour
Ah	Ampere Hour
NSDWQ	National Standard for Drinking Water Quality
EC	Electrical Conductivity
DO	Dissolved Oxygen

ABSTRACT

Atmospheric water harvesting can be a viable solution to tackle water scarcity. This paper presents an experimental study using solar-powered thermoelectric coolers (TECs) to collect clean atmospheric water at a low relative humidity (RH). The system consists of 4 TEC modules arranged in parallel, coupled with heat sinks on the hot sides and condensers on the cold sides of TEC. The thermal performance of TECs was enhanced by adding fans to heat sinks. The effect of different design parameters was explained and examined. The proposed atmospheric water generator (AWG) can generate 25.5 ml/h at a humidity of 65% in a controlled environment. The results show the highest water generation of 25.5 ml/h at 58.7 relative humidity (RH) and 27.8 °C. The AWH was able to harvest 11.5 ml/h and 14.6 ml/hr at lower RH of 35% and 45%. The quality test was also conducted on the water extracted from this device, showing that all parameters were within the range specified by the World Health Organization (WHO). The study demonstrates the potential of solar-powered AWG systems to provide clean drinking water in low to medium-level humidity regions, ensuring a sustainable framework to avoid scarcity of water in the affected places.

Keywords: Atmospheric Water Generator, Water Scarcity, Thermoelectric Cooler, Water Crisis in Pakistan, Renewable Energy, Clean Water

CHAPTER 1: INTRODUCTION

1.1 Background and Motivation

1.1.1 Overview of the global water crisis

Water scarcity is one of the most critical global challenges in the 21st century, affecting billions of people across the world. According to the United Nations, 2.3 billion people currently live in countries experiencing water stress, and over 733 million live in countries facing severe water shortages [1] [2]. The situation is expected to worsen as the global population grows and climate change accelerates. Projections indicate that by 2050, more than half of the world's population could be living in areas where water scarcity is a reality for at least one month each year [3]. This global water crisis not only threatens human health and economic development but also exacerbates inequalities, as the poorest populations are often the most affected by inadequate water supply and sanitation systems.

Water scarcity is driven by several factors, including population growth, climate change, unsustainable water management, and increasing agricultural demands. Only 2.5% of the world's water is freshwater, and a large portion of this is trapped in glaciers and ice caps, leaving less than 1% accessible for human use [4] [5].

1.1.2 Global Water Scarcity

Water scarcity is one of the biggest 21st Century challenges facing humanity. It occurs in both developed and developing nations but is the most severe in arid and semi-arid regions with already limited water resources. The United Nations says 2.3 billion people live in water-scarce countries and that more than 733 million live in countries with severe water shortages [6], [7], [8], [9]. As the global population rises and agricultural and industrial demands rise, however, this issue is expected to get worse. Climate change also makes the situation worse by changing precipitation patterns and depleting the world's freshwater resources. Global water demand will increase about 20 to 25% by 2050. The number of watersheds with significant annual variability in water supplies (i.e. less predictable water supplies) is expected to increase by 19% concurrently. This is even more worrying in the Middle East and North Africa, where the entire population will be faced with hugely high levels of water stress from mid-century as depict in figure 1-1[8], [10]

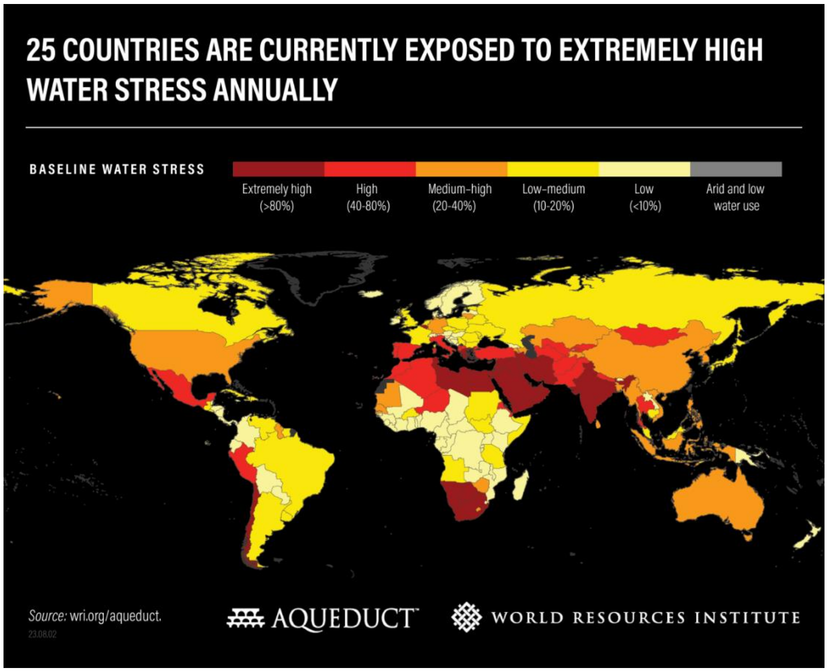


Figure 1.1: By 2050, global water demand is expected to rise by approximately 20% to 25%.[9], [10]

1.1.3 Overview of Global Water Scarcity: Causes and Implications

Water scarcity is mainly caused by population growth, augmented agricultural requirements and expanded industrial provisioning, which further boosts the need for freshwater. More than 70 percent of global freshwater withdrawal is for agriculture, a demand that is growing as population expands as depicted in figure 1.2 [11], [12][13]. Additionally, extractions of groundwater resources in many regions have increased due to urbanization and economic development that typically exceed natural replenishment rates[14], [15] [16] [17] [18]. Especially in the developing countries like Pakistan where agricultural sector plays an important role the issue of water shortage has become severe of both food and health concern[19], [20] [21] [22]

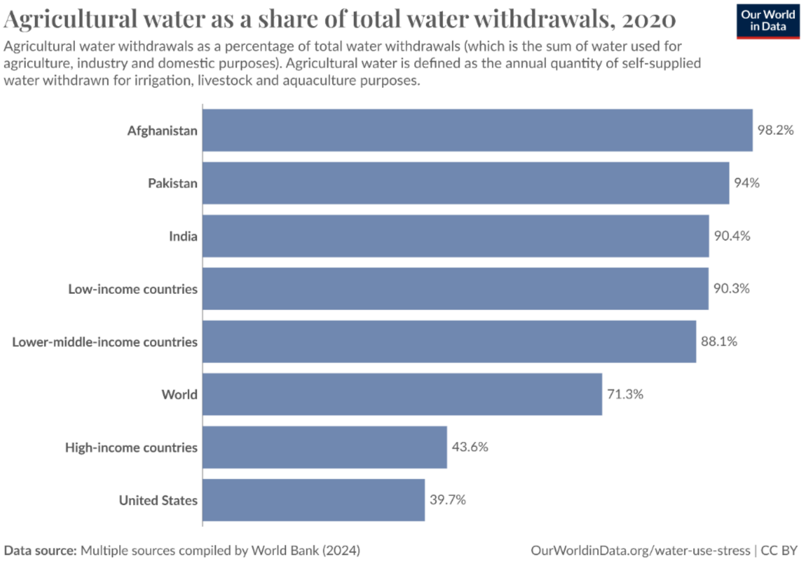


Figure 1.2: Data source: Multiple sources compiled by World Bank (2024) [11]

Water scarcity has far-reaching implications. However, they can and do jeopardize food production and economic stability, as well as adversely affecting inequalities and creating conflicts over water resources. For example, in the Middle East and North Africa (MENA) region, water-related tensions have become a hot spot because the climate is arid and because of shared transboundary water systems[23] Moreover, ecosystem health is directly affected by as many rivers as possible, lakes wetlands, and other wetland systems themselves diminish or entirely disappear leaving negative impacts on biodiversity[24][25]

1.1.4 Explanation of atmospheric moisture as a Potential water Source.

Alternative solutions to this problem are sorely lacking today to resolve the issue of how well and to what extent water is to be supplied for domestic use and irrigation. One of the interesting solutions is in the air, which contains a virtually inexhaustible water supply in the form of vapor. Studies reveal that the water vapor in the Earth's atmosphere amounts to about 13,000 trillion liters and this can effectively address world water needs if only the right technology is applied [26]. Desalination of seawater or the generation of water reservoirs by construction of dams is very expensive, energy consuming, and sometimes geographically and infrastructurally challenging compared to extraction of the water directly from the atmosphere. Atmospheric Water Generation (AWG) technologies rely on the direct conversion of air to liquid dew point water through the process of cooling the air below its dew point [27]. AWG is especially useful in areas of low rainfall, either arid or semi-arid regions where conventional water resources are likely to be a problem.

1.1.5 AWG in addressing water shortages

The use of renewable energy, specifically solar energy in conjunction with the AWG systems, provides a renewable solution to water scarcity. AWG systems that are powered by solar can be used in locations that are designed as independent or/off grid due to their ability to work by themselves in terms of electrical power. Solar energy is more available in many arid areas and the countries like Pakistan, which avail high solar intensity annually [28]. Through harnessing the power of solar energy, it is equally possible to deliver AWG systems that offer clean water to the people without polluting the environment or necessitating ownership of fossil fuels.

TEC technology is widely incorporated in many AWG systems owing to aspects such as simplicity, reliability, and non-mechatronic characteristics which incorporate the AWG system. TEC systems utilize the Peltier effect whereby heat flows between two electrical conductors of separate materials when voltage is connected to develop a temperature differential between the two faces of a thermoelectric component [28]. The cold side of the module is intended to cool the air to temperature below its dew point and that would lead to condensation of water vapor. The condensed water is then collected separately and meanwhile the heat on the hot side of the module is largely dissipated through several heat sinks. TEC based AWG systems are convenient for applications due to their compact size, low operating costs, and insensitivity to environmental conditions.

1.1.6 Current Water Generation and Conservation Methods and Their Limitations

The following approaches are currently being used to mitigate the problem of water scarcity; desalination, rainwater harvesting and construction of water storage basins. But each one of these methods has its merits and demerits and the most prohibitive aspects that are in question today include the cost in terms of the energy used, and the impact on the environment.

- **Desalination**

Desalination has become popular especially in regions with limited water supply around the coast, especially the GCC countries[29]. But, water desalination is a process that needs much power and is costly and not friendly to the environment as it creates problems to marine life since it produces high salt concentration water called brine[30] [31]High operating costs and another disadvantage of desalination is that it constantly uses sources of the fossil fuel which brings into question its sustainability [32], [33], [34]

- **Rainwater harvesting**

Another source of water that is employed to support the availability of water resources is rainwater harvesting, which mostly applies to the rain-fed regions, farming and by agriculturalists. Although the use of this method can be cheaper and easy to carry out it greatly depends on local rainfall pattern which has been observed to be unpredictable due to climate change[35], [36], [37]. Hence, the simple process of using rainwater harvesting to provide for households is not very effective for entire districts or during spells of a long drought.

- **Water reservoirs**

Artificial water sources such as dams and artificial lakes are widely built on purpose to store water for intended agricultural production and domestic use. Yet, establishing and sustaining big dams represent huge capital costs and are associated with negative social and eco-social effects including evictions of people and loss of agriculturally productive lands[38] . Evaporation loss from reservoirs is another inefficiency since, especially in hot and arid climates, its primary reservoirs can suffer severe evaporation.

With such challenges, researchers and policymakers have started to look for alternative water generation technologies, including Atmospheric Water Generation (AWG), a renewable and scalable solution for water-scarce regions. In regions with low to moderate humidity, AWG systems extract water directly from the atmosphere and are a promising option for domestic as well as agricultural use[27].

1.1.7 Climate Change and Its Exacerbating Effects on Global Water Resources

Accurately, climate change is exacerbating of global water crisis through changes of precipitation pattern, the frequency, and severity of droughts, and the glacial melt speeding up to supply large peoples with water. Global warming is ramping up the hydrological cycle, leading to more wild weather such as extreme dry spells and bouts of torrential rain, which can all hurt short supplies[39], [40]

In addition, climate change is costing many parts of the world to deplete their groundwater reserves at an accelerated rate. Groundwater, though essential as a critical buffer during times of surface water shortage, is being extracted at unsustainable rates, causing land subsidence and contamination of remaining stores of water with brine[41], [42]. Glacier and ice shrinkage is another and rather alarming one especially for those areas that rely on the melted water as its source of fresh water like the Himalayan[43]

1.1.8 The role of renewable energy in sustainable water generation

Solar is one of the abundant sources of energy in Pakistan where water shortage is a real problem; thus, return flow AWG systems holding distinct promise . These systems have the potential of transforming an independent and renewable water supply both for human consumption and for irrigation into areas that are not easily accessible to conventional water sources such as ravines in the less developed rural and arid regions. This research aims at designing an AWG system that is cheaper and consumes less power than the traditional systems, especially for low to medium humidity conditions. This research has sought to enhance the general performance of a solar energy system connected to TEC technology in a way that increases water production while reducing energy use. In addition, the study aims at ensuring that the water generated is safe for consumption meeting the world health organization (WHO) standard of portable water.

1.1.9 The research's relevance to Pakistan's water scarcity issues

This research could make a positive and significant impact towards solving the water crisis issue in Pakistan and regions which has similar issues. In addition to providing a viable solution to the problem of water shortage, therefore, this research works to address climate change by investigating a sustainable solar-induced AWG system that will also minimize the use of conventional sources of energy.

1.2 Problem Statement

The availability of water is quickly becoming a crisis, even more so in the areas with policing regionally defined medium to low RH. With people massively settled, especially in the regions of the world that are characterized by arid and semi-arid weather conditions, the natural water sources continue to diminish as climate change takes its toll; therefore, many parts of this world are struggling to afford clean water for both domestic and agricultural uses. Desalination, groundwater and reservoir development also have their own limitations in these areas of operation. Desalination is an expensive and energy-demanding process, which has problematic environmental effects, such as the discharge of brine, to make it unviable for areas located in the interior[44]. Pumping of groundwater used intensely in irrigation sectors has resulted in exhaustion of aquifers, reduced availability of water and water quality deterioration in many areas[45], [46]. And water reservoirs are owned by seasonal rains that are normally scarce in areas experiencing climate change; this makes the management of water resources a very hard task[47]. These challenges point to the need for innovative sources of water provision since conventional sources cannot suffice for the increasing demand in water starved countries located in arid and semi-arid zones. Taking these constraints into consideration, there is zero doubt that there is a need for a cost-effective and efficient Atmospheric Water Generation (AWG) machine to address the L/M regions. AWG technology provides a good chance for a new and unconventional source of water to be available to humidity of air and bringing it below dew point for water vapor condensation[48]. However, conventional AWG systems become inefficient in low humidity environments because of the high power it consumes. One consistent approach is using solar energy in combination with Thermoelectric technology for cooling AWG systems hence providing an efficient renewable energy source. This approach is believed to lower operating costs and enhance the ecological potential of AWG systems as feasible for applications in the remote and off-grid zones[28].The goal of this research is to design a portable AWG integrated with solar energy and TEC technology to meet critical water demand in low relative humidity areas at the lowest possible power consumption. Besides, this study will assess the quality of water generated by the system for the purpose of determining the suitability of the water produced by the system to WHO standards of portable water to supply safe water especially for drinking and irrigation in water-deficit areas.

1.3 Research Objectives

The main objective of this study is to design, implement and enhance a solar AWG system with TEC for getting water in regions that have low to moderate RH%. The aim of the research is to develop a more sustainable, low-energy-consuming technology that provides water as clean as WHO recommendations demand. Integrated into the system are TEC solar powered modules of which promise to provide clean and sustainable water than the conventional methods such as water desalination and pumping water from groundwater sources. The TEC modules are placed in parallel and consist of heat sinks and fans to facilitate better dissipation of heat; besides, they are placed at a 33-degree angle to allow naturistic water flow. To achieve the maximum overall energy efficiency in water production and reduce electricity consumption the number of TEC modules, the airflow rate, and the condenser area will be chosen as the optimization parameters. Dew point and energy efficiency will theoretically dictate the optimization process, targeting the lowest possible energy input combined with the highest possible dew point output. Confirmation of the operability of the proposed system will be conducted in the laboratory as well as in real working conditions in areas of low to moderate humidity, like in Islamabad. In addition, water quality testing will be done to confirm that the produced water will be commensurate with the WHO standards for potable water which makes the system ideal for drinking and agriculture. This work is novel for its detailed optimization and practical approach toward using solar energy in AWG system design for water-deficit areas.

- Design and development of a solar-powered AWG system using thermoelectric cooling (TEC) technology.
- Optimization of the system for low energy consumption and maximum water production efficiency.
- Validation of the system's performance in controlled laboratory settings and real-world environments.
- Ensuring water quality meets WHO standards for potable water.

1.4 Research Scope

The research of this work therefore aims and covers the implementation and enhancement of a solar-powered Atmospheric Water Generation (AWG) system that utilizes thermoelectric cooling (TEC) technology. Specifically, the study involves areas with RH of 30% to 65 % RH, including some states of Pakistan and other arid areas where water is a real problem. The study intends to examine the efficiency of generating water by the system in such conditions that desalination and other usual water supply methods are not as effective because of high energy requirements[30], [45], [46] .In turn, the study focuses on such difficult conditions with the aim to offer a renewable and effective solution for the problem of water shortage particularly in rural and remote regions [3], [49].

This work includes theoretical and experimental analysis of the TEC-based AWG system. Analytical models are utilized to estimate the amount of water generated by the material under various relative humidity and temperature regimes, while experimental validation is performed in both laboratory and actual settings. Optimization tests are conducted in the prototype system mainly for evaluating water production efficiency and energy use. The study also presents the new design configurations of the TEC modules like the parallel arrangement of the dissimilar TEC modules, the heat sink structure for better thermal performance and the fan for the better air flow leading to better water collection [27], [28].

Furthermore, the contribution of this study seeks to examine how critical environmental variables, including RH, temperature, and air speed impact with water production. The influence of different RH (35%-65%), temperature changes, and air speed to the system is also investigated. Therefore, by adjusting these parameters this study seeks to enhance the performance of the AWG system to effectively function in low relative humidity areas besides consuming less energy [50], [51].

1.5 Limitations in System Scalability

While the system performance showed that it was possible to scale it to meet the needs of the large-scale water generation projects, there are challenges and limitations which may affect the scaling up of the system. These issues must be solved to make this system more useful for community-based or industrial scale usage.

- **System Complexity and Costs:** When systems are designed to address the requirement of small communities of people or low-intensity industrial uses, the systems may not necessarily have to complicate or cost more when scaled up to address the requirements of larger numbers of people or high intensity industrial uses. This is because as the number of TEC modules, solar panels and energy storage units increase, the capital costs of setting up the system reach astronomical propositions. Besides, thermal load and energy consumption of larger systems can be cumbersome when it comes to their management through engineering.
- **Heat Dissipation and System Performance:** While scaling up the system, other issues such as heat dissipation become challenging and paramount. In the present scheme, heat dissipation is well controlled using heat sinks and fans; however, at a system level, improving thermal control would be necessary to avoid overheating of the TEC modules. Lack of efficient heat management on a large scale would have a negative impact on the efficiency of such a system and its durability.
- **Limitations in Long-Term Durability:** Another important factor is the relative stability of the AWG system in the long run. Although TEC technology has the benefit of having no moving parts so there are no worries about wear and tears and less need for maintenance other parts of the system for instance the solar panel, batteries and heat sinks will gradually deplete over time especially when exposed to bad and unforgiving environments.

- **Durability of Solar Panels and Batteries:** In any case, the panels and the batteries that are employed to feed the system are known to degrade with time. For example, the efficiency of the photovoltaic solar panels used to convert sunlight into electricity reduces with time due to degradation while batteries used to store the electricity reduce on their ability to store electricity because of degradation of their ability to retain the electric charge upon charging. The following could affect the system's functionality in terms of running continuously; Some parts of the systems may need to be replaced after certain intervals of time.

1.6 Thesis Outline

- Chapter 1: Introduction: Provides an overview of global water scarcity, the potential of solar-powered atmospheric water generation (AWG) systems, and the importance of renewable energy for water generation.
- Chapter 2: Literature Review: Reviews existing AWG technologies, particularly TEC-based systems, along with a comparison of various water generation methods and challenges in low-humidity environments.
- Chapter 3: Methodology and Experimentation: Outlines the methodology for designing and setting up the AWG system, including the components used (TEC modules, solar panels, condensers), and explains the experimental process for testing water generation rates and energy efficiency.
- Chapter 4: Results and Discussion: Presents the results of water generation and energy consumption, including the impact of humidity, temperature, and airflow on system performance.
- Chapter 5: Conclusion and Recommendations: Summarizes key findings, discusses contributions to AWG technology, and provides recommendations for future improvements and studies.

CHAPTER 2: LITERATURE REVIEW

2.1 Atmospheric Water Generation (AWG) Technology

The global water crisis is intensifying, and Atmospheric Water Generation (AWG) technologies are a potential solution to generating fresh water from ambient air. AWG technologies harness the earth's climate and exploit the fact that water vapor exists in the atmosphere, condensing it as liquid water, thereby providing an alternative to traditionally used water resources like rivers, lakes and underground aquifers. In areas lacking conventional water sources, unreliable or contaminated, AWG technologies can be particularly useful. This section then explores the history of AWG technologies, compares multiple AWG methods, highlights thermoelectric cooling (TEC) as a viable and novel water harvesting technology, and maps the success of previous AWGs to chart the course for future AWG development.

2.1.1 History of AWG Technologies: Early Methods and Recent Advancements

The idea of totaling water from the air has been around for millennia, most commonly, in the arid and semi-arid zones where water resources are strained. There were early civilizations in the early days, which have proved quite simple techniques of collecting moisture from the atmosphere such as dew collectors, fog nets and Air wells. For instance, the Inca and the Maya peoples-built structures out of stone to capture fog in condensation which could be subsequently harvested for drinking, depicted in figure 2.1 [52].Those traditional techniques have shown that atmospheric water harvesting was possible long before advancement in technology made it more effective on a small scale.

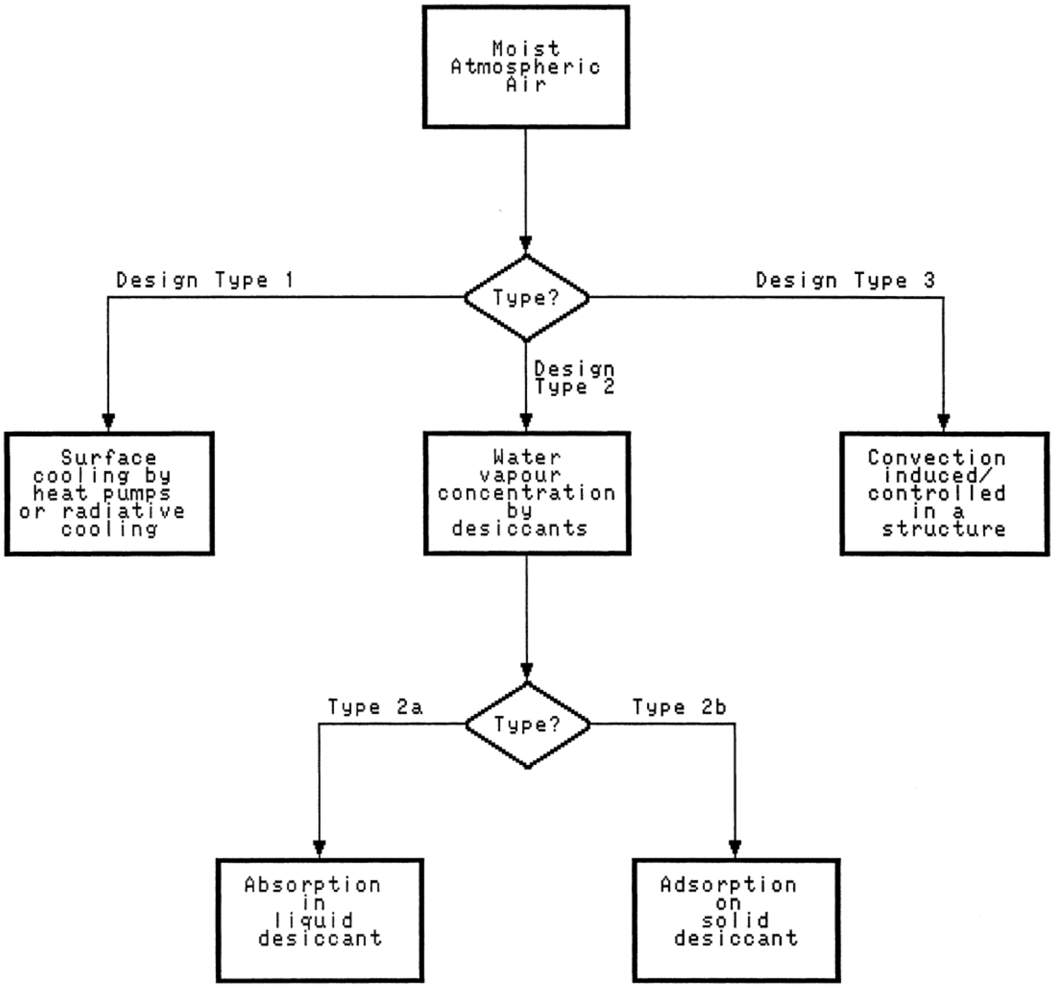


Figure 2.1: Atmospheric Water Condensation different methods [52]

Modern AWG technologies originated in the mid-20th century with the use of cooling technologies. The first systems applied the vapor-compression refrigeration cycle wherein cold ambient air is cooled to a dew point so that water vapor is condensed [53]. These systems were mainly used in industrial and military applications to produce water in areas devoid of water and or hard to access.

Relatively recent developments in renewable energy technologies and the increasing necessity to develop faster and larger AWG systems have prompted advancements made in the AWG systems. However, today, modern AWG systems employ different cooling technologies including vapor compression, absorption chillers, radiative sky cooling, and

Thermoelectric cooling (TEC), all of which have higher efficiency and location-independence[54]

2.1.2 Comparison of Different AWG Methods

The mechanisms of water condensation that are used by AWG technologies are all different, and each comes with benefits, disadvantages and applications. Vapor compression, absorption chillers, radiative sky cooling and thermoelectric cooling (TEC) are the four primary AWG methods.

- **Vapor Compression:** It is the most popular commercial AWG method. Depicts in figure 2.2. Vapor compression AWG systems cool ambient air to the dew point below which put refrigerant(s) and vapor to conditions whereby water vapor condenses from the air. These systems are effective but rely on a heavy energy load for compressors and other components and have limited scalability in an off grid or resource constrained setting. Vapor compression systems are also expensive to install and maintain [55][56]

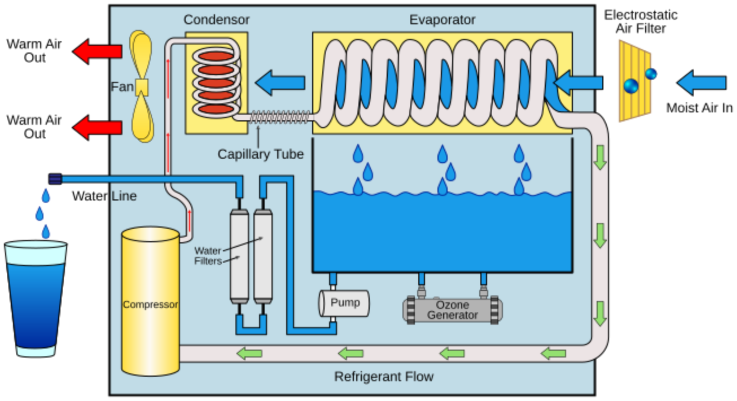


Figure 2.2: Vapor compression AWG systems[55]

- **Absorption Chillers:** Absorption based AWG systems generally using a liquid refrigerant, e.g. water or lithium bromide, cooling air and condensing water vapor. Because these systems use waste heat or solar power to drive the absorption process, they are more energy efficient than vapor compression systems.

Absorption chillers, although more complex and larger, are often too large for portable and small-scale applications. Their frequent use is in industrial processes where waste heat is available [57], [58]

- **Radiative Sky Cooling**: Radiative sky cooling, like this is a relatively new method of integrating AWG which employs Earth surface radiation at infrared wavelengths. Heat is radiated away from the surface to space, through use of special materials such as metamaterials or highly emissive surfaces that cool the surface below ambient air temp as shown in Figure 2.3. When it cools the surface, it allows water vapor to condense. Though this method is energy efficient, not requiring electrical input, its effectiveness is limited by environmental factors including cloud cover and nighttime operation [59], [60], [61], [62], [63]. Radiative cooling is still in the experimental phase and has not yet been widely commercialized.

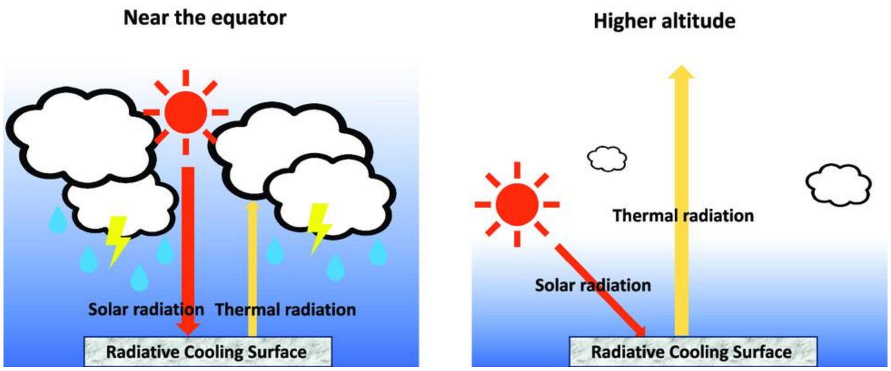


Figure 2.3: Left: illustration of the weather condition near the equator relevant for radiative cooling. The outgoing thermal radiation is highly attenuated by the opaque atmosphere and the heavy clouds. Right [64], [65]

- **Thermoelectric Cooling (TEC):** The Peltier Effect is used by TEC systems to produce a temperature gradient between two plates, and to cool one side while the other heats up. Water vapor on the ambient side of the TEC module is condensed into a liquid on the cooled side. TEC systems are highly portable, quiet with no moving parts, and thus perfect for small scale or off grid applications [66] and since TEC systems can be powered using renewable energy such as solar photovoltaic (PV) panels as depicted in Figure 2.4, they are potential means toward sustainable water generation in remote or water scarce areas. Yet TEC systems are more energy wasteful than vapor compression or absorption chillers by more electricity is needed to generate the necessary cooling effect in thermoelectric [27], [66], [67].

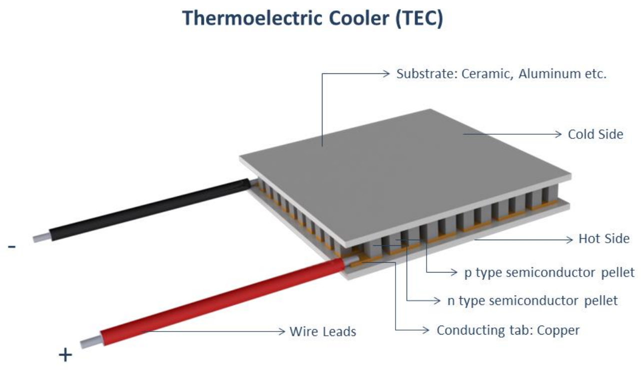


Figure 2. 4: Thermoelectric Cooler [68]

2.2 Thermoelectric Cooler (TEC) Systems

Because they are simple and do not require complex mechanical parts, Thermoelectric Cooler (TEC) systems are emerging as promising technology for Atmospheric Water Generation (AWG). Peltier effect-based TEC systems tap into the phenomenon to separate the sides of a semiconductor material, creating temperature differences that can evaporate water from the atmospheric environment. This section discusses the working principle of TEC systems, TEC performance factors and a review of some key studies on TEC based water generators; the findings and challenges are reported.

2.2.1 Detailed Working Principles of TEC and the Peltier Effect

The Thermoelectric Cooler (TEC) systems are based on Peltier effect itself as discovered in 1834 by French physicist Jean Charles Athanase Peltier [69], [70]. An electric current coming into two conductors or semiconductors of different thermal conductivities will drive heat from one junction and out the other, an effect known as the

Peltier effect. This creates a temperature gradient: The TEC module becomes one side of that cold, and the other side of the cold becomes One side hot [69]

The standard TEC module is made up of many p type and n type semiconductor pairs (typically bismuth telluride) between a pair of ceramic plates. As shown in Figure 2.6 When a direct current (DC) is applied then electrons spend the energy from the p-type to the n-type material releasing heat at the cold side (cooling junction) and absorbing heat at the hot side (heating junction) [68] .Critical to such applications as water harvesting is the ability to harvest the temperature differential across the TEC module itself; the cold side of the TEC module cools the surrounding air to a temperature less than the dew point temperature, rendering atmospheric water vapor present on the surface, condensing. As compared with traditional cooling technologies, TEC systems have the advantages of having no moving parts (for less maintenance), as well as compactness (suitable for portable applications [71]. In addition, TEC systems can be powered by renewable energy sources (e.g. solar panels) further enhancing the possibility of TEC systems working as sustainable off grid water generating solutions.

2.2.2 Thermoelectric Cooling as a Viable Method for Water Harvesting: Advantages, Limitations, and Applications

Recently, a potential AWG method that has received attention is thermoelectric cooling (TEC), which shows unique advantages and is ideally suited for small scale, sustainable water harvesting applications. Based on the Peltier effect, TEC systems operate using semiconductor devices known as thermoelectric modules, in which a temperature is generated by a current through them. This temperature difference allows cold side of the module to cool air below its dew point, so that water vapor is condensed[72], [73], [74].

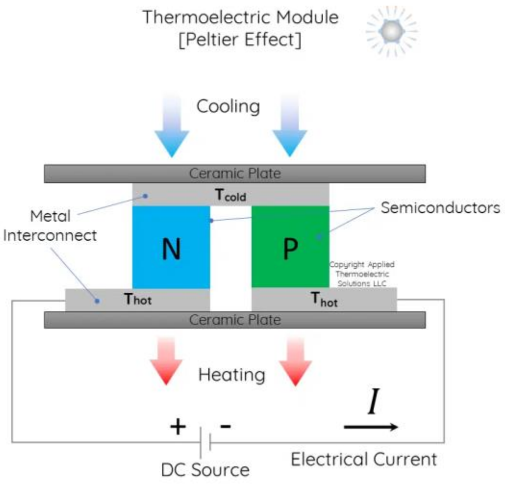


Figure 2. 5: TEC working based on Peltier Effect [75]

Portability and Scalability: Tight packaging, coupled with modular design, allows TEC systems to be tailored for use in portable, small scale water generation. As such, they are highly suited to rural or off grid regions where conventional water infrastructure is unavailable [71].No Moving Parts: Because TEC systems have no moving parts, they can be exceptionally reliable and thus require little or no maintenance whatsoever or be less subject to mechanical failure. This is a major benefit to vapor compression systems which rely on complex components such as compressors and pumps that typically need frequent maintenance [76].Renewable Energy Integration: In fact, solar energy is also a viable power source for TEC systems and, along with polyethylene film, offers a sustainable water harvesting alternative. Active water gas systems driven by solar energy have been successfully installed in remote areas where grid electricity is not available or unreliable, and solar powered TEC based AWG systems can have zero carbon emission and therefore made useful contribution to climate change mitigation efforts.[77], [78]. Energy Efficiency: It is one of the fundamental limitations of TEC systems that their energy efficiency is lower than that of vapor compression and absorption chillers. This results in a high electrical energy requirement for the thermoelectric process to generate the cooling effect necessary, which places a limit on the scalability of TEC based systems for large scale water production [27]. Lower Water Production Rates: The relatively low TEC module cooling capacity results in lower water output quantities in TEC based AWG systems compared to vapor compression systems. This would make TEC systems suitable for personal or household use but their wider adoption in large scale agricultural or industrial uses may be limited [79], [80], [81]

2.2.3 Review of Studies on TEC-Based Water Generators

The use of TEC systems for AWG applications has been investigated by numerous studies with the aim of optimizing water production efficiency, minimizing energy consumption and of optimizing system design. Below is a review of key findings and challenges from recent research in this area.

Kadhimi et al. [82] designed a prototype with a single TEC module dimension (4x4 cm2) depicted in figure 2.6. The prototype was tested using experimental and numerical studies at different air flow rates. All components were assembled in a housing duct with a conical condensing surface to help collect droplets. They showed that raising the airspeed on the hot side of the heat sink significantly increased heat transfer and water collection. Their findings showed the importance of air flow rate optimization for maximizing water efficiency.

Figure 2.6: Single TEC module [82]

M Eslami et al. [83] conducted a thermodynamic analysis on a thermoelectric cooler to produce water from humid air. Their primary focus was optimizing the water yield per unit of energy consumed. The study investigates how several design aspects, such as thermal resistances, fin geometry, the quantity of TECs, channel length, TEC current, and air speed, affect the system. Their system could produce 26 ml water per hour of air at 75% relative humidity at 318 K. The most efficient arrangement in their study uses 18 TECs with a 1.386-meter channel length.

Alenezi et al. [50]. carried out numerical and experimental methods, examining the impact of ambient factors. The device produced 231 mL of water within 8 hours. However, water production increased to 405 mL over the same time when tested under an environmental chamber, set to temperature 313K and RH at 85%. An additional numerical study suggested that, in similar situations, water production might rise to 437 mL/8h. This study showed that raising the air's relative humidity significantly increased the water-harvesting efficiency of the devices.

Joshi et al. [79] carried out an experimental study on a small water generator that used TECs depicted in figure 2.7. During their tests at 30°C with 90% RH, the device generated 1 mL of water per hour while using 60W power. The study also shows a clear correlation between the increase in condenser areas and the increase in the amount of water produced. The device produced a maximum of 240 mL of water in 10 hours by increasing the condenser area. The research highlighted how important it is to maximize flow rates and condensation surface area to increase the effectiveness of thermoelectric water harvesting devices.

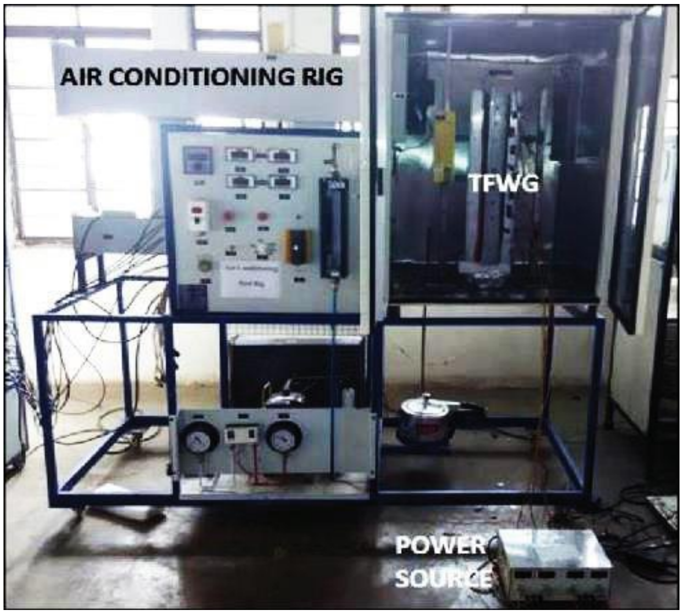


Figure 2.7: Experimental Setup [79]

Zhang et al. [84] An advanced water generator with enhanced dehumidification efficiency was introduced, by introducing the use of heat pipe technology in combination with thermoelectric cooling depicted in figure 2.8. This came up with a very innovative way to get more water out or cooling capacity. Humid air precooled by the heat pipe flows to TEC. A footprint of a 34.11 W increase in maximum cooling capacity and a 38.95 mL/h water generation rate was the outcome of the study.

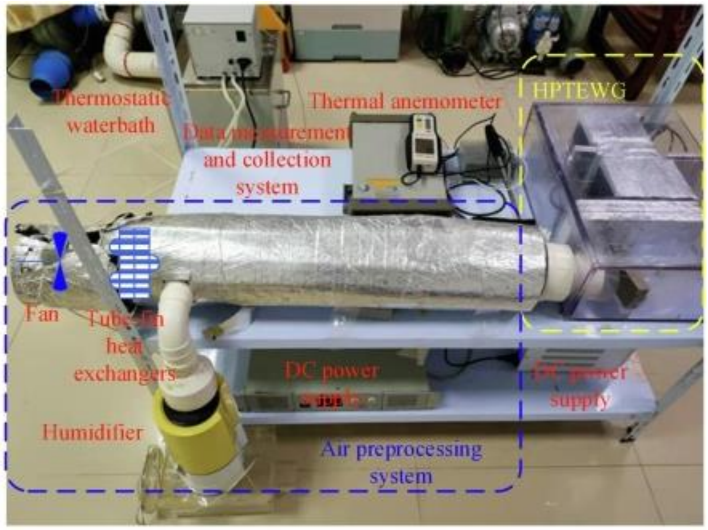


Figure 2.8: Use of heat pipe technology in combination with thermoelectric cooling[84]

The humidity dependence issue is also critical. TEC systems are most efficient in high humidity environments; however, their efficiency decreases sharply in arid climates (low humidity conditions). [50] As such, the deployment of TEC-based AWG systems in regions with low relative humidity remains challenging, necessitating further research into adaptive designs that can function across varying environmental conditions.

2.3 Solar-Powered Water Systems

Readily integrating renewable energy sources, in particular solar power, with Atmospheric Water Generation (AWG) systems is a fundamental step towards developing sustainable and scalable water scarcity solutions. Solar energy is a feasible and green power source to rely on in arid and semi-arid zones where abundance of sunlight is all that exists, except for very few traditional water resources. This section then demonstrates the necessity of solar integration into AWG systems, as well as the recent developments of solar powered Thermoelectric Cooling (TEC) systems, and a study of photovoltaic (PV) systems and energy storage solutions to keep AWG systems continuously running. Several studies have demonstrated the potential of solar-powered TEC systems for water generation:

Nandi et al. [85] In high humidity regions, a solar powered AWG system using TEC modules for condensation of water was designed. The system consisted of three TEC modules and was driven by a 120W photovoltaic panel. In 80% relative humidity conditions it also produced 150mL of water per hour proving that TEC modules could be used in tandem with solar energy. But the study said the system became less efficient in low humidity conditions, when there was less water vapor available for condensation.

John et al. [86] TEC modules were optimized for a portable solar powered water generator. The system was designed to run out in remote areas and produce 2 liters of water in 12 hours when 80 percent humidity. The system was able to run constantly day and night, utilizing the stored energy from batteries when it was dark. The feasibility of using renewable energy to power portable water generators for both domestic and agricultural applications was demonstrated by this study.

Shourideh et al. [76] The application of solar powered TEC systems for water generation was explored in low to medium humidity regions. The system used a battery Storage solution so that they could be continuous, and they were able to produce 18.3 mL of water per hour in medium humidity conditions. Finally, the researchers noted that the design of the TEC system should be optimized for energy efficiency and water production rates.

2.4 Solar-Based AWG and TEC-Based Systems

Thus, a critical analysis of the past studies on solar based Atmospheric Water Generation (AWG) and thermoelectric cooling (TEC) systems is needed, to understand where the field is at, and to highlight limitations and potential in future research. This section provides a critical review of key research papers with a particular emphasis on the various systems explored that are understood and attempted to address the performance shortcomings seen in these systems in low to medium humidity environments. It also improves important gaps in the extant literature, with critical omissions such as absence of optimization for low humidity regions, deficient water quality testing, and almost no consideration for system scalability. There are many studies on solar powered AWG and

TEC based systems, trying to improve energy efficiency, water production rate and system design. But such research is often context driven, with most research concerned with high humidity environments where water vapor is easily available, and condensation is relatively easy to achieve. Below is a critical review of some key studies in this area:

Shourideh et al. [76] explored the performance of a TEC-based AWG system in controlled laboratory conditions, focusing on optimizing the system's cooling performance using TEC modules depicted in figure 2.9. The study demonstrated that TEC-based systems could be effective in generating water in high-humidity environments, producing up to 38.95 mL/h of water. However, the research highlighted that the system's efficiency dropped significantly when operated in low-humidity regions, pointing to the challenges of deploying TEC systems in arid climates where atmospheric moisture levels are limited.

Figure 2.9: Prototype of AWG using TEC[76]

Nandi et al. [85] developed a solar-based AWH system using TECs. This research was conducted in India. They incorporated three Peltier coolers with dimensions of 4x4x0.8cm, a speed fan with 3000 rpm for air circulation, carbon filter papers, an aluminum-based condenser as heat sinks for quick heat dissipation, and a photovoltaic module. The maximum output power was 120 W. The limitation of this device was it could only be used in high humidity regions.

Atta et al. [71] presented a prototype that includes 3 TECs, a solar panel, and aluminum alloy heat sinks for Peltier, each of 15 x 15 cm, and a 12V fan of 6000 rpm that can generate 500 cfm of airflow for forced convection heat transfer shown in figure 2.10.

The prototype was tested in Yanbu's climate. The system was powered by solar cells, ran at a maximum current of 3.6 A, and produced up to 1 L of water per hour. The solar unit supplied a maximum electrical power of 120 watts for 3 TECs. However, this method was insignificant when relative humidity decreased to 20% or below.

Figure 2.10: Water Condensation system [71]

Zhang et al. [84] introduced an advanced water generator intending to improve dehumidification efficiency by coupling heat pipe technology with thermoelectric cooling. This innovative method was designed to increase water output and cooling capacity. The heat pipe precools the humid air before reaching TEC. The study produced an outcome of a 34.11 W increase in maximum cooling capacity and a 38.95 mL/h water generation rate.

M Eslami et al. [87] conducted a thermodynamic analysis on a thermoelectric cooler to produce water from humid air. Their primary focus was optimizing the water yield per unit of energy consumed. The study investigates how several design aspects, such as thermal resistances, fin geometry, the quantity of TECs, channel length, TEC current, and air speed, affect the system. Their system could produce 26 ml water per hour of air at 75% relative humidity at 318 K. The most efficient arrangement in their study uses 18 TECs with a 1.386-meter channel length.

These studies illustrate the progress made in the development of solar-based AWG and TEC systems, particularly in environments with moderate to high humidity. However, the limited testing of these systems in low-humidity environments remains a significant gap in the literature, as many regions experiencing severe water scarcity also face low RH levels.

2.4.1 Research works on Medium Humidity Environments

While most studies focus on high-humidity conditions, some research has specifically investigated the performance of AWG and TEC systems in low to medium humidity environments. These studies are particularly relevant to regions such as Pakistan, where humidity levels can fluctuate between 30% and 65% depending on the season.

John et al.[86] has Designed and optimized a portable atmospheric water harvester using TEC modules as shown in figure 2.11. At 80% relative humidity (RH) system generated 2L of water in 12 hours. The researchers found that integrating TEC modules for small-scale atmospheric water producers is an economical and environmentally benign approach.

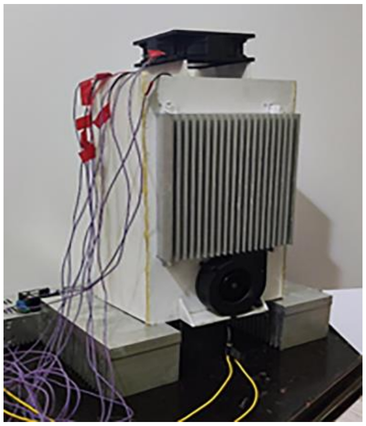


Figure 2.11: Device Testing of AWG[86]

Alenezi et al. [50]. carried out numerical and experimental methods, examining the impact of ambient factors. The device produced 231 mL of water within 8 hours. However, water production increased to 405 mL over the same time when tested under an environmental chamber, set to temperature 313K and RH at 85%. An additional numerical study suggested that, in similar situations, water production might rise to 437 mL/8h. This study showed that raising the air's relative humidity significantly increased the water-harvesting efficiency of the devices.

Liu et al. [88] developed a small device using 2 TECs and tested the performance of it in an experiment. The thermoelectric modules weigh 7 kg, and the system was designed with them placed along the walls of a humid air passage channel. A cooling fan was used to generate the airflow. Airflow rates and the relative humidity (RH) of the air were studied in the effects of effects of the airflow rates and the air's relative humidity (RH) of the air on the condensation and water generation rates. By their estimates, the system could generate 25.1 g of water hour−1 at a peak power input of 58.2 W and 0.216 m2 of surface condensation.

They show how TEC based systems can potentially be operated in low to medium humidity environments, and at the same time point to formidable challenges in operating these systems with consistent water production in such environments. These challenges may be overcome by developing hybrid systems of TEC coupled with other cooling technologies, or by using energy efficient designs, but much more research is required to investigate these possibilities.

2.4.2 Research Gap and Proposed Solution

Many previous works have focused on maximizing the amount of water generation by applying high RH (>65%) values in a controlled chamber; less focus has been given to the area with low relative humidity. Some have also studied the effect of air velocity on condensation, and only a few studies have been conducted to conduct water quality testing. In this work, a self-sustaining solar-powered AWG has been designed which contains an assembly of 4 TECs, 4 condensers, and 4 four heat sinks. Experiments were performed in a closed chamber with various relative humidity values ranging from 35-65% and device testing was also performed in ambient conditions. Moreover, the effect of air speed and relative humidity on the rate of water generation has been studied. The quality of generated water has been thoroughly investigated using turbidity, pH, and mineral tests. Additionally, this device was oriented 33 degrees from the baseline to allow water to flow naturally downward due to gravity ensuring direct collection of water from the device.

CHAPTER 3: METHODOLOGY AND EXPERIMENTAION

This chapter presents a detailed description of the system components, and the methodology used in the design and operation of the solar-powered Atmospheric Water Generation (AWG) system. The focus is on the materials, configuration, and specifications of the components such as thermoelectric cooling (TEC) modules, condensers, heat sinks, fans, solar panels, and energy storage systems. Understanding these components is critical to optimizing the system for efficient water generation under varying environmental conditions.

3.1 Design of the Solar-Powered AWG System

To ensure efficient water condensation and the operating sustainability of the solar-powered Atmospheric Water Generation (AWG) system, the design and assembly of the solar-powered Atmospheric Water Generation (AWG) system are important. In this section, the key system components are described and configured, and the assembly process is detailed as depicted in Figure 3.1. This system works on thermoelectric cooling (TEC) technology using solar panels, along with a series of heat sinks, condensers, and fans to optimize water production during different environmental conditions.

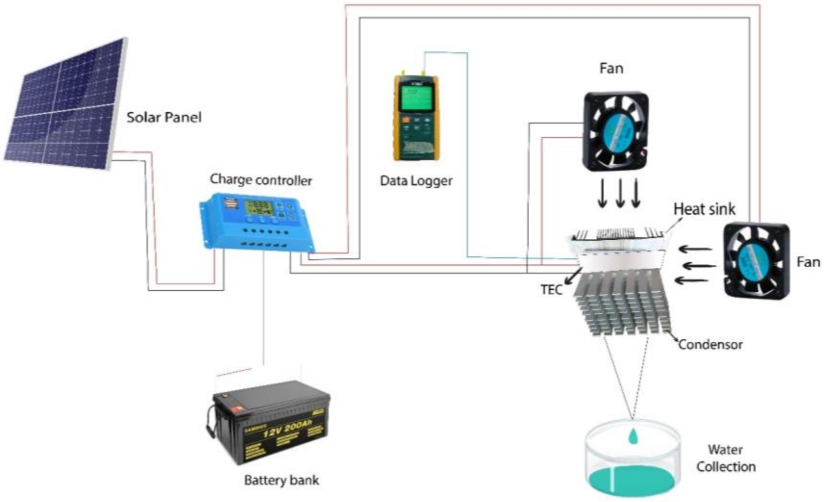


Figure 3.1: Schematic Diagram of Atmospheric Water Harvester

3.2 Description of Key System Components

Table 3.1: Components of the Experimental Apparatus

Components	Material	Dimension	Other Specifications
Peltier Module	Ceramic	40mm x 40mm x 3.6mm	Max Voltage: 12V Max Current:3.4A
Cold Side Heatsink	Aluminum	40mm×45mm×30mm	-
Hot Side Heatsink	Aluminum	75mm×75mm×85mm	-
DC Fan	Plastic	92mm×92 mm×25mm	Max Voltage:12V Max Current:0.4
Solar Panel	Polycrystalline	1.6m×1m×0.04m	Output Power: 280 watts
Battery	Lithium Ion	180mm×75mm×70mm	Voltage: 12V Battery Capacity: 200Ah

- *TEC Modules:* The thermoelectric cooling (TEC) modules, which are the heart of the AWG system, are Peltier operated. In these modules, when a current passes through them, they create a temperature difference and they'll have a cold surface, so actually they cool down the surrounding air colder than the dew point and the water vapor is going to condense. Using four TEC modules, water production was optimized to the greatest extent possible in this system. Connected in parallel to maximizing cooling efficiency, each module is powered by a 12V DC power supply and only consumes 3.4A of current.

Figure 3.2: Thermoelectric Cooler TEC1-12706[69]

- *Heat Sinks:* The TEC modules are mounted on both sides in the cold and hot sides to ensure efficient heat dissipation, and to prevent thermal buildup. On the cold side, a small aluminum heatsink 40mm x 45mm is placed for increased water condensation surface area to prevent ice forming and increase water collecting. To dissipate the heat produced by the TEC modules, a larger aluminum heat sink, 80mm × 75mm, is installed on the hot side. It keeps the temperature differential needed to get efficient cooling.

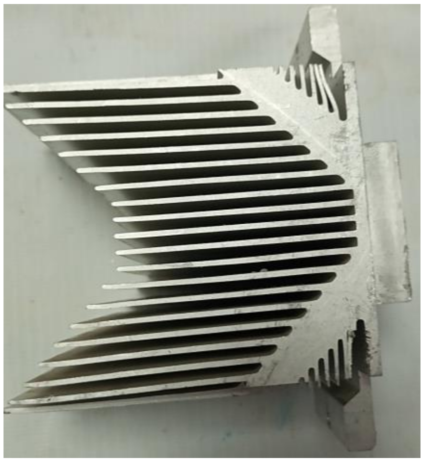


Figure 3.3: Heatsink for Heat Dissipation

- *Fans:* The system has four 92mm x 92mm x 25mm fans integrated to increase convection heat transfer and improve airflow. The hot heat sinks are supplied with two fans to accelerate heat dissipation and the TECs are supplied with two additional fans placed in the air inlet to promote water condensation of the cold surfaces of the TECs. The fans are 12V powered the same supply, with each fan drawing just shy of 0.85A of current. A variable power supply allows you to set the fan speed to suit airflow to your environmental conditions.
- *Condensers:* So, the design of the aluminum condensers maximizes the collected condensed water dissolved correctly. In selecting the aluminum material for its lightweight, cost effectiveness and good thermal conductivity, etching solutions and anisotropy were also considered. The water generated during the cooling process is collected by the condensers placed in the surroundings of the TEC cold surfaces.

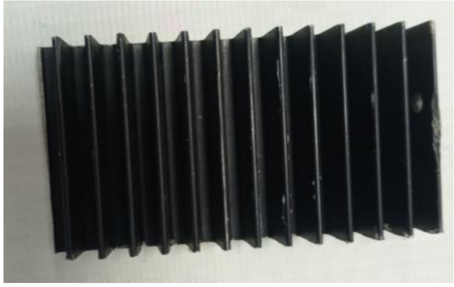


Figure 3.4: Condenser on Surface of TEC1-12706

- *Solar Panels:* The system is made possible by a solar photovoltaic (PV) panel that harnesses sunlight to generate power for the TEC modules and fans to operate. The solar panel used has a maximum output of 120W, and the TECs and fans will continue to power continuously over daylight hours. The system is integrated with a battery electricity storage system to hold excess solar energy, such that the system can provide power at night or during periods of low solar irradiance.

Figure 3.5: Solar Photovoltaic Panel for AWG [82]

- *Battery:* The system was designed to include a rechargeable battery to store the energy harvested from solar panels. To provide continuous operation under times of low sunlight or when it gets dark, the thermoelectric cooler and other system components were powered by this stored energy. The battery supplied a stable energy source, resulting in system efficiency and performance.

Figure 3.6: Battery for running during night

- *Charge Controller:* The charge controller was an important part as it held the charge between the solar panels and the battery flowing energy. The overcharging of the battery was prevented, and the energy stored was used to power the system in a most efficient manner. The charge controller helped to make the system long lasting and stable by maintaining a balance between the energy put into the system by the solar panels and the changing needs of the battery.

Figure 3.7: PWM charge controller

- *Temperature and Humidity Sensors*: To monitor the environmental conditions and system performance, temperature and humidity data loggers (e.g., Extech TM500 and TL-505 Digital Sensors) are installed. These sensors provide real-time data on ambient temperature, relative humidity, and dew points, allowing for performance optimization and system adjustments.

Figure 3.8: Temperature and Humidity Datalogger

3.3 Experimental Protocols

This section outlines the step-by-step experimental process followed to test the performance of the solar-powered Atmospheric Water Generation (AWG) system. The experiments were conducted under both controlled laboratory conditions and ambient environmental conditions, using various humidity, temperature, and airflow parameters to optimize water generation. The experimental protocols are designed to ensure repeatable, consistent results and provide comprehensive data on the system's performance.

3.3.1 Explanation of System Assembly and Configuration

The device was made from a 4mm thick acrylic sheet with dimensions of (12inch×13.5inch×5.5inch). The acrylic sheet was selected due to its lightweight and exceptional weather-resistance properties [89], [90]. Moreover, acrylic sheets provide better visibility and easy processing. The acrylic sheet was cut using high-speed Galvo laser cutting engraving machine ZJ(3D)-9045TB for precise cutting, and chloroform was used to bind the box to maximize the device's thermal performance and to prevent water leakage that can occur due to leakage. Each TEC module was sandwiched between two heat sinks, as shown in Fig 4.1. Figure 3.9(a) shows the AWG working in an ambient environment. The Aluminum heat sink (40mm×45mm) was mounted on the cold surface of the Thermoelectric cooler and was selected for two primary purposes: first, to increase surface area to condense more water and avoid ice formation. A high-quality thermal paste

(Silicon grease dielectric paste) was used to stick TEC with heat sinks to maximize heat transfer between them. An aluminum heat sink (80mm×75mm) to support fast heat dissipation was mounted on the hot side of the thermoelectric cooler. Furthermore, a fan (92×92×25mm) was screw-tightened with a heat sink to increase the rate of conventional heat transfer. Four fin Peltier modules with the above-mentioned configuration were used to condense a high quantity of water. Four TEC modules were mounted onto two sides of an acrylic box, two each, as shown in Figue 3.9(b). Each pair has a separate heat sink of dimension (80mm×75mm) with fins (92×92×25mm). These heat dissipation fans were placed outside the main AWH chamber to increase the heat transfer rate. Aluminum condenser is selected due to its lightweight and cost-effective nature. Two fans (92×92×25mm) each are connected to the top side of the device, and fan speed is controlled using a variable power supply with varying voltage. To prevent contamination of water, air is filtered by use of an air filter as shown on the figure below temperature and humidity sensors data loggers (Extech TM500) and (TL-505 Digital temperature and Humidity Sensor) are used to collect data that is stored in a separate test that were performed at controlled RH and Temperature in chamber. A Pirex glass vial (100ml) has been used to measure the amount of generated water. Solar panels are used as sources of electrical energy to power the system, Peltier modules, and the fan. Every Peltier module is arranged with a gap of 12 cm between them. Droplet formation on the condenser surface is shown in Figure 3.9(c).

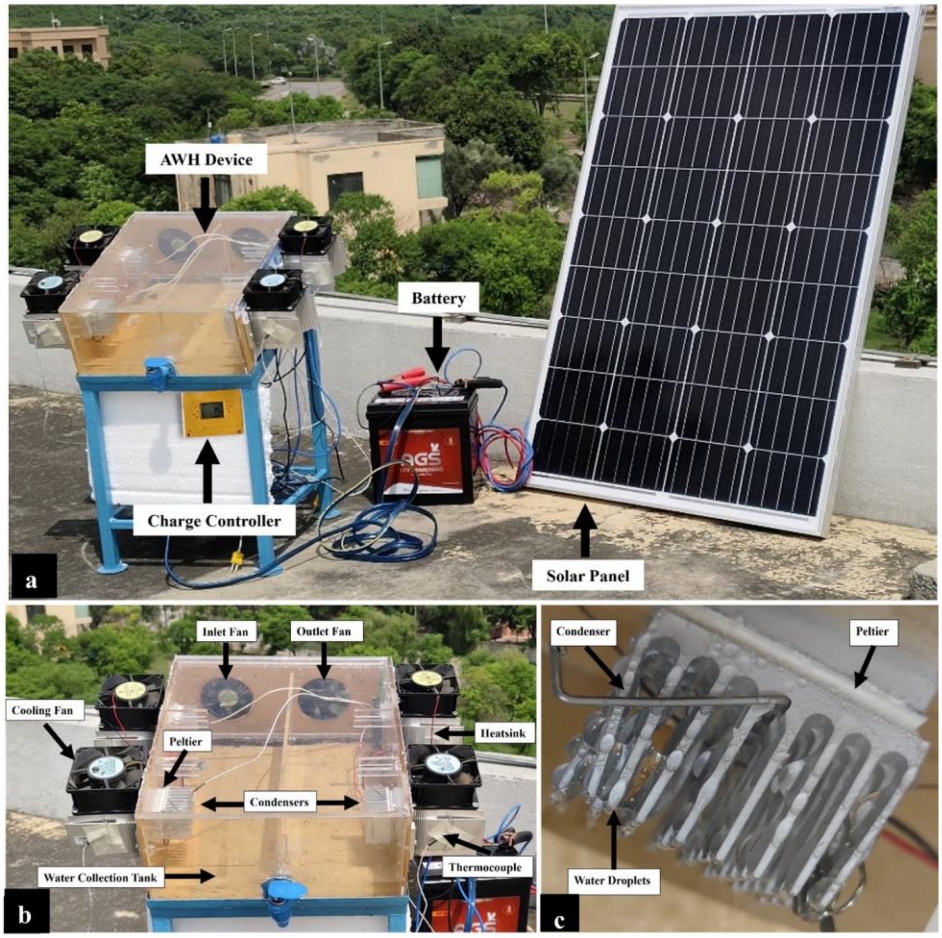


Figure 3. 9: (a) Components of AWG (b) Experimental Water formation on the cold side of Thermoelectric cooler Experimental Photo of Device at the Roof Top of USPCASE NUST University Islamabad Pakistan

3.3.2 Parallel TEC Module Arrangement

A Peltier system was designed and connected with a 12V DC power supply to find the feasible electrical configuration of the TECs devices. TECs were initially configured in series, and 2.4A current was distributed among each TEC while connecting them in series. However, this series configuration decreased water generation because of voltage division. TECs were then reconnected in parallel to optimize performance, and 3.4A current was consumed by each TEC device. Water generation was increased by connecting TECs in parallel configuration by supplying more current.

Connecting four TEC devices in Parallel with a power supply of 12V is the most favorable electrical configuration. Furthermore, for maximizing heat dissipation at the hot side of TECs, four fans with larger heatsinks were attached. Fans were connected in parallel to the 12V supply, each fan rated at 0.85A current, and two fans were installed on top of the device for air inlet on the cold surface of TECs with a rated current of 0.58A connected in parallel with 12V power source and an air velocity of fan with 3 m/s. These were also connected in parallel with the 12V supply. For improving system efficiency and increasing water generation this was the most effective electrical configuration.

3.3.3 Detailed Description of the Experimental Setup

The experimental setup was designed to ensure that the system could be evaluated under a wide range of conditions, simulating the variability found in real-world environments. The key components of the setup included the testing chamber, instruments used for data collection, and methods for controlling airflow, temperature, and humidity.

- **Testing Chamber**

The experiments were primarily conducted in a programmable temperature and humidity chamber (E001) as shown in Figure 3.10, which allowed precise control over the ambient conditions to test the AWG system. The chamber could simulate temperatures ranging from 10°C to 40°C and RH levels from 35% to 65%, reflecting the varying environmental conditions in regions such as Islamabad, where the system was designed to be deployed. The controlled environment provided a consistent and repeatable testing space, free from external fluctuations that might affect the results.

The testing chamber dimensions allowed for proper airflow around the AWG system, and the chamber included inlet and outlet fans to maintain a consistent supply of fresh, humid air. These controlled conditions were essential for isolating specific variables such as humidity, temperature, and airflow, allowing a thorough analysis of how these factors influenced water production.

Figure 3. 10: Environmental Chamber of RH and Temperature

3.4 Data Acquisition Station

The experimental setup incorporated several **instruments** to measure and control the environmental variables critical to the system's performance as depicted in Figure 3.11.

3.4.1 Temperature and Humidity Sensors

To monitor the temperature and RH inside the chamber, Extech TM500 temperature loggers and TL-505 digital humidity sensors were used. These sensors provided accurate and real-time data on the environmental conditions, allowing precise adjustments during the experiments. The sensors were calibrated to ensure consistent measurements, especially under varying temperatures and humidity.

3.4.2 Airflow Meters

Airflow plays a significant role in the condensation process, as discussed in previous sections. To measure and control the airflow over the thermoelectric cooler (TEC) modules, anemometers assess the speed of air entering and exiting the system. The airflow was controlled using fans rated at 3 m/s, and the speed could be adjusted via a variable power supply. Accurate airflow measurements were essential for optimizing the system's performance, as excessive or insufficient airflow could reduce water condensation efficiency.

3.4.3 Data Loggers

Digital data loggers were connected to the system to continuously record the temperature, RH, and water generation rates over the course of each experiment. This data was critical for analyzing how the system performed under different conditions and identifying any potential areas for improvement in the design or configuration.

3.4.4 IR Camera

The system included an infrared (IR) camera to take thermal images. These images have also helped show how heat is distributed over and between the different components, to expose inefficiencies in the system.

3.4.5 Amps Meter

An amp’s meter was used to find out the ‘Electrical current ‘ flow through system to assess the power consumption. They were critical for evaluation of water harvester energy efficiency as this was optimized when manipulating operational parameters.

Figure 3. 11: (a) An anemometer measures wind velocity produced by the intake fan at the top side. (b) A digital multimeter measures the current voltage of the AWH system. (c) Temperature and Humidity sensors Measure the temperature and relative humidity(d) IR camera provides temperature profile (e) Clamp meter measures the electrical consumption(f) temperature datalogger for measuring temperature

CHAPTER 4: RESULTS AND DISCUSSION

4.1 Theoretical calculations

Water in the atmosphere is present in gaseous form (water vapor), which is widely available across the world [91], [92]. The main objective of AWG is to collect water by liquifying moisture present in the atmosphere [93]. This is done by cooling the ambient temperature below its dew point and collecting the condensate [94]. Therefore, it is paramount to find the dew point temperature at a specific ambient temperature and RH value before experimenting. It helps to design the system according to the environmental conditions in Islamabad. For theoretical calculations, the climate data of Islamabad was obtained from World Data [95]. Based on this climatic data, the temperature range selected for this study was from 10°C to 40°C with a step size of 1°C, while the RH levels were considered 35%, 45%, 55%, and 65%. The dew point was found using the Magnus-Tetens approximation method [96].

4.1.1 Saturation Pressure

The saturation pressure of water vapour in the air is a function of temperature [97]. It represents the maximum pressure water vapors exert at a given temperature before condensing into water droplets. The saturation pressure was calculated using the Magnus-Tetens formula as shown in equation (4.1):

$$\mathrm{Psat} = 0.61078 * \mathrm{EXP}\left(\frac{17.27 * \mathrm{T}}{\frac{\mathrm{T}+237.3}{100}}\right) \tag{4.1}$$

where:

- Psat is the saturation pressure in bar,
- T is the temperature in degrees Celsius (°C).

This formula was applied to calculate the saturation pressure for temperatures ranging from 10°C to 40°C, as observed in the Islamabad climate data. The detailed tables are given in the supplementary (Table 1-4).

4.1.2 Partial Pressure of Water Vapour

The partial pressure of water vapour was calculated using Saturation pressure values. Partial pressure is the actual pressure exerted by the water vapour in the air, and it varies with the relative humidity (RH) of the environment [98]. The relationship between partial pressure and relative humidity is given by equation (4.2):

$$(Pv) = \frac{RH \times Psat}{100} \tag{4.2}$$

where:

- (Pv) is the partial pressure of water vapour in bar,
- RH is the relative humidity in percentage (%),
- $(Psat)$ is the saturation pressure at temperature (T)

This equation allows the calculation of the actual water vapour pressure for each temperature and humidity level considered in this study. The detailed values of partial pressure are given in supplementary (Table 1-4).

4.1.3 Humidity Ratio and Water Estimation

The humidity ratio measures the mass of water vapour available per unit mass of dry air. It is an essential parameter in atmospheric water studies as it directly correlates with the potential yield of water harvesting systems [98]. The humidity ratio was calculated using the following equation (4.3):

$$W = \frac{0.622 \times Pv}{1.013 - Pv} \tag{4.3}$$

Where:

- W is the humidity ratio (dimensionless),
- 0.622 is the ratio of the molecular weight of water to that of dry air,
- Pv is the partial pressure of water vapour,
- 1.013 bar is the standard atmospheric pressure at sea level.

This equation provides a mass of water vapour per kilogram of dry air under various conditions. Figure 4.1(a) shows that the absolute amount of water vapour in the air increases as humidity and temperature increase. This implies that areas with high humidity will likely have more water for the Peltier device to condense, increasing water yield.

4.1.4 Dew Point Calculations

The atmospheric temperature (at a specific value of partial pressure and relative humidity) at which condensation occurs and water droplets start to form is known as the dew point [99]. Magnus-Tetens approximation method was used to find the dew point temperature using the formula as shown in equation (4.4) [100].

$$Td = \frac{b * \gamma\ (T, RH)}{a - \gamma\ (T, RH)} \tag{4.4}$$

where:

- Td is dew point temperature
- a = 17.27
- b = 237.7

It can be seen from Figure 4.1(b) that the dew point is the function of both temperature and relative humidity. It can be deduced from the figure that for a single ambient temperature value, the dewpoint continues to increase with relative humidity. For example, when the ambient air temperature is 25°C, and RH is 35%, the dew point temperature is 8.462 °C and at the same temperature, but at 65% RH, the dew point is

17.952 °C which is nearer to the ambient temperature. The same is true with RH. The calculated theoretical temperature and relative humidity corresponded with the experimental results as increased temperature and relative humidity levels increase water production.

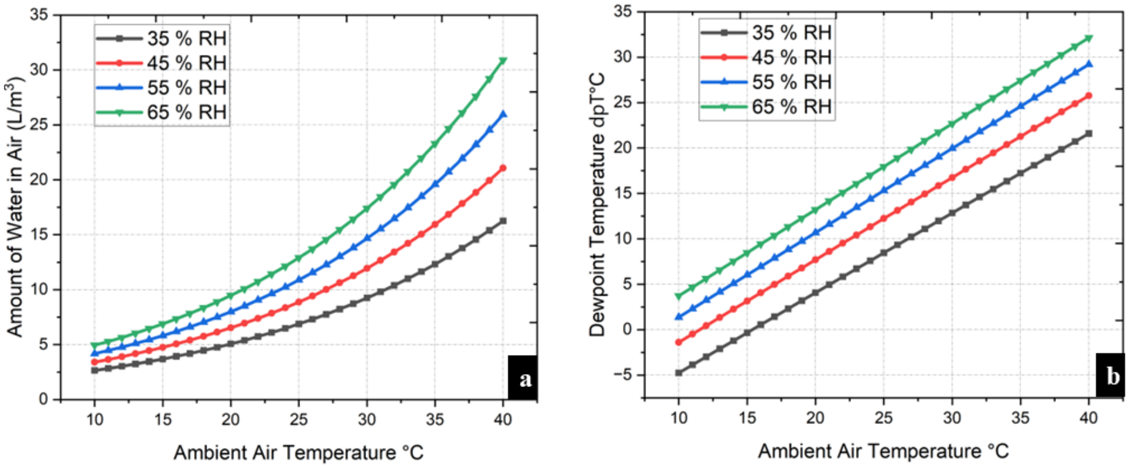


Figure 4.1: (a) The theoretical value of the Amount of Water under different relative humidity and temperatures (b) Calculated value of dew point under different ambient temperature and humidity

4.2 Thermal Analysis

The thermodynamic performance of the system was evaluated to improve its efficiency. Mathematical models were used to determine key parameters of mass flow rate, cooling load, and water production and to calculate their interrelationships.

- *Mass Flow Rate of Air*

The mass flow rate of air was calculated as a function of air velocity, density, and the cross-sectional area of flow:

$$m = \rho \cdot A \cdot v \qquad (4.5)$$

Where:

- $m^{\cdot}$: Air density (kg/m³)

- A: Cross-sectional area of flow (m²).
- v: Air velocity (m/s).

- *Cooling Load*

The cooling load was derived using the specific heat capacity of air and the calculated mass flow rate:

$$Q = m^{\cdot} \cdot Cp \cdot \Delta T \qquad (4.6)$$

Where:

- $m^{\cdot}$: Mass flow rate (kg/s).
- Cp: Specific heat capacity of air (1.007 kJ/kg·K).
- ΔT: Temperature difference between the inlet and outlet.

- *Amount of Water Generated:* The quantity of condensed water was determined based on the system's cooling capacity and the dew point temperature of the air. This value was pre-calculated.

Table 4. 1: Variation of Cooling Load and Water Generation with Air Speed

Air Speed	**Area**	**Volume flow rate**	**Density of air**	**Mass flow rate**	**T (in)**	**T (out)**	**dT**	**Cp**	**Cooling load (Q)**	**Amount of water**
m/s	**mm^2**	**m^3/s**	**kg/m^3**	**kg/s**	**(C)**	**(C)**	**(C)**	**kj/kg. K**	**Watts**	**(ml/h)**
1.4	4562	0.006386	1.184	0.007561	29.5	20.8	8.7	1.007	66.24298	16.5
1.9	4562	0.008667	1.184	0.010262	29.4	19.6	9.8	1.007	101.268	17.1
2.4	4562	0.010948	1.184	0.012962	29.3	19.1	10.2	1.007	133.1386	17.8
2.9	4562	0.013228	1.184	0.015663	29.5	18.6	10.9	1.007	171.9163	18.3
3.4	4562	0.015509	1.184	0.018363	29	18.8	10.2	1.007	188.613	17.8
3.9	4562	0.01779	1.184	0.021063	29.2	19.2	10	1.007	212.1081	16.8
4.4	4562	0.020071	1.184	0.023764	28.9	19.8	9.1	1.007	217.7643	15.6
4.9	4562	0.022352	1.184	0.026464	28.8	20.9	7.9	1.007	210.5309	14.6

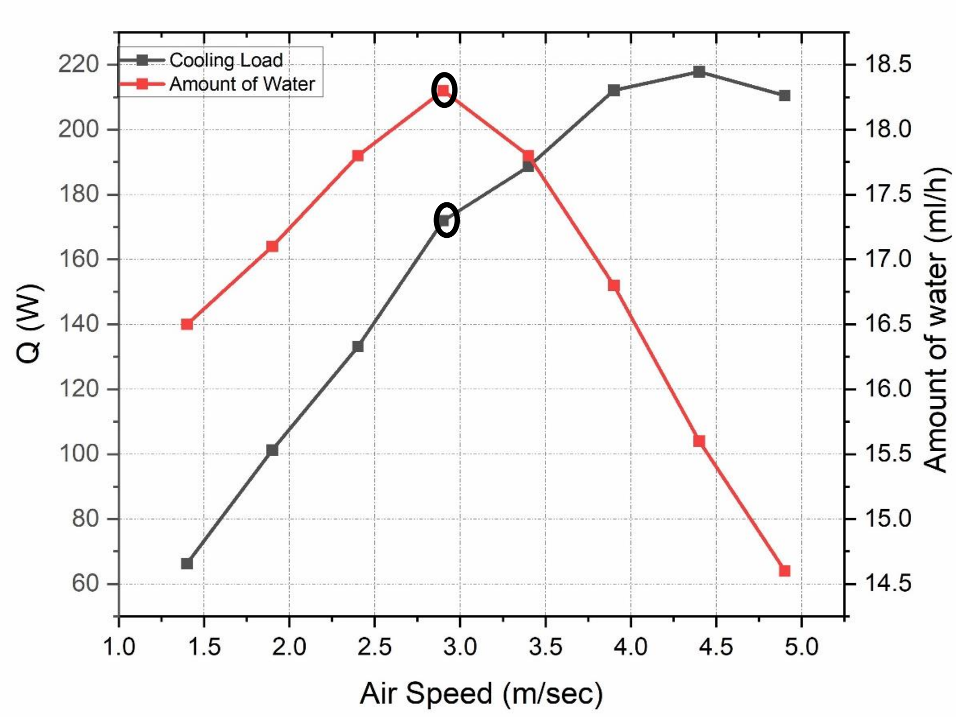


Figure 4. 2: Water Generation at different air speeds and Qc

- *Relationship between cooling load and water generation*

As depicted in the graph, while the cooling load increased with air velocity, water generation was contingent on the condenser's efficiency in condensing water vapor. Initially, both water generation and cooling load rose with increasing air velocity. However, while the cooling load continued to rise to 4.5 m/s, the amount of water produced began to decrease beyond 2.9 m/s. Consequently, the system was designed to balance optimal water production and cooling load. This analysis highlights the importance of optimizing air velocity in thermoelectric cooling (TEC)-based atmospheric water generators. Although higher air velocities improve convective heat transfer, excessive speeds can reduce the overall efficiency of water generation. Therefore, the system design adopted a balanced approach to maximize both water production and energy efficiency.

- *Coefficient of Performance (COP)*

The thermodynamic efficiency of the system was measured by employing the Coefficient of Performance (COP). COP in TEC-based systems is the measure of the relationship between energy consumption and cooling capacity. For TECs, COP is defined as the ratio of the useful cooling effect (Qc) to the electrical power input (Pe)required to achieve the cooling:

$$COP = \frac{Qc}{Pe} \tag{4.7}$$

- Pe = 193.2 W,
- Qc = 171.9 W
- COP = Qc /Pe = 0.88
- *Heat Transfer Analysis*

Several assumptions were made to simplify the analysis of the TEC 12706 paired with an aluminum condenser and heat sink. Assuming one-dimensional heat transfer and the system operating under a steady state, the heat transfer rate across the TEC module was calculated using the following formula:

$$Q = h.A \cdot (T_h - T_c) \tag{4.8}$$

Where,

Q = The heat transfer rate

h = heat transfer coefficient = 100 W/m$^{2\text{-}}$C

A = The surface area of Heat Sink = 0.276 m^2

Th = Temperature at hot side = 27.8 ˚C

Tc = Temperature at cold side = 18.3 ˚C

The value of the heat transfer coefficient was taken from the heat transfer coefficient table [1].

$$Q = 100\,\frac{\mathrm{W}}{m^2\mathrm{C}} \times 0.276\,m^2 \cdot (27.8\,^{\circ}\mathrm{C} - 18.3\,^{\circ}\mathrm{C})$$

4.3 Experimental Calculations

The AWG was examined in a temperature and relative humidity chamber Supplementary (figure 3), under different Relative humidity (RH) and Temperature. Afterward, the effect of inlet fan airflow speeds was studied on water generation to find the optimized air flow rate for maximizing water generation. Finally, AWG was placed outdoors on a roof in ambient conditions, and values of relative humidity, and temperature were recorded using dataloggers. The water generation per hour was found by dividing total water generation by 12 hours. This comprehensive testing approach for the prototype served multiple purposes.

4.3.1 The effect of Relative Humidity (RH) on Water Generation

Figure 4.2(a) shows water collected at different Relative humidity (RH) for an hour in a control temperature and humidity chamber. The increase in RH also increases the dewpoint temperature, which helps decrease the difference between the air temperature and the dew point temperature. Diminishing the difference helps with condensation and the amount of water collected.

Experiments were carried out at 35°C with RH concentrations of 35%, 45%, 55%, and 65% while measuring water accumulation after one-hour intervals. It was evident from the results that there is a direct correlation between RH and water collection, where 35% RH yielded the least amount of water, and 65% RH resulted in the highest water generation of 25.5mL/hr.

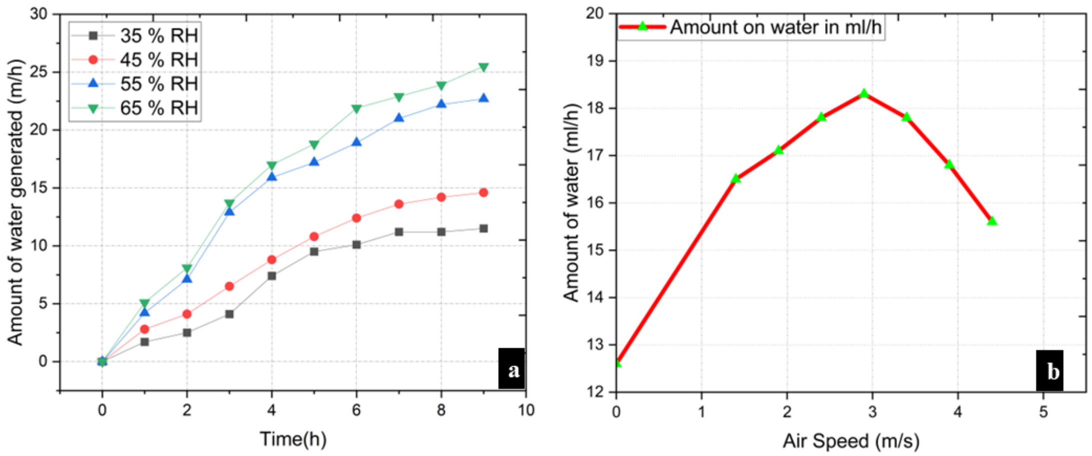


Figure 4. 3: (a) Water Generation in a Controlled Temperature and Humidity Chamber (b) Airspeed vs water generation

4.3.2 The effect of air speed on the Water Generation

4.3.3 The effect of ambient temperature and relative humidity

After experimenting in controlled chamber, and optimizing the inlet air flow rate, the AWG was tested in ambient conditions during the month of September in Islamabad, Pakistan. Tests were conducted for four days, from 7th to 10th September 2024.

Table 4. 2: water production experiments for 4 days experiments

Date	Duration	Air Temperature(c) Avg T(°C)	Relative Humidity Avg RH (%)	Dew Point Temperature Avg(°C)	Avg. Water Generated (ml/h)
9/7/2024	12	27.1	57.2	17.9	24.6
9/8/2024	12	27.8	58.7	19.0	25.5
9/9/2024	12	28.2	60.1	19.7	25.2
9/10/2024	12	30.1	55.8	20.0	23.1

Table 4.2 shows the average relative humidity (RH), average air temperature (Ta), and average amount of water produced per hour for four days (September 7th–10th, 2024) from 12:00 AM to 12:00 PM. This indicates a clear relationship between increasing daily average RH and decreasing daily average Ta with an associated increase in average water production.

The highest average water yield was recorded on September 8, 2024, at 25 mL, corresponding to the highest RH of 58.15% and the lowest Ta of 32.39°C. On September 10, 2024, the hourly water production exhibited a distinct correlation with the fluctuations in RH and Ta, as illustrated in Supplementary (Table 6). RH decreased from 57.2% at 4:38 AM to a minimum of 48% by 3:30 PM, before gradually increasing to 58% by 9:00 PM. In contrast, Ta increased steadily from 26.8°C at 4:38 AM, peaking at 35.9°C by 3:30 PM and subsequently dropping to 28.7°C by 9:30 PM. In conclusion, these findings depict the relationship between environmental conditions with the efficiency of AWG at a specific time of the day.

4.4 Water Testing:

The water collected from the atmospheric water harvester was characterized by its physicochemical properties as shown in Figure 4.3. It was compared with the World Health Organization (WHO) and National Standard for Drinking Water Quality (NSDWQ) standards to determine its fitness for human consumption.

4.4.1 Water Quality Analysis

This evaluation includes solar powered atmospheric water generation (AWG) system water quality testing, which is an important part of any evaluation. Water quality tests are done to prove that the water being collected by the system meets the World Health Organization (WHO) guidelines and National Standards for Drinking Water Quality (NSDWQ) for potable water. Different physicochemical and microbiological parameters were tested to ascertain the safety and fitness of the water for human consumption.

4.4.2 Methods for Testing Water Quality

The collected water samples were subjected to several key tests, the purpose of which being to ascertain the water quality according to these important characteristics of pH, turbidity, mineral content and microbiological contamination. These following tests are conducted to meet potable water standards.

4.4.2.1 pH Measurement

The pH of water is an essential metric that helps to indicate the acidity or alkalinity in it and overwhelms the taste as well as safety type of related issues. The water samples were used for determination of pH and the measurement was carried out using a pH meter. WHO, pH 6.5-8. The pH value of water generated by AWG system was 7.32 where both WHO and NSDWQ indicate such a level as safe for drinking that means the quality is neither too acidic nor not to alkaline effecting human ingestion.

4.4.2.2 Turbidity

Turbidity measures the clarity of the water, and the higher the number of suspended particles per volume of water, the higher the number is, and therefore the higher the level of 'scum' in the water, the more likely there is the possibility of potentially harmful bacteria or parasites. Turbidity of the water was measured using a turbidimeter. Turbidity in drinking water is recommended by WHO guidelines to be no more than 5 NTU. Turbidity in the current study was lower this could not have been contaminant or bad filtration because it was below acceptable limits as well as safe clear water.

4.4.2.3 Mineral Content

The water was tested for key mineral content, including:

- **Sulfate:** Hydrogen sulfide can cause unpleasant taste and gastrointestinal irritation, and excessive sulfate can cause unpleasant taste and gastrointestinal irritation. The sulfate limit in WHO drinking water is 250 mg/l. Levels of sulfate were found to be only 3.74 mg/l in the collected sample, much below the permissible limit, inferring no sulfate-related health risk.

- **Chloride:** When chloride amounts are high in water systems, salty taste and corrosion results. The NSDWQ and WHO recommend a maximum chloride concentration of 250 mg/l. The chloride level of 2.37 mg/l of the sample was normal.
- **Nitrates:** Elevations in the blood levels of nitrate can lead to methemoglobinemia (blue baby syndrome) in infants. According to the WHO guideline, the limit for nitrate is 50 mg/l. Not only was the nitrate level in the sample 0.008 mg/l which was much less than the limit, but it was safe for consumption.

4.4.2.4 Total Hardness

A concentration of calcium carbonate ($CaCO_3$) in the water is known as total hardness and contributes to water quality and usability. Too much hardness — causes scaling in pipes and appliances; too little is corrosive. NSDWQ and the WHO recommend less than 500 mg/l. The hardness of the water sample was 140 mg/l or moderately soft and safe.

4.4.2.5 Electrical Conductivity (EC)

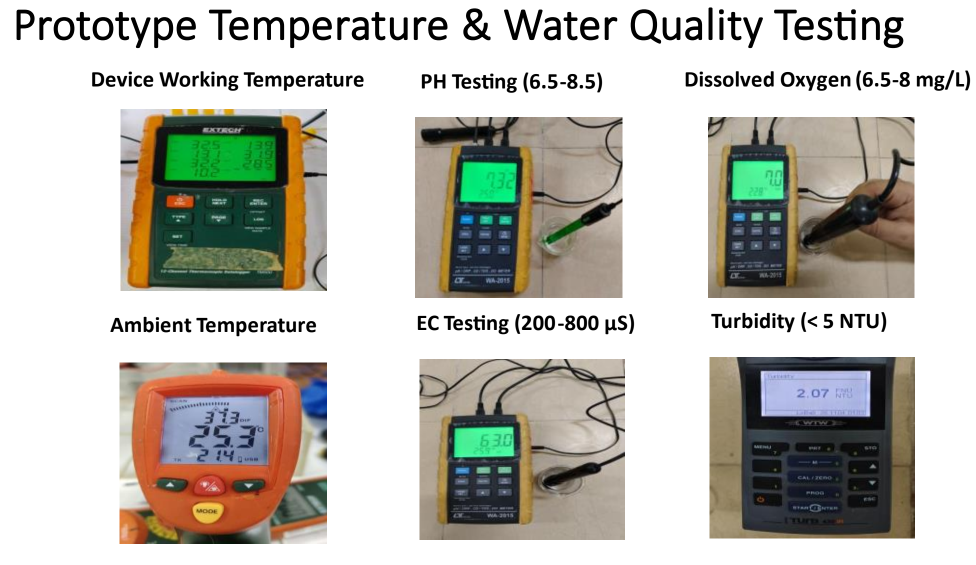
Electrical conductivity (EC) measures water's electrical conductivity or how electrically conductive the water is, this relates to its ionic content. When EC values are high this indicates contamination from dissolved salts. According to WHO, the maximum conductivity should not exceed 800 µS/cm. EC of the water sample was 63 µS/cm which indicates low ionic content and pure water, so water is safe for drinking.

4.4.2.6 Dissolved Oxygen (DO)

Dissolved Oxygen is critical in keeping our water fresh and clean from test purpose purifying and pollutants that consume oxygen (such as organic waste). Normally, the dissolved oxygen level in drinking water should range from 6.5 → 8 mg/l. Dissolved oxygen level was found equal to 7.0 mg/l which is above adequate oxygenation and indicating safe water for consumption.

4.4.2.7 Microbiological Analysis

The reason for micro analysis is for knowing whether there are harmful pathogens in there like bacteria, viruses, protozoan or any other microbes. WHO guidelines for potable water require detection of 0 Escherichia coli (E. coli) and coliform bacteria/100 ml water. Membrane filtration and culture techniques were used to test water samples for the absence of microbial contaminants. The water, it turned out, was safe for human consumption, and no microbiological contamination was detected in the tests.



Source: National Standards for Drinking Water Quality (NSDWG)

Figure 4. 4: Water Quality Testing

Table 4. 3: The table compares the sample's water quality parameters to the guidelines set by WHO and NSDWQ.

S. #	Sample ID	Sulfate (mg/l)	Nitrate (mg/l)	Total Hardness (CaCO3) (mg/l)	Chlorides (mg/l)	Electrical Conductivity (EC) (µS/cm)	Dissolved Oxygen (DO) (mg/l)
	WHO Guidelines [102]	<250	50	<500	250	800	6.5-8
	NSDWQ	<250	<50	<500	<250	800	-
1	Sample 1	3.74	0.008	140	2.37	63	7.0

The samples were analyzed using standard analytical instruments and procedures as shown in Supplementary(Figure 4). As per the above-mentioned physicochemical parameters of water sample analysis, it is under safe permissible limits. Notably, the tests carried out showed that all observed parameters were within the WHO and NSDWQ regulatory benchmarks shown in Table 4.3. The sulfate, nitrate, total hardness, chloride, electrical conductivity, and dissolved oxygen show that the water is safe for consumption. Water does not pose any threat of containing any reagents that may pose health risks to humans, hence can be drunk and used in other domestic activities. The value of the pH of drinking water is most often within the limits of 6. 5 to 8. 5 [102], [103].In testing of the water produced by our system, the pH has a value of 7.32 which implies that the water is safe for drinking regarding the permit standard for the pollutant in water sources. An alkaline or acidic water level was also measured using a pH meter.

4.5 Comparison with other TEC-based AWG devices

A comparison with other related studies to the present study was made. The water generation rates achieved in the present experimental system, equipped with 4 TECs were comparable to the literature data considering the relative humidity, which ranged from 35% to 65%. Although the system's power consumption was 180 W, which is higher compared to some works, it was lower than other settings with similar TEC setups. Notably, the present work device could sustain an optimal performance even in low-humidity environments, which was a rare observation. The comparison results are shown in Table 4, where it is shown that the present work maintains energy consumption and water production, demonstrating the effectiveness in various humidity settings.

In this section we give a comparative analysis of the results obtained in the solar powered AWG system with respect to our existing thermoelectric cooling (TEC) based AWG systems. It presents an assessment of the benefits of the proposed system on water production, energy efficiency and cost effectiveness particularly for low to medium humidity environments. From a comparison standpoint, the present system is compared to other systems reported in the literature.

4.6 Comparison of Results with Existing TEC-Based AWG Systems

An evaluation of the performance of the proposed AWG system based on the water generation rates, energy consumption and performance under different environmental conditions is also a key aspect. The present system is compared to other TEC based AWG devices of relevant studies in Table 5.

4.6.1 Water Generation Rate

The water generation rates achieved by the proposed system were within or better than those reported by others in low to mid RH regime. The present system performed very efficiently with a water generation rate of 25.5 mL/h at 65% RH while remaining efficient at lower RH levels (35–55%) that is a typical problem of AWG devices. For example, at 80% RH Joshi et al. (2017) reported generation of 20 mL/h, and Tan and Fok (2012) 17 mL/h, but both at higher humidity for best performance.

4.6.2 Energy Consumption

AWG systems are an energy consuming system that is a key parameter in their efficiency. During operation, the proposed system consumed 180 W, which is moderate compared to other systems that also consume similar or greater energy. For example, Udomsakdigool et al. (2007) achieve 18.98 mL/h of water generation at the cost of 22.8 W energy, achieving a lower scalability but an energy efficiency of water generation. Nevertheless, the present system is distinct from these studies by the ability to operate in low RH environments, that is it can continue to operate even when humidity is less than ideal.

4.6.3 Number of TECs and System Configuration

Optimal performance of the present system was demonstrated using 4 TEC modules configured in parallel. This number agrees with other studies (Shourideh et al. 2018, also using 4 TECs to achieve water generation rate of 112 mL h $^{-1}$ at 80% RH, with 206 W power consumption). Eslami et al. (2018) optimized the system, with 18 TECs, yielding a higher water generation rate (26 mL/h) at 75 % RH, at the expense, though, of a much more complex, more precise configuration system.

Table 4. 4: Comparison of studies with other existing AWG devices.

Device	**Water Generation Rate (mL/hr)**	**Power consumption (W)**	**No. of TEC**	**Relative Humidity**	**Ref.**
Present Work	11.5	163.2	4	35	-
	14.6			45	
	22.7			55	
	25.5			65	
Udomsakdigool et al.	18.98	22.8	-	60-75	[104]

Joshi et al.	20	-	10	80	[105]
Tan and Fok	17	124		79	[106]
Vián et al.	45	100		80	[107]
Eslami et al.	26	20	18	75	[108]
Pontious et al.	5.1	-	-	69.6	[109]
Shourideh et al.	30	60	4	80	[110]
Shourideh et al.	112	206	4	80	[110]

4.6.4 Advantages of the Proposed System

Several key advantages of the proposed system, as relative to water production, energy efficiency and economics, are reviewed drawing comparison with the previous proposal.

4.6.4.1 Efficient Water Production at Low Humidity

The proposed system is effective under various humidity conditions with optimum efficiency under low humidity. Unlike other AWG systems developed by Joshi et al. and Tan and Fok that need relative humidity to be higher than 75% to produce adequate quantities of water, the present system can still produce water at 35% relative humidity though the flow rate is 11.5 mL/h. This makes it highly suitable for arid and semi-arid regions and often in places with low humidity but water scarcity.

4.6.4.2 Balanced Energy Efficiency

Although the system consumes 180 W that is moderate relative to some studies, its ability to work under low humidity conditions improves the system’s overall efficiency. While systems like those described by Shourideh et al. (2018) did consume a lot of energy (about 206 W or more to get greater water yield and were only effective at higher humidity levels. The present system’s design is balanced so there is a tradeoff that results in continuous and energy efficient operation in uncontrolled environments where high humidity is not a given.

4.6.4.3 Cost-Effectiveness

By using 4 TEC modules in parallel and using a solar powered setup, the setup can be run in a sustainable manner with little ongoing operational costs. Compared to Eslami et al. (2018) who used 18 TECs, the proposed system is simpler to construct and lower in cost to maintain, making it a more economical means of water generation for remote or off grid specific uses. In addition to reducing reliance on grid power, the integration of solar panels and battery storage further increases system viability in places where the infrastructure is limited.

Conclusion

The experimental results reveal that the sensitivity of the TEC-based AWG system is very high to RH, temperature and air speed. The responses reached an optimum at higher RH above 55% with ambient temperature ranging 25- 28°C AND an air speed of 2.9m/s. These results thus give a guide to how the AWG system can be further improved for use in environments that range from low to medium humidity to give the best results in terms of power consumption and water production. In the evaluation of the AWG system, the discussion of the flow regime necessitates an appropriate airspeed for water production. The self- experiments revealed that an air speed of 2.9 m/s was the most optimal as it gave the coolest and least water droplet evaporation and formation of ice. At higher air speeds, water production was reduced because the surface stayed wet for a shorter time, concerning only a layer of droplets without deep contact with cold surface, and the evaporation of finer droplets. It is possible to use the principles of ventilated cooling to increase the amount of collected water, reduce energy consumption and avoid such common problems as cooling beyond necessity or heat loss.

4.7 Energy Efficiency and Power Consumption

The solar powered Atmospheric Water Generation (AWG) system is an energy efficient system, which can be viable in regions of limited or expensive energy resources. This section looks at the energy efficiency of the AWG system, specifically looking at how to develop a ratio of water generated per unit of electricity used, and how it relies on solar energy input and energy storage to maintain continuous operation.

4.7.1 Energy Efficiency Analysis: Water Generation per Unit of Electricity Consumed

By comparing the total energy consumed by operation of TEC modules, fans and other system components to the total water generated, the energy efficiency of the AWG system was calculated. Watt hours (Wh) were measured as energy consumed and milliliters (ml) were measured as water production. This measure of system efficiency is the ratio of water production to energy consumption.

- *Controlled Chamber Tests:* The system demonstrated an average water production rate of 25.5 ml/h under controlled environment experiments (at which temperature and humidity were precisely regulated), using a total of 180 Wh in 12 hours. The energy efficiency then is 0.14 ml/Wh.
- *Field Tests:* Under real-world ambient conditions, the system produced 23.1 ml/h at 55.8% RH on average, with an energy consumption of approximately 200 Wh per 12 hours. The energy efficiency in this case was 0.12 ml/Wh, slightly lower than in the controlled tests, likely due to natural fluctuations in temperature and humidity that reduced the overall efficiency of the TEC modules.

Table 4. 5: Water Generation per Unit of Electricity Consumed

Test Type	**Average Water Production (ml/h)**	**Energy Consumption (Wh)**	**Energy Efficiency (ml/Wh)**
Controlled Chamber	25.5	180	0.14
Field Test (Ambient)	23.1	200	0.12

As shown in Table 4.5, the system demonstrated better efficiency under controlled conditions, where environmental factors such as RH and temperature were stable. The energy efficiency decreased slightly during field tests due to the challenges of maintaining optimal conditions in a natural environment, where solar irradiance, RH, and temperature fluctuate throughout the day.

4.7.2 Energy Storage and Continuous Operation

- *Battery Specifications:* The system was equipped with a lithium-ion battery with a capacity of 200Ah. This battery stored excess solar energy generated during the day for use at night or during cloudy conditions. With a voltage of 12V, the battery was able to supply enough power for continuous operation when the solar panel was not producing energy.
- *Battery Usage:* The system was powered by stored energy in the battery during times of low sunlight, such as early mornings and later evenings, or cloudy days.

CHAPTER 5: CONCLUSION AND RECOMMENDATIONS

In this final chapter, we summarize the main findings of research resulting from the development of solar powered Atmospheric Water Generation (AWG) system along with the optimal conditions for water generation as well as the efficiency and water quality produced through the system.

5.1 Conclusion

An experimental study of a solar-based atmospheric water generator using 4 TEC modules has been performed. The system consists of AWG, a photovoltaic module, and a battery to store energy and supply power to AWG during the night. The size of the system components (condenser, heat sink, fans, AWG chamber) has been optimized to maximize the water collection from ambient air by using a minimum amount of energy. The heat sinks, condensers, and fans are assembled in such a way as to improve heat dissipation. The AWG chamber is partitioned so that the moisture air supplied by the inlet fan, which becomes dry when interacting with the condenser surface, is exhausted by the outlet fan immediately to ensure a continuous supply of humid air. A theoretical study was conducted at varying RH and temperature values to find the dew point temperature and moisture in the air. The results were validated when AWG was tested in a controlled chamber with varying relative humidity. It was found that an increase in RH and temperature value also increased the amount of moisture present in the air, which was in line with the theoretical values. Furthermore, the effect of air speed on water generation was studied. The water production was highest (18.3ml/h) at an air speed of 2.9 m/s. It was because the condensation cooling efficiency increased due to increased temperature, and the collection of water droplets to the surface of the condenser was reduced because of airflow. It was also concluded that a further increase in the airspeed reduces performance because the air moisture could not condense on the condenser surface due to the high air speed of incoming air. RH effect on the amount of generation was studied. It was found that the water generation per hour was low initially, increased with time, and gradually became constant after operating for 7 hours. The reason for this behavior is that condensers initially took some time to achieve the dew point temperature, and secondly, droplets were tiny initially, and the air speed or gravity was insufficient to offset those tiny droplets from the condenser fins. Furthermore, it was found that mounting the condenser fin on the cold surface of the thermoelectric cooler significantly increased the amount of water without a significant increase in power consumption. The water generation was enhanced because of the increased surface area for condensation as more moist air was falling on the cold surface. The availability of fins on TEC sides also enhanced the heat distribution and inclusion of fans and increased heat transfer. It was found that the AWG can produce about 11.5 ml/h water at lower RH of 35% and 14.6 ml/h at a RH of 45% in a controlled chamber provided that the air flow rate is optimized. A quality test of collected water was done, and it was found that all parameters were within the range set by WHO.

In addition to adding to the scientific understanding of Atmospheric Water Generation (AWG) systems, these findings also provide practical applications for regions that lack water. With its reliance on the solar powered AWG system that features thermoelectric cooling (TEC) there is great potential for agricultural and domestic water use in arid and semi-arid areas. The system also provides the scalability for larger water generation scale projects and provides a potential solution for real world applications.

5.2 Future Work

In this section, recommendations for future research and improvement of the design and performance of the solar-powered Atmospheric Water Generation (AWG) using thermoelectric cooling (TEC) are presented. The limitations and findings discussed are used to suggest some areas for future work to improve system efficiency, scalability and practicality. Examples include making the design more efficient with new technologies, conducting long term field studies, or studying the use of several renewable energy sources.

In the future, the device can be examined with a higher number of different TECs to increase water harvesting. Future experiments can also be conducted for a year in different environments. Another study can be performed to find the effect of air density on water generation and for water quality, devices can be tested at different locations.

- **Recommendations for Improving the Design**

The current AWG system works well in low to medium humidity environments but can be optimized further. Improvements in key areas are the reduction of the TEC modules' efficiency, additional condenser materials, and implementation of advanced cooling methods.

- **Using More Efficient TEC Modules**

Thus, one of the most important recommendations for future work involves investigation of how more efficient TEC modules could be used. The current TEC modules were effective, however the energy consumed by the TEC modules is a limiting factor especially in low humidity. The system could benefit from significant improvements in overall efficiency if TEC technology kept advancing.

- **Alternative Condenser Materials**

Another important determining factor in the system's efficiency is the choice of condenser materials. This current design would use aluminum heat sinks for their efficiency at a low cost and weight. However, thermal conductivity may not be as good as possible for the maximization of water collecting.

- **Advanced Cooling Techniques**

Another capability improvement area is the development of more advanced cooling techniques—such as more efficient cooling—that will improve heat dissipation and system performance. Because the current systems utilize air cooled heat sinks and fans, more advanced thermal management solutions may increase efficiency even more.

- **Hybrid Systems Using Wind and Geothermal Energy**

Future work perhaps may investigate hybrid AWG systems that additionally integrate other renewable energy resource systems such as wind and geothermal energy with solar systems. In such regions, especially with abundant wind resources, wind farms may also be used together with solar systems to minimize back up electric energy.

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LIST OF PUBLICATIONS

Experimental Study of Solar-Powered Atmospheric Water Generator for Extracting Potable Water from Air

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ABSTRACT

Atmospheric water harvesting can be a viable solution to tackle water scarcity. This paper presents an experimental study using solar-powered thermoelectric coolers (TECs) to collect clean atmospheric water at a low relative humidity (RH). The system consists of 4 TEC modules arranged in parallel, coupled with heat sinks on the hot sides and condensers on the cold sides of TEC. The thermal performance of TECs was enhanced by adding fans to heat sinks. The effect of different design parameters was explained and examined. The proposed atmospheric water generator (AWG) can generate 25.5 ml/h at a humidity of 65% in a controlled environment. The results show the highest water generation of 25.5 ml/h at 58.7 relative humidity (RH) and 27.8 °C. The AWH was able to harvest 11.5 ml/h and 14.6 ml/hr at lower RH of 35% and 45%. The quality test was also conducted on the water extracted from this device, showing that all parameters were within the range specified by the World Health Organization (WHO). The study demonstrates the potential of solar-powered AWG systems to provide clean drinking water in low to medium-level humidity regions, ensuring a sustainable framework to avoid scarcity of water in the affected places.

Keywords: Atmospheric Water Generator, Water Scarcity, Thermoelectric Cooler, Water Crisis in Pakistan, Renewable Energy, Clean Water

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