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A Cost-Benefit Analysis for Extraction of Atmospheric Water by Direct Cooling in South Korea

한국의 직접 냉각에 의한 대기 수자원 추출의 비용 편익 분석

Fatemeh Yektaie* · Byung Seol Byun**
옉터이 파티마 · 변병설

Abstract: In this study, the aim is to first determine the atmospheric water potential, as a sustainable water resource, in the six major cities of South Korea. Thus, a cost-benefit analysis was performed to assess the economic feasibility of atmospheric water in three scenarios: Inbound, Outbound, and Hybrid. The findings from the empirical results show that all six South Korean cities had a positive net present value (NPV) less than a year after the use of air water generator (AWG) devices in Inbound and Hybrid scenarios. Finally, considering the drinking capacity of atmospheric water, this study examined the potential reduction in CO_2 emissions through a reduced consumption of water bottles. The results show that using a single AWG device will reduce on averagethe consumption of 5421.5-liter water bottles in a five-year period , equivalent to 135.76 Kilograms of GHG emission reduction.
Key Words: Atmospheric Water Harvest, Sustainable Water Management, Renewable Water Resource, GHG Emission Reduction, Cost-Benefit Analysis

요약: 본 연구는 먼저 대한민국 6개 도시(서울, 인천, 대전, 대구, 부산, 제주도)에서 지속 가능한 수자원으로써 대기 수자원의 잠재력을 파악하는 것을 목표로 한다. 두 번째로 본 연구 방법의 타당성을 경제적으로 평가하기 위해 인바운드, 아웃바운드 및 하이브리드의 세 가지 시나리오에서 비용 편익 분석을 수행한다. 실증적 결과에 따르면 한국의 6개 주요 도시 모두 인바운드 및 하이브리드 시나리오에서 AWG 장치를 사용한 후 1년 이내에 양의 순현재가치(NPV)를 갖는다. 세 번째로 대기 수자원의 음용량과 관련하여 물병 소비량 감소를 통한 잠재적 CO_2 배출량 감축 가능성을 조사하였다. 본 연구 결과는 단일 AWG 장치를 사용하면 1.5 리터 물병 소비량의 평균 542개를 줄일 수 있음을 보여준다. 이는 5년 동안 135.76 kg의 GHG 배출 감소와 동등한 효과이다. 토론 부분에서는 한국의 대기 수자원 관리에 대한 향후 정책 입안을 개선하기 위해 여러 안건을 다루었다.
핵심주제어: 대기 수자원 추출, 지속가능한 물 관리, 재생가능한 수자원, 온실가스 배출량 감소, 비용편익 분석

* First author, Ph.D. student, Department of Sustainability Management, Inha University
** Corresponding author, Professor, Department of Sustainability Management, Inha University

I. Introduction

Water is considered a vital factor for the life of human beings and other organisms on the planet earth. Despite the abundance of water on earth (71% of the earth's surface), only a tiny portion consists of freshwater, whereas the significant part (96.5%) is held within the ocean as saline water (USGS, 2021). Unfortunately, water resources have been threatened seriously by population growth, urbanization, and water stock overuse. Moreover, climate change caused by excessive carbon emissions from human actions aggravates the shortage of water resources (Hoff, 2009; Vörösmarty et al., 2010). Considering the unsustainability of the global water system, the enhancement of the existing water resource management and finding alternative freshwater recources are urgent. A sustainable water system promotes the coordinated development and management of water, land, and related resources. Furthermore, it leads to economic and social welfare equitably without harming the biosphere stability (Kim et al., 2018; Loukas et al., 2007).

The surrounding atmosphere of the earth contains a high proportion of renewable water (approximately 13,000 km^3 which can be used as a new freshwater resource. The amount of this atmospheric water reservoir exceeds the amount of the total freshwater in rivers, marshes, and wetlands in the world. More specifically, in most places of the earth, one square kilometer of atmospheric air contains 10,000 to 30,000 m^3 of pure water. The atmospheric water is mostly (98%) in vapor form and the remaining 2% in liquid (cloud droplets and fog) form, which can be considered as a sustainable freshwater source. Although it is easier to collect the liquid form, its low occurrence rate limited to specific coastlines makes it a less accessible resource rather than the vapor form (Beysens and Milimouk, 2000). While numerous studies were conducted to study various extraction methods in the past decades, a straightforward extraction method is direct cooling in which energy is actively consumed to cool down the humid air below its dewpoint. In this method, vapor condensation happens, consequently, as a result of exceeding the moisture saturation capacity of the chilled air (Gido et al., 2016). Notably, water extraction from the air is considerably affected by ambient temperature and relative humidity (RH). As an example, the dew temperature of the air at 20°C and 80% relative humidity is 18°C while the dew temperature falls to 10°C if the RH is only 25% (Beysens and Milimouk, 2000). Therefore, the metrological features of a region play a fundamental role in the feasibility of using atmospheric water as a sustainable water source.

Furthermore, based on previous water analysis which compares the features of tap water, distilled water and sky water in Sydney, it can be concluded that the atmospheric water possesses high quality and can be treated easily to achieve the potable water quality standard regarding PH and electrical conductivity (Milani et al., 2014). As this study showed, sky water (5.50) possesses a lower PH, compared to tap water (7.4) and distilled water (5.90), and has acidic characteristic and needs to be neutralized before use. In case of water electrical conductivity, sky water (0.23 mS/m) has a comparable conductivity with distilled water (0.40 mS/m) but a very low conductivity compared to tap water (39.5 mS/m) (Milani et al., 2014). Electrical conductivity (EC) is a measure of dissolved solids in water that enables it to transmit current. Based on WHO standards a range of 0-40 mS/m is considered as the good drinking water for humans (Meride and Ayenew, 2016). Therefore, atmospheric water has great potentials to be used as a sustainable potable water resource as well.

In this study, the aim is, first, to determine the atmospheric water potentials, as a sustainable water resource in six cities of South Korea (Seoul, Incheon, Daejeon, Daegu, Busan, and Jeju Island). Second, a cost-benefit analysis is performed to assess the feasibility of this method economically in three different scenarios (Inbound, Outbound, Hybrid). Third, considering the drinking capacity of atmosphere water, the potential CO_2 emissions reduction through less consumption of water bottles is examined. Finally, based on the empirical finding, this paper recommends a need for policymaking regarding the usage of the atmospheric water resource management in South Korea.

Ⅱ. Background Studies

1. Drinking Water Bottle Carbon Footprint

Carbon emission is defined as the total greenhouses gases (GHG) emissions released into the atmosphere which is expressed as carbon dioxide equivalent. Based on Choi et al. (2017), a 1.5-liter water bottle creates 250 grams of CO_2. In other words, a household consumes 800 bottles of drinking water per year, which creates 160 kg CO_2 emission. The CO_2 emission is quantified based on polyethylene GHG emissions in a 1.5-liter water bottle production process, and the transportation-related emission is excluded. 〈Table 1〉 shows the carbon emission for a single 1.5-liter bottle and the total worldwide amount of bottled water as well as its share from the total CO_2 emissions.

〈Table 1〉 The carbon emission for different water bottle quantities (Boucher et al., 2019, Corp, Dormer et al., 2013, Zheng and Suh, 2019)

Category	CO_2 emission
1.5-liter bottle	250 Grams
Total bottled water	80 Billion Kilograms
Total bottled water from total CO_2 emission	0.21%

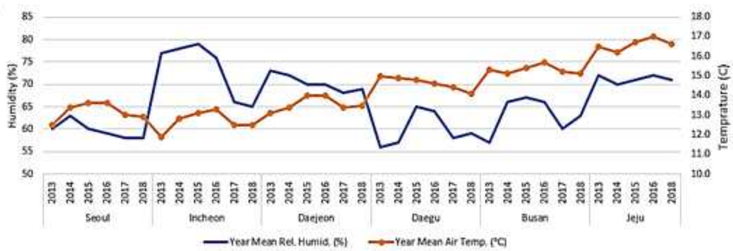
2. Atmospheric Water Potential in Korea

Water extraction from the air is notably affected by ambient temperature and relative humidity (RH) (Beysens and Milimouk, 2000). The Air-Water-Generator (AWG) devices can operate in a wide range of ambient temperatures approximately between 10~43°C and at relative humidity as small as 28% (AW solution Inc., 2021). However, higher relative humidity values enhance the AWG device efficiency. Relative Humidity (RH) is the ratio of the actual water vapor pressure to the saturation water vapor pressure at the prevailing temperature. In other words, the amount of water vapor present in the air is expressed as a percentage of the amount needed for saturation at the same temperature. At dew point temperature, the actual water vapor content of the air is equal to the saturation water vapor pressure. If the air is gradually cooled while maintaining the moisture content constant, the relative humidity will rise until it reaches 100%. Therefore, in dew point temperature, the moisture content in the air will saturate the air, and if the air is cooled further, some of the moisture will condense (Beysens and Milimouk, 2000).

〈Figure 1〉 shows the yearly mean metrological data from 2013 to 2018 for six major cities in Korea. In addition, based on Korean statistical organization data in KOSIS (2021), we found that the yearly air temperature is in a range between -17.8 to 39.6 in Seoul, -17.1

to 35.9 in Incheon, -17 to 39.4 in Daejeon, -13.9 to 39.2 in Daegu, -10.2 to 36.4 in Busan and -5.8 to 36.7 in Jeju Island. The average six-years minimum RH varies from 57% in Seoul, 65.3% in Incheon, 67.2% in Daejeon, 55.8% in Daegu, 56.1% in Busan and 70.12% in Jeju Island. The relative humidity in all six cities is over 55.8%, which is quite favorable for AWG devices.

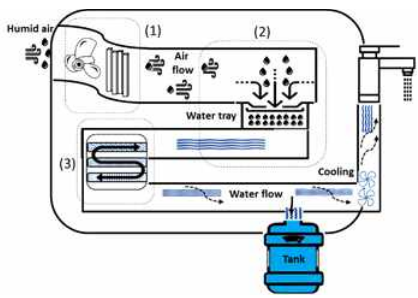
〈Figure 1〉 Yearly air temperature and relative humidity from 2013 to 2018 for six cities in Korea (KOREA, 2021)



3. Atmospheric Water Generator Model

〈Figure 2〉 clarifies the process of generating freshwater from atmospheric water through the following steps: (1) air purification, (2) dehumidification, and (3) water purification.

〈Figure 2〉 The process of generating drinking water using AWG (AW solution Inc., 2021, p.4)



In step (1), all air pollutants such as dust, dirt, small particles are removed thoroughly in a way that only pure air passes into the AWG. In stage (2), the purified air passes through the channel of the heat exchanger and cooler. In the dew point state, the condensation process occurs, and liquid water is collected. In step (3), the water is directed into a multi-level filtering process intending to remove impurities and add minerals while sustaining freshwater taste. In the last step, the water with high quality is stored in a built-in or external tank. Previous Literature suggested that Membrane Bioreactors (MBR) are efficient in microbial removal without the need for disinfection (Pidou et al., 2007). We will discuss the operational cost of the total heat interaction on the energy consumption of AWG devices.

4. Literature Review on Atmospheric Water

Relevant previous 3. Atmospheric water potential in Koreaon worldwide usage of AWG device for drinking water is described in Figure 3. In terms of the input data, the previous researches wrote by Gido et al. (2016), the proposed paper, Asiabanpour et al. (Asiabanpour et al., 2019; Moghimi et al., 2021), and Salehi et al. (2020) studied the atmospheric water generation by using collected data such as RH, temperature and Dewpoint. In terms of outputs data such as MHI, Energy consumption, Cost of water, NPV each paper results is shown in 〈Table 2〉, respectively.

〈Table 2〉 Relevant previous literature on usage of atmospheric water

Author(s), YoP[1]	Inputs	Outputs	SD[2], CPoR[3]	RS[4]
The proposed paper	RH, Temperature, and Dewpoint	MHI, Energy consumption, Cost of water, NPV, CO_2 reduction, Bottle reduction, Generated water	6 cities Korea-2014~2019	quantitative
Gido et al. (2016)	RH, Temperature, and Dewpoint	Energy consumption, Cost of water, Generated water	30 cities world wide-2005~2014	quantitative
Asiabanpour et al. (2019), Moghimi et al. (2021)	RH, Temperature, and Dewpoint	Energy consumption, NPV, Generated water	San Marcos, 2019	quantitative
Salehi et al. (2020)	RH, Temperature, and Dewpoint	Energy consumption, Generated water	30 cities world wide-1981~2017	Review

[1] Year of publication (YoP) [2] Sample data (SD) [3] Corresponding period of research (CPoR)
[4] Research methodology (RS)

The proposed paper outputs the result related to CO_2 reduction and the number of bottle reduction, which enable the proposed paper to not only shows the net present value (NPV) of costs (capital, and operational but it also indicates the benefits (generated water) based on a financial assessment that show the sustainability effect of using atmospheric water as a source for drinking water in the household scale in Korea.

Moisture Harvesting Index (MHI) indicates the proportion of the energy consumed for the water condensation method to the total energy consumed in the cooling of the condensable as well as the incondensable gasses in the air bulk. The total heat interaction in the condensation process (q) is calculated by the sum of the sensible heat and the latent heat whereas sensible heat is associated with the temperature change of the air and vapor, and the latent heat is associated with the vapor enthalpy of condensation. The paper wrote by Gido et al. (2016) suggested the Moisture Harvesting Index (MHI) for facilitating the assessment of moisture harvest potentials as well as process efficiency and cost-effectiveness (Gido et al., 2016). In a steady-state situation, the portion of the latent heat out calculated by dividing the enthalpy of condensation, ENT_{vapor}, by q. This quotient is designated MHI,

$$MHI = \frac{ENT_{vapor}}{q} \tag{1}$$

Ⅲ. Research Methods

This section describes various categories of added costs and benefits considered in this study. Five years is considered for the life cycle analysis. Moreover, multiple correlation analyses were performed to identify influential factors that make usage of AWG more economically viable. Three types of scenarios are chosen in this study to perform a cost-benefit analysis for inbound, hybrid, and outbound atmospheric water 〈Table 3〉.

〈Table 3〉 The assumptions for AWG's scenarios specifications

AWG's scenarios	AWG's Installation location	Expected Temperature	Expected RH
Inbound	Indoor	22°C	Inside RH~Outside RH
Outbound	Outdoor	Outside Temperature	Outside RH
Hybrid	Mixed Indoor and Outdoor	Highest Value	Outside RH

1. Inbound

In the Inbound scenario, AWG is installed inside the residential unit where the temperature is fixed at a specific range between 19°C and

25°C. In this paper, an average temperature of 22°C is considered as the Inbound scenario constant temperature. Furthermore, Inbound temperature is used to calculate the water content generation and energy consumption by AWG based on Equations (10-14). Finally, a total added cost and benefit of Inbound scenario is calculated using Equations (10-14).

2. Outbound

In the Outbound scenario, AWG is installed outside the residential unit where the temperature varies based on the environment temperature. In this paper, the average environment temperature and humidity for six major Korean cities are considered as the Outbound scenario temperature and humidity respectfully. Furthermore, Outbound temperature and humidity is used to calculate the water content generation and energy consumption AWG based on Equations (10-14). Finally, a total added cost and benefit of Outbound scenario is calculated using Equations (10-14).

3. Hybrid

In low temperatures, the AWG device is not economically efficient. In the hybrid scenario, AWG is installed outside the residential unit when the temperature is in the expected range of working for devices, whereas AWG is installed inside the residential unit when the outside temperature is in lower than expected range as described in Equation. (2). WGP_H denotes as the water generated product using a hybrid scenario, whereas $WGP_{\in}$ and WGP_{OUT} denote as the water generated product using Inbound and outbound scenarios.

Therefore, a combination of Outbound and Inbound temperature is used to calculate the water content generated based on Equations (10-14) and energy consumed by AWG based on Equations (10-14).

$$WGP_H = \begin{cases} WGP_{\in} & WGP_{OUT} < WGP_{\in} \\ WGP_{OUT} & WGP_{OUT} \geq WGP_{\in} \end{cases} \tag{2}$$

1) Added Costs

The added costs include capital, operational, maintenance, and repair costs. This study compares the cost of the water from the AWG to the cost of purchasing an equivalent amount of water in bottle freshwater, Inbound AWG, Outbound AWG, and hybrid AWG scenarios. water bottles that are available in convenience Korean stores for 2.14 USD per 10 liters (Chang et al., 2017). The net present value (NPV) of costs (capital and operational) and benefits (generated water) is used for a financial assessment. This study compares the cost of the water from the AWG to the cost of purchasing an equivalent amount of water in three different scenarios. The estimated AWG system's useful life is 25 years (Asiabanpour et al., 2019; Moghimi et al., 2021).

2) Capital Costs

Capital costs include the purchase and installation costs of treatment AWG units. Selected AWG provides water storage (tanks), cooling system for vapor collection, atmospheric water deacidification, and microorganism filtering membrane. The initial cost of a commercially available A type of the AWG system including tax and shipping cost: 2,000 USA Dollars (USD) and the expected installation cost of treatment AWG unit is 100 USD (Asiabanpour et al., 2019).

3) Operational Costs

Operational costs include the repairs and energy costs and maintenance (e.g., filter exchange) for the selected five years. Maintenance and repair costs for the AWG, including filters exchange, estimated to be 100 USD /year in Korea (Asiabanpour et al., 2019; Moghimi et al., 2021).

Energy costs calculation. The total heat interaction in this process (q) is calculated by the sum of the sensible heat, associated with the temperature change of the air and vapor, and the latent heat associated with the vapor enthalpy of condensation (Vörösmarty et al., 2010).

〈Table 4〉 Notation list for AWG energy costs calculation

Notation	Description
$\overline{Q}$	Yearly total heat interaction
q	Total heat interaction
$q_{sensebile}$	Sensible heat
q_{latent}	Latent heat
M	Mass of the air
C	Specific heat
T_{ambi}	Environmental Temperature
$T_{Dew-point}$	Dew Temperature
$\triangle\theta$	Difference between ambient and dewpoint temperature
ENT_{air}	Air Enthalpy
ENT_{vapor}	Water vapor Enthalpy
WC_{air}	The water content of air

⟨Table 4⟩ shows the notations with their descriptions used to estimate the costs of energy consumption (3~8) at home in Korea.

$$\overline{Q}= \frac{1}{5\times 356\times 24}\sum_{k=2014}^{2019}\sum_{j=1}^{356}\sum_{i=1}^{24} q \quad (3)$$

$$q = q_{sensebile} + q_{latent} \quad (4)$$

$$q_{sensible} = MC\triangle\theta \quad where,\ \triangle\theta = T_{ambi} - T_{Dew-point} \quad (5)$$

$$q_{latent} = ENT_{air} + ENT_{vapor} \quad (6)$$

$$ENT_{air} = 1.007(T) - 0.026 \quad (7)$$

$$ENT_{vapor} = WC_{air}(2501 + 1.84(T)) \quad (8)$$

⟨Table 5⟩ The AWG specifications and cost in Korea

Types	Usage	Price	Water Generation Capacity
A	Home	2000 USD	15~20 L/D
B	Building	15000 USD	450 L/D
C	Large Area	250000 USD	3120 L/D

⟨Table 5⟩ shows AWG specifications and cost in Korea, where Type A is the one for household scale. Moreover, this paper provides additional findings regarding cost such as AWG average daily energy consumption, average local energy price and Korea average inflation rate as follows,

- AWG's average daily energy consumption is 10.25 Kilo Watt per Hour (KWH) to generate room temperature water.
- AWG energy increases by 25% to convert inbound water's temperature to cold water.
- AWG average daily energy is 10.25×1.25= 14.06 KWH to generate cold water.

- The average local energy price is USD 0.113/KWH (KOREA, 2021).
- Korea average inflation rate is 1.8% (KOREA, 2021).

The EWA technology can be adjusted to any required capacity up to 1,000 m^3/d.

In this study, the direct benefit is considered as the value of purchasing bottle water. In another word, the direct benefit of atmospheric water generation is to lower household costs for drinking water by using a decentralized cost-efficient sustainable alternative. Once the AWG devices are widely used in a city, the need for high-quality water treatment site as well as potable water pipelines and infrastructure is withdrawn from the water distribution network. Besides, an indirect benefit estimated in this study is the amount of plastic bottle 2 reduction. As shown in Table 5, the AWG specifications and application differs from the household (Type A) to the building (Type B) and Large Area (Type C). In this study, the household (Type A) is used as a reference which accounts for a daily average between 15 and 20 liters of water generation in a 10°C and 35°C range of ambient temperature.

〈Table 6〉 The notations used to estimate the costs of scenario (1) and (2)

Notation	Description	Value
E_{rate}	Energy cost (KW.H) in the base year	5.61 USD
$E_{\infty - rate}$	Average yearly inflation ration	0.018
CPC	The capital cost of devices	1500 USD
P_i	Average benefits from generating AWG water in year-i	Varied
C	AWG system energy consumption	Varied
R	Energy rate in the base year	Varied
F	Average energy inflation rate	Varied
WGP	Amount of water generated in year-i	Varied
MVW	The market value of water in the base year	0.214 USD
$AAOC$	AWG system operation cost	215 USD

〈Table 6〉 shows the notations with their descriptions and values used to estimate the costs of scenario (1), (2), and (3) in the household scale in Korea. The present value for each year calculated and shown in the results section considering all energy-saving benefits and investment cost (KOREA, 2021).

$$Benfit \text{ for } year \;\; i = (P_i - C) \times R \times (1 + F)^{i-1} \tag{9}$$

The breakeven point for each scenario is calculated by equation 2. Net Present Value (NPV) method considers the difference between the total discounted benefits minus the total discounted costs. Projects with positive net benefits are considered to be viable and a project with a lower NPV is measured to be less lucrative.

$$NPV = \sum_{i=1}^{n} PV\left[WGP \times MVW \times (1 + E_{\infty - rate})^{i-1} \right] - \left(CPC + \sum_{i=1}^{n} PV\left[AAOC + E \times E_{rate} \times (1 + E_{\infty - rate})^{i-1}\right]\right) \tag{10}$$

In other words, the higher the NPV, the greater the calculated benefits of the project. Besides, PV is Present Value, and n is the first year that the NPV equation sign turns from negative to positive.

Payback Period. This is the period required for the total discounted costs of a project to be surpassed by the total discounted benefits. The payback period of an AWG device is calculated through cumulative discounted benefit and cost for five-consecutive-year. The year that the cumulative benefits exceed the cumulative costs is the payback period year of the project. In other words, the year following the project payback period net profits or benefits of the project could be exploited.

Carbon footprint analysis. The total Carbon emission for drinking water bottles (TCE) is calculated using Equations (11-12) by the sum of the daily carbon emission created by daily total drinking water bottle (TB) used by citizens (Chang et al., 2017; CU Co., 2021; Salehi et al., 2020).

$$TCE_{city} = \sum_{i=2014}^{2019} \sum_{j=1}^{12} TB_{city,i,j} \times UCE \times 30 \tag{11}$$

$$TB_{city,year,month} = \frac{\overline{WC}_{city,year,\ month}}{1.5} \tag{12}$$

Ⅳ. Results

〈Table 7〉 shows the monthly assessment of MHI and energy consumption for atmospheric water potentials based on the given metrological data for six major cities in Korea.

〈Table 7〉 The monthly assessment of MHI and energy consumption in Korea

City	Month of the year	AV. 5 year mean Rel. humidity (%)	AV. 5 year mean air temp. (°C)	AV. 5 year mean dew point temp. (°C)	Energy consumption (KW.H/L)	MHI
Seoul	Jan.	52.40	2.12	11.18	N/A*	N/A
	Feb.	52.40	0.26	9.22	N/A	N/A
	Mar.	52.60	7.12	2.96	N/A	N/A
	Apr.	55.20	13.66	3.42	2.08	0.42
	May	56.60	19.02	8.96	0.97	0.44
	Jun.	63.20	23.34	15.08	0.59	0.51
	Jul.	72.60	26.56	20.74	0.37	0.58
	Aug.	69.40	26.84	20.16	0.44	0.58
	Sep.	62.40	22.24	13.94	0.61	0.50

	Oct.	60.00	15.34	6.94	0.89	0.46
	Nov.	60.40	7.62	0.32	N/A	N/A
	Dec.	55.40	0.52	9.02	N/A	N/A
Incheon	Jan.	63.80	1.60	7.92	N/A	0.61
	Feb.	64.60	0.38	6.02	N/A	0.52
	Mar.	69.00	6.30	0.36	N/A	0.51
	Apr.	70.00	12.36	6.14	0.66	0.52
	May	73.60	17.36	11.82	0.40	0.55
	Jun.	81.00	21.72	17.82	0.23	0.60
	Jul.	87.80	25.38	22.94	0.14	0.66
	Aug.	83.80	26.24	22.86	0.21	0.64
	Sep.	75.00	22.18	16.98	0.34	0.58
	Oct.	70.20	15.52	9.56	0.46	0.51
	Nov.	68.80	8.08	2.14	1.35	0.52
	Dec.	63.60	0.20	6.36	N/A	N/A
Busan	Jan.	46.80	3.76	7.46	N/A	N/A
	Feb.	50.20	5.22	5.28	N/A	N/A
	Mar.	58.20	9.64	0.92	N/A	0.41
	Apr.	64.00	14.62	7.04	0.76	0.48
	May	67.20	18.72	11.82	0.52	0.52
	Jun.	77.00	21.42	16.92	0.27	0.58
	Jul.	82.60	25.36	21.92	0.21	0.64
	Aug.	77.20	26.58	21.92	0.28	0.61
	Sep.	74.80	22.44	17.40	0.32	0.58
	Oct.	66.60	17.84	11.10	0.51	0.51
	Nov.	60.20	12.34	4.14	1.27	0.46
	Dec.	50.20	5.60	5.60	N/A	N/A
Daegu	Jan.	51.00	1.02	9.10	N/A	N/A
	Feb.	49.00	3.18	7.66	N/A	N/A
	Mar.	52.40	8.96	1.96	N/A	N/A
	Apr.	55.20	15.14	4.32	1.83	0.40
	May	53.20	20.58	9.08	1.22	0.44
	Jun.	3.20	23.32	14.84	0.62	0.51
	Jul.	70.60	26.92	20.40	0.42	0.58
	Aug.	72.40	26.48	20.40	0.39	0.58
	Sep.	72.60	21.50	15.74	0.38	0.56
	Oct.	68.20	15.86	9.16	0.55	0.50
	Nov.	63.60	9.34	1.70	2.41	0.47

	Dec.	54.00	2.48	6.86	N/A	N/A
Jeju	Jan.	65.00	6.26	0.08	N/A	N/A
	Feb.	64.20	5.66	1.02	N/A	N/A
	Mar.	64.60	9.80	2.78	1.35	0.47
	Apr.	68.20	14.94	8.20	0.61	0.51
	May	68.60	18.86	12.20	0.49	0.52
	Jun.	78.60	22.08	17.76	0.26	0.59
	Jul.	83.00	26.38	23.04	0.20	0.64
	Aug.	80.80	26.76	22.90	0.24	0.63
	Sep.	77.60	22.94	18.54	0.27	0.60
	Oct.	70.00	19.28	13.40	0.41	0.55
	Nov.	70.60	12.52	6.88	0.53	0.53
	Dec.	68.00	7.00	1.16	2.14	0.49
Daejeon	Jan.	68.00	0.86	6.52	N/A	N/A
	Feb.	61.20	1.38	6.08	N/A	N/A
	Mar.	59.40	7.70	0.92	N/A	N/A
	Apr.	62.60	14.16	5.74	1.05	0.47
	May	62.60	19.50	11.00	0.72	0.50
	Jun.	69.40	23.38	16.72	0.45	0.56
	Jul.	81.20	26.58	22.78	0.23	0.63
	Aug.	78.00	26.70	22.04	0.29	0.62
	Sep.	75.80	21.60	16.62	0.31	0.57
	Oct.	75.60	14.90	10.10	0.36	0.56
	Nov.	74.40	8.04	3.20	0.71	0.54
	Dec.	70.20	0.90	4.42	N/A	N/A

The empirical results show that cities like Seoul, Daegu, and Busan have, on average, twice of MHI index, compared to those of the Jeju, Incheon, and Daejeon in 〈Table 7〉. Also, the cities like Incheon, Daejeon, and Busan have a 35.4% lower energy consumption, compared to those of the Jeju Island and Seoul, and have a 48.7% lower energy consumption, compared to the Daegu city. The finding shows that Daegu has the highest energy consumption among all six major Korean cities.

Table 8 shows the assessment of the yearly average applicable MHI and total applicable energy consumption for six major cities in Korea.

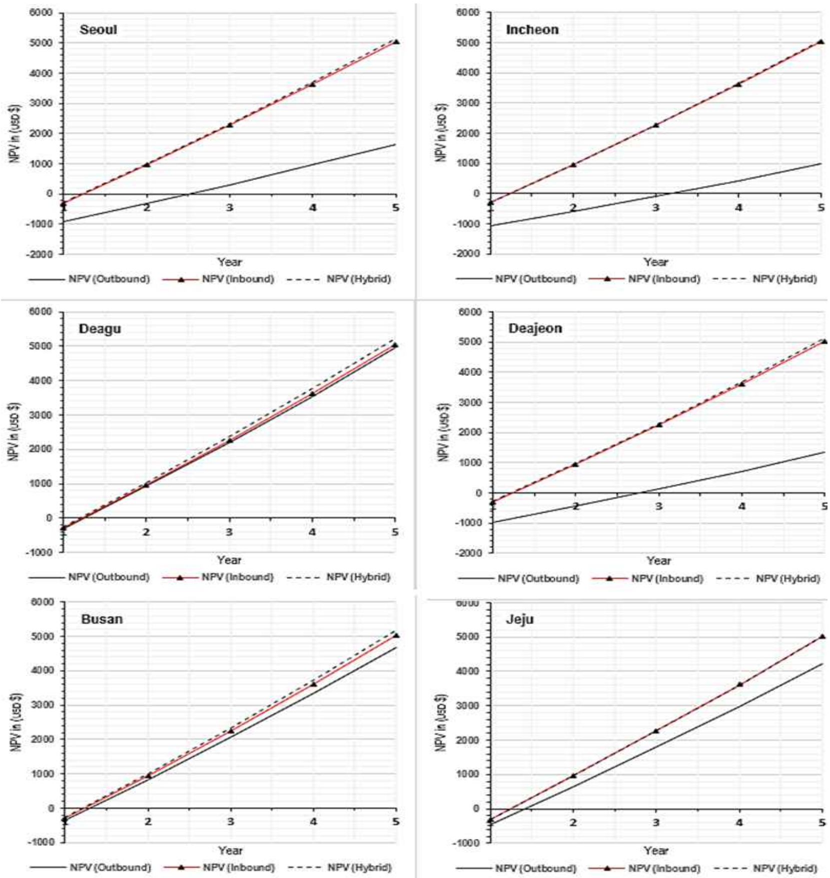
〈Table 8〉 The assessment of the yearly average applicable MHI and total energy consumption in Korea

City	The number of favorable months per year	Favorable times (%) (MHI 〉 0.3)	Yearly energy consumption (KW.H/L)	Avg. MHI
Seoul	7	58	5.953264958	0.49857435
Incheon	8	67	3.783271879	0.565113752
Daejeon	8	67	4.118579979	0.554940252
Daegu	8	67	7.829513164	0.506006684
Busan	8	67	4.140372639	0.52980597
Jeju Island	10	83	6.48676126	0.553039605

In 〈Table 8〉, in terms of the number of favorable months per year, cities like Incheon, Daegu, Daejeon, and Busan have the average eight months (~67%) among all months in the year, whereas those of Jeju Island and Seoul have in average seven months (~58%) and ten months (~83%), respectively.

The finding shows that practically Jeju Island is the most favorable city, and Seoul is the least favorable city among all six major Korean cities when using AWG devices. However, the finding shows that Jeju Island has a relatively a high MHI index and only two months not applied for calculation due to shallow temperatures in the month of the January and February.

〈Figure 3〉 The assessment of the yearly NPV for the given scenarios in Korea



〈Figure 3〉 shows the assessment of the yearly NPV for the Inbound, Outbound, and Hybrid scenarios of in Korea. In figure 3, the empirical results show that all six major Korean cities will have NPV positive less than a year after the usage of the AWG devices in case of the Inbound and Hybrid scenarios. However, in case the Outbound scenario, the cities like Daegu, Jeju Island, and Busan cities will have NPV positive less than a year, whereas Seoul and Daejeon cities will have NPV positive less than three years after the usage of the AWG devices and Incheon city will have NPV positive after three years of the usage of the AWG devices.

〈Figure 3〉 also shows that the Outbound Scenario is the worst scenario for the usage of the AWG devices among Inbound and Hybrid scenarios. However, even the Outbound scenario will have NPV positive after three years of the usage of the AWG devices.

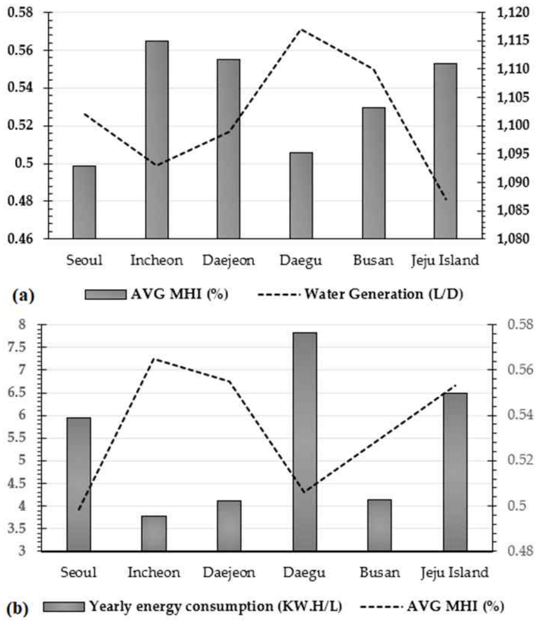
〈Table 9〉 The overall 5-years result of using AWG devices in Korea

City	AWG's Scenario	CO_2 reduction	Bottle reduction	Water Generation (L/D)	Recommendation
Seoul	Outbound	88958.00	355	532.68	Low
	Inbound	181985.45	726	1,089.73	High
	Hybrid	184067.18	735	1,102.20	High
Incheon	Outbound	84894.51	339	508.35	Low
	Inbound	181607.75	725	1,087.47	High
	Hybrid	182599.64	729	1,093.41	High
Daejeon	Outbound	93436.61	373	559.50	Low
	Inbound	181685.86	725	1,087.94	High
	Hybrid	183694.13	733	1,099.96	High
Daegu	Outbound	179608.71	717	1,075.50	High
	Inbound	181954.96	726	1,089.55	High
	Hybrid	186626.18	745	1,117.52	High
Busan	Outbound	173439.30	692	1,038.56	High
	Inbound	181836.85	726	1,088.84	High
	Hybrid	185436.73	740	1,110.40	High
Jeju	Outbound	162554.53	649	973.38	High
	Inbound	162554.53	649	973.38	High
	Hybrid	181636.33	725	1,087.64	High

Ⅴ. Discussion

Water scarcity is one of the emerging problems in the world. This study aims to suggest a new water management system (in South Korea) in which the present vapor in the atmosphere is accumulated, filtered, and used as a new resource of freshwater. The atmospheric water can be used not only as a sustainable water resource but also as a potable one. Currently, a significant portion of drinking water is distributed in plastic bottles, which consequently produces lots of waste. Furthermore, besides the GHG emissions of the polyethylene production process, product transportation has a remarkable carbon emission share as well. The more the GHG emissions, the higher the global temperature rises, and the worse the global warming consequences will be in the upcoming decades. Nowadays, GHG emissions reduction is widely considered by governments to reduce the risks to a minimum. In case of Korea environmental policy stringency has significantly increased from 2002 and generally more stringent compared to the OECD average (Yun and Yoon, 2016; Lee and Park, 2020). However, it is still far from the designed goal. The proposed paper highlighted the findings and their implications in the broadest context.

〈Figure 4〉 The effect of the MHI on water generation (a) and energy consumption (b) in Korea



〈Table 9〉 shows that the overall 5-years recommendation of using AWG devices in Korea reaches 83% high. The implementation of AWG is not recommended in the outbound scenario of Seoul, Incheon and Daejon due to significant lower water generation capacity. Based on the paper finding illuminated in Table 9, on average, usage of an AWG device in Korea will reduce CO_2 by a minimum of 84.894 Kg in Incheon (Outbound) and a maximum of 186.626 Kg Daegu (Hybrid) in a five-year period. Based on figure 4(a) empirical results, there is a significant negative relationship between MHI and water generation due to having a correlation coefficient of -0.6167, and there is even a higher negative relationship between energy consumption and MHI index due to having a correlation coefficient of -0.71199.

The implementation of AWG devices for potable water generation reduces GHG emissions and urban planning costs by eliminating the need for water treatment sites, pipelines and infrastructure, water production factories, water Supply chain and transportation, waste management, and recycling (water bottles). In this study, the GHG emissions produced by the water bottle process is only quantified. Future research is necessary to determine the exact amount of GHG emissions water treatment sites, pipelines and infrastructure, water production factories, water Supply chain, and transportation. Due to the abundant surface water resources and a massive amount of rainfall Korea was traditionally known to have no water shortage problem. However, the rapid indrustrializiation that began in the 1960s has resulted in an annual rainfall per capita of one-sixth of the world average now (Chang et al., 2017). The water treatment site and its transportation to remote areas cost a lot. Moreover, this process itself and the wastes created afterwards consume much energy leading to higher GHG emissions. Therefore, the application of this technology in future urban planning is very beneficial for improving the GHGs reduction scheme. Furthermore, by extracting the atmospheric water, the humidity is reduced, and the need for the usage of dehumidifiers is eliminated, which lessen the GHG emissions. Also, less humidity leads to a cleaner air environment by removing the growth possibility of multicellular fungus (mold) on walls. These microorganisms are the reason for some respiratory problems and allergies (Yang et al., 2015). Therefore, the AWG devices application in Korea can improve air sanitation to a meaningful extent as well.

Ⅵ. Conclusion

The atmosphere holds a tremendous amount of water, which can be used as an alternative and sustainable freshwater resource. Furthermore, the atmospheric water possesses high quality and can be treated efficiently to achieve the potable water quality standard. This study is the first research to address the possibility of using atmospheric water as a sustainable potable water resource in South Korea. Furthermore, in the present study the relationship between atmospheric water harvest and GHG emission reductions was examined. Based on the empirical paper finding, on average, an AWG device in a single household in Korea can generate water content equal to 656 L/D in a period of five years. Furthermore, AWG will reduce CO_2 by a minimum of 84.894 Kg in Incheon (Outbound) and a maximum of 186.626 Kg Daegu (Hybrid) in a five-year period. The implementation of AWG is highly recommended in all scenarios except the outbound scenario of Seoul, Incheon and Daejon. Overall, the assessment of the atmospheric water harvest in different cities of South Korea indicates that this country is a desirable location for the implementation of this technology. Therefore, considering the huge drinking bottle consumption in Korean major cities, it is highly recommended that Korean government provides funds for household owners to buy AWG devices to significantly reduce bottle consumption and relative waste management costs. Globally, the application of AWG technology can play a fundamental role in water management in dry regions (including South Mediterranean countries), as well as countries suffering from polluted water, including tropical countries, and the countries located far from the seashores where long-pipe systems are not available. The combination of renewable energies such as solar energy can enhance the environmentally friendly and economical aspects of AWG devices (LaPotin et al., 2021). In this study, the GHG emissions produced by the water bottle process is only quantified. Future research is necessary to determine the exact amount of GHG emissions water treatment sites, pipelines and infrastructure, water production factories, water supply chain, and transportation.

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Fatemeh Yektaie: PhD student at Sustainability Management of Inha University. Her research interests are Sustainable Water Management and Smart Waste Management (fatemeh@inha.edu).

Byung Seol Byun: Professor at department of Urban Planning at Inha University. His research interests are Urban Planning, Public Administration and Urban Metabolism (byun@inha.ac.kr).

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