

## Feasibility Study of Atmospheric Water Harvesting by Direct Cooling in Thailand

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### ABSTRACT

The objective of this work is to assess the potential of the atmospheric water harvesting (AWH) by direct cooling under the climate of Thailand. The assessment was considered from water scarcity, meteorological data and engineering analysis, including moisture harvesting index (MHI), water capability and energy cost. The meteorological data between 2012-2021 were used as primary data for engineering analysis. The results showed that Thailand has the potential to supply freshwater by using AWH with direct cooling. The average MHI of Thailand is 0.548 which is comparable with high potential of global assessment. 71 cities from 77 cities in Thailand have MHI over 0.50, which is the favorable condition for AWH by direct cooling. From the calculation under Thailand conditions, the water harvesting rates by direct cooling could be in the range of 0.97-1.30 L/h with energy costs as low as 0.047 USD/L for 71 cities in Thailand.

### KEYWORDS

Atmospheric water harvesting;  
Moisture harvesting index;  
Thai meteorological data;  
Direct cooling;  
Water scarcity.

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## 1. Introduction

Freshwater scarcity is an emerging issue globally. The global population growth unbalanced the global water demand. For decades of the twenty-first century, the increase in global water consumption is 600% for global population growth by 300% [1], [2]. Moreover, climate change and man-made contamination in water sources increase the level of water scarcity. To supply freshwater, there are technologies to obtain or treat freshwater, e.g. reverse osmosis, filtration, distillation and purification. These technologies are available in areas where they are near water sources such as the sea or underground water. For remote and landlocked areas, it is difficult to use these technologies because the water sources are limited.

Atmospheric water harvesting (AWH) is a promising solution for water shortage, because moisture in the air or atmospheric water is available everywhere and free from hydrologic conditions [3]. Atmospheric water is presented in the form of vapor or droplets in the air about 13,000 km<sup>3</sup> of water [1]. Moreover, the natural atmospheric water cycle makes this alternative freshwater source reliable and sustainable. There are several types of AWH, e.g. direct cooling, thermoelectric effect, underground condensation desiccants and natural structures [4]. For desiccants and natural structures, the moisture is collected by sorption and desorption process, while AWH by direct cooling, thermo-electric effect and underground condensation forced the moist air to a dew point where the condensation is obtained. Among these technologies with high efficiency and capacity, the practical AWH is now only AWH by direct cooling as reviewed in [4], [5]. However, efficiency, water production rate and cost of AWH by direct cooling depend on the climate. It is favorable under high temperature and humidity conditions [6]. The minimum humidity to obtain a good performance of AWH by direct cooling is greater than 30%. The energy cost of commercial AWH by direct cooling is about 50% of the total cost for operation [4].

Moisture harvesting index (MHI) is a parameter for evaluating the energy requirement and capability of AWH by direct cooling. To estimate the MHI, the meteorological data were used to calculate the energy interaction between energy for water condensation and total energy used for the cooling process. From global MHI assessment of different locations by Gido et al. [7], they concluded that the most suitable condition was found in the tropical region, i.e. MHI = 0.59 at the Cabanatuan in Philippines, and production cost is reasonable if MHI is greater than 0.3.

Thailand is a tropical country where almost 2/3 of locations in Thailand faced drought in short duration every year since 2019, and water scarcity trends to be longer [8]. Although Thailand experienced water shortage for months, the average lowest-relative humidity in drought periods is as high as 60%. With high humidity and temperature, it is possible to use AWH by direct cooling in Thailand. However, there is no precise information on the potential of AWH by direct cooling in Thailand, and engineering analysis has not yet been fully assessed. Therefore, the objective of this study is to investigate the feasibility of atmospheric water harvesting by direct cooling under the climate of Thailand from an engineering perspective. The drought situation and climate in Thailand are initially discussed to understand the context of Thailand. The engineering analysis, including moisture harvesting index, water harvesting rate, energy consumption and energy cost of water production, is then presented to assess the potential of Thailand for AWH based on direct cooling.

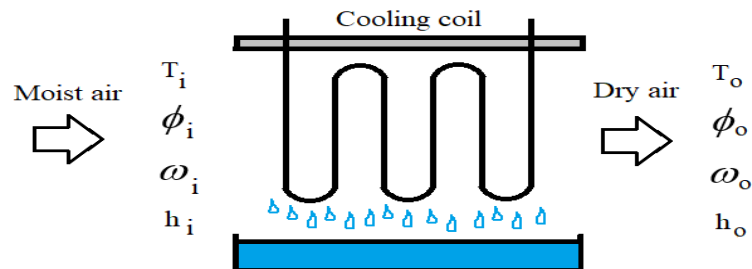
## 2. Methodology

### 2.1. Atmospheric Water Harvesting by Direct Cooling

The principle of atmospheric water harvesting (AWH) by direct cooling is simply explained in Fig. 1. Moist air is cooled by a cooling system until water vapor is saturated at dew-point temperature. Then liquid water droplet is obtained at the cooling surfaces and collected in a bath. The important thermodynamic properties for AWH are dry-bulb temperature ( $T$ ), humidity ratio ( $\omega$ ), relative humidity ( $\phi$ ) and enthalpy of moist air ( $h$ ). Their correlations are shown in (1) and (2) [9].

$$\omega = 0.622P_v/(P-P_v)$$

$$\omega = 0.622\phi P_g/(P-\phi P_g) \quad (1)$$



**Fig. 1.** Atmospheric water harvesting by direct cooling.

$$h = h_a + \omega h_g \quad (2)$$

where  $P$  = atmospheric pressure or moist air pressure (kPa)

$P_v$  = partial pressure of water vapor (kPa)

$P_g$  = partial pressure of saturated water vapor (kPa)

$h$  = enthalpy of moist air (kJ/kg<sub>a</sub>)

$h_a$  = enthalpy of dry air (kJ/kg<sub>a</sub>) =  $C_{pa}T$

$h_g$  = enthalpy of saturated vapor (kJ/kg<sub>w</sub>)

$$= h_{g@0^\circ C} + C_{pv}T$$

$h_{g@0^\circ C}$  = enthalpy of saturated vapor at 0 °C (kJ/kg<sub>w</sub>)

$C_{pa}$  = specific heat of air (kJ/kg<sub>a</sub> °C)

$C_{pv}$  = specific heat of vapor (kJ/kg<sub>w</sub> °C)

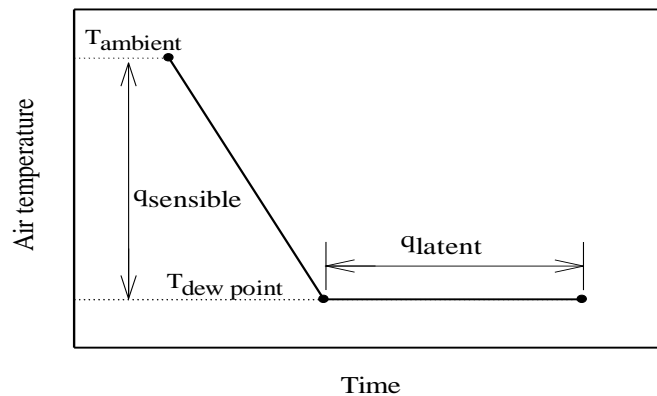
## 2.2. Moisture Harvesting Index (MHI)

For atmospheric water harvesting by direct cooling, the desired product is liquid water. Total heat removed from moist air consists of sensible and latent heats as shown in Fig. 2. Latent heat removal is required for vapor condensation, while sensible heat removal is used for temperature reduction considered as an overburdened cooling load. The thermal efficiency of the system depends on the ratio of heat removal. Higher thermal efficiency can be obtained with smaller sensible heat involved. Under constant atmospheric pressure, the total heat removal from the air to produce 1 kg of liquid water is the sum of sensible heat and latent heat which is obtained by the enthalpy difference between atmospheric air ( $h_i$ ) and outlet air of AWH device ( $h_o$ ) shown in (3).

$$q_t = (h_i - h_o) / (\omega_i - \omega_o) \quad (3)$$

where indices i and o stand for inlet and outlet conditions. The difference in humidity ratio at inlet and outlet ( $\omega_i - \omega_o$ ) in (3) is used to change the unit from kJ/kg<sub>a</sub> to kJ/kg<sub>w</sub> for the total heat for harvesting 1 kg of liquid water.

With heat removal interaction, the moisture harvesting index (MHI) can be defined as the ratio of the latent heat removal to total heat removal as shown in (4) for evaluating the overall energy used by AWH system [7]. In this study, the cooling coil temperature of 4 °C, where condensation takes place, was used as the reference point that is referred to the condition of commercial AWH systems. However, any dew-point temperature of water vapor can be able to calculate MHI by using (4).



**Fig. 2.** Heat interaction during atmospheric water harvesting process.

$$MHI = q_l / q_t = h_{fg@de\text{w point}} (\omega_i - \omega_o) / (h_i - h_o) \quad (4)$$

where  $q_l$  = latent heat removal (kJ/kg<sub>w</sub>) =  $h_{fg@de\text{w point}}$

## 2.3. Energy Consumption

The coefficient of performance (COP) influences on energy demand of AWH system. In practice, COP of AWH system can be estimated from the ratio of total heat removal ( $q_t$ ) to work required for system ( $W$ ) as

$$COP = q_t / W \quad (5)$$

Then the energy consumption of AWH system can be calculated by

$$EC = \rho_w W / 3600 = \rho_w q_t / (3600 COP) \quad (6)$$

where EC is energy consumption (kWh/L),  $\rho_w$  is water density (kg/L). From (4), the total heat removal can be rewritten as

$$q_t = h_{fg@de\text{w point}} / MHI \quad (7)$$

In this work, COP of 4 and 5 was chosen for calculation. COP of 4 is typical for general air conditioners. However, COP of 5 is possible for AWH system because cold air after cooling coil was returned to cool intake air and the condenser coil [7], [10].

#### 2.4. Water Harvesting Rate

Water Harvesting Rate corresponding to the calculated MHI can be estimated with an assumption that the temperature of inflow air can be decreased to the dew-point temperature. The water harvesting rate depends on the cooling capacity of the AWH and total heat removal as shown in (8).

$$V_w = Q_c / \rho q_t = Q_c / \rho (h_{fg} / MHI) \quad (8)$$

where  $V_w$  = water harvesting rate (L/h)

$\rho$  = water density (kg/L)

$Q_c$  = cooling capacity of AWH system (kW)

For residential use, the nominal power for AWH device with capacity of 30 L/day is 1.5 kW [1].

### 3. Results

The assessment of the possibility of use of AWH by direct cooling in Thailand was considered from water scarcity, climate, engineering analysis and the energy cost of water production.

#### 3.1. Drought Situation in Thailand

Although Thailand has abundant rain and a lot of fresh water resources, almost 2/3 areas of Thailand face with a short period of drought and water shortage every year during 2019-2021 as shown in Fig. 3. These areas covering 30,619 villages were announced as drought disaster areas by the department of disaster prevention and mitigation of Thailand [8]. Most of drought disaster are in land and far from the sea. With conventional solutions, e.g. well drilling and water delivery, the Thai government have spent millions USD for this crisis [11].



**Fig. 3.** Water scarcity locations in Thailand for a short period during 2019-2021.

### 3.2. Climate of Thailand

The climate of Thailand was classified as tropical and savanna types by the Köppen-Geiger climate classification [12]. Yearly statistic meteorological data of all locations of Thailand (77 provinces) [13] was plotted as shown in Fig. 4. The average and lowest RH are 74% and 56%, respectively. In comparison with the minimum RH requirement, i.e. 30%, for AWH by direct cooling [4], the RH of Thailand is much higher. It can be implied that AWH by direct cooling is available in Thailand. However, more engineering analysis is required. MHI, water harvesting rate, energy consumption and cost were reported in the next section.

### 3.3. Atmospheric Moisture Harvesting of Thailand

With the meteorological data for the years 2012-2021, the moisture harvesting index (MHI) calculated by (4) was plotted versus air temperature and relative humidity as shown in Fig. 5. Favorable conditions for AWH occurred at high temperature and high relative humidity. The average, lowest and highest MHIs in Thailand are 0.548, 0.452 and 0.595, respectively. The average MHI of Thailand is comparable with the average MHI of Cabanatuan (Philippines), where it is the most suitable location for AWH calculated by using global meteorological data [7]. However, the highest MHI of Thailand is as high as the average MHI of Cabanatuan.

Fig. 6 shows the average MHI map of Thailand separated by province. It is clear that higher MHI is available in eastern and southern, located near the sea, while inland areas, i.e. northern and northeastern, show smaller MHI due to higher altitude which has lower relative humidity and temperature. In addition, high mountains in northern and northeastern Thailand obstruct moisture transport from the sea. Low MHI

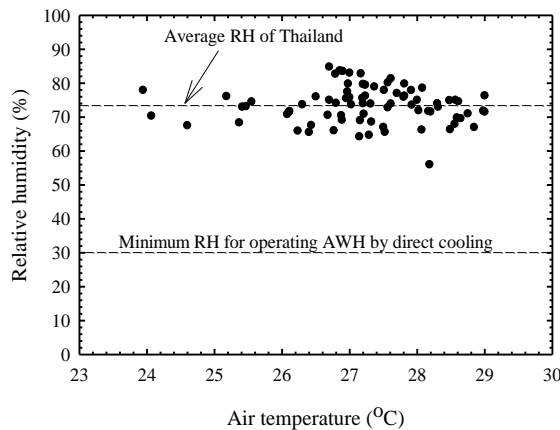


Fig. 4. Air temperature vs relative humidity (RH) of Thailand for all locations plotted from meteorological data during 2012-2021.

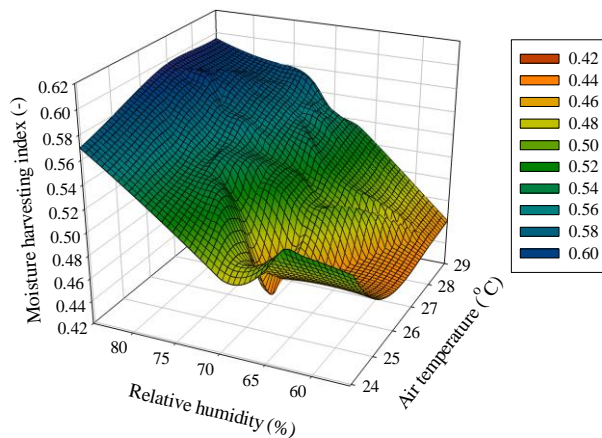
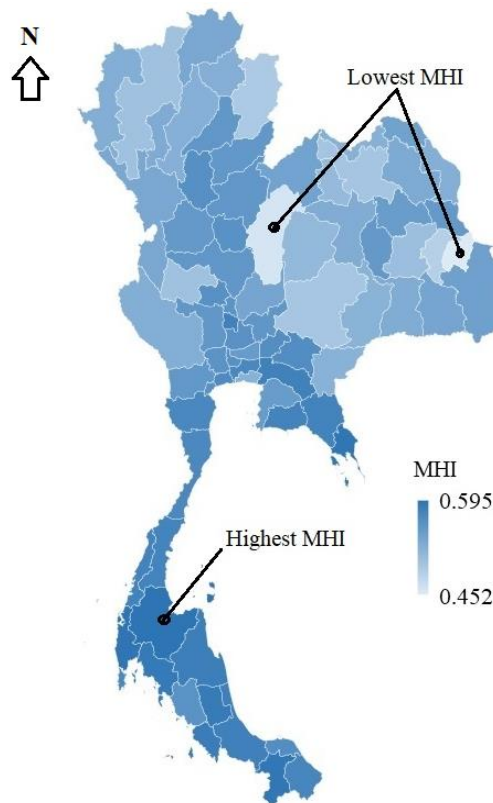


Fig. 5. Moisture Harvesting Index (MHI) vs air temperature and relative humidity of Thailand using meteorological data for the years 2012-2021.

due to high mountains obstruction can also be observed in the middle west areas. From the average MHI category of Thailand shown in 0, over a half of cities in Thailand has MHI higher than 0.55, and only 7.79% of MHIs is less than 0.50, where the energy over 50% is used for air cooling rather than water condensation. However, the lowest MHI in Thailand, i.e. 0.452, is still available for AWH, compared with the minimum favorable condition (MHI=0.3) [7].

Fig. 7 shows the water harvesting rate and energy consumption related to the moisture harvesting index. Water harvesting rate increases linearly with increased MHI. With the assumption of continuous operation, water harvesting rates are in the range of 0.97-1.30 L/h for MHI of Thailand. Energy consumption was calculated by using (6) based on COP of 4 and 5. COP of 4 and COP of 5 represent the AWH system with and without sensible heat recovery, respectively. The energy consumption for COP of 5 is lower approximately 6% than that of COP of 4 for MHI range of Thailand. As expected, the energy consumption decreases as MHI increases because higher MHI requires smaller sensible heat removal and most of the heat removal from air spend on latent heat. Therefore, AWH system working at higher MHI consumes lower energy. Unfortunately, water harvesting rate and energy consumption shown in Fig. 7 were only calculated from the average monthly climate data. Daily and seasonal climate conditions are not available. Therefore, this work cannot specify the appropriate time for AWH by direct cooling during the day in the seasons. This could be the future work of assessment of suitable times for daily water production in Thailand.



**Fig. 6.** The MHI map of Thailand.

**Table 1.** Category of the Average MHI

MHI	Number of Province	%
0.452<MHI<0.50	6	8
0.50<MHI<0.55	29	38
MHI>0.55	42	54

Fig. 8 shows the energy cost of water production with COP of 4 and 5 which was calculated at an electrical rate of 0.135 USD/kWh [14]. The energy cost of water production decreases with increased MHI, corresponding to energy consumption in Fig. 7. The energy cost of AWH with COP of 5 is lower than that of COP of 4 for all MHI as expected. Considering  $MHI > 0.50$ , for COP of 4, the energy costs of water production for AWH by direct cooling are less than 0.047 USD/L for 71 cities from 77 cities in Thailand. With this energy cost, the atmospheric water harvesting by direct cooling may be applicable for water shortage in Thailand, especially the locations where they are scattered communities and far from the infrastructure. However, the experimental study of AWH by direct cooling to compare with other technologies for AWH is required under climate in Thailand. Moreover, the novel technology is also required to be practical and optional solutions to reduce the production cost of AWH.

#### 4. Conclusions

The feasibility of atmospheric water harvesting (AWH) by direct cooling in the case of Thailand was investigated. The water scarcity, climate, moisture harvesting index (MHI), water production rate, energy consumption and energy cost of production were used for assessment. MHI was estimated based on the meteorological data of Thailand during 2012-2021. The main conclusions from this study are as follows.

- The average MHI of Thailand is 0.548. The lowest MHI of Thailand is 0.452 which is still available for atmospheric water harvesting compared with the minimum favorable MHI required.
- There are 71 cities from 77 cities in Thailand that show  $MHI > 0.50$  (most of the total energy used for water condensation).

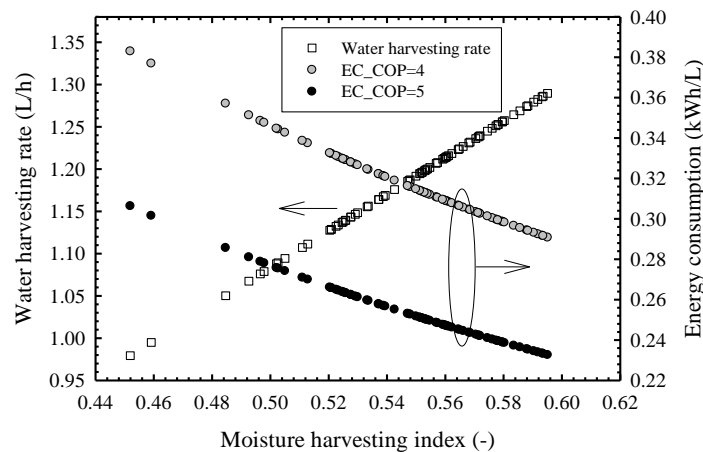


Fig. 7. Assessment of water harvesting rate and energy consumption under climate condition of Thailand at cooling coil temperature of 4 °C of 1.5 kW AWH device.

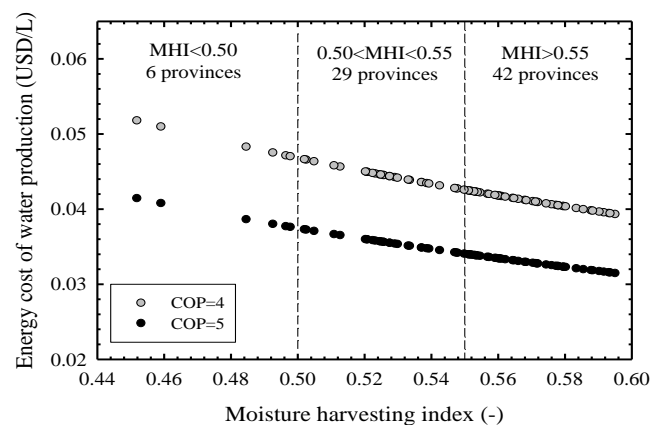


Fig. 8. Energy costs of water production of AWH device ( $COP = 4$ ) at the range of moisture harvesting index of Thailand.

- With continuous operation, water harvesting rates by direct cooling under Thailand's climate are in the range of 0.97-1.30 L/h, and they increase linearly with increased MHI, while energy consumption shows an inverse trend with the water harvesting rate. COP of AWH system plays a crucial role for energy consumption.
- The energy costs of water production for AWH by direct cooling with COP of 4 are less than 0.047 USD/L for 71 cities in Thailand.

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