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Assessment of Atmospheric Water Generator for Rural and Remote India

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Abstract: *With increasing human population drinking water demands are going to constantly increase which is expected to deplete water sources at ever increasing rate. United Nations SDG goals recognize this issue and identifies access to safe water is essential to human health and to environmental sustainability and economic prosperity of human kind. To cater to this need Government of India has initiated a program called "Har Ghar Jal" to provide safe drinking water to every household premise in India by 2030. In this paper, current national scenario on drinking water and its challenges are analyzed for rural and remote areas of India. Alternative water source namely atmospheric water has been assessed and atmospheric water generator (AWG) technology requirements have been reviewed for "Har Ghar Jal" program. Finally, AWG technological challenges for meeting the requirements have been identified and solution space for the challenges have been defined. The assessment suggests AWG technology would be able to meet all technological challenges for "Har Ghar Jal" targets and AWG has negligible effect on environment.*

Keywords **-** *AWG, SDG, Har Ghar Jal, superhydrophobic surface, supercapacitor*

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I. Introduction

The Sustainable Development Goals (SDGs) are a set of 17 "Global Goals" under a United Nations Resolution (Paragraph 54, Resolution: A/RES/70/1 of 25 September 2015) which has been built on the principles of "The Future that we want" [1]. It is a broader intergovernmental agreement involving 193 member countries of United Nations which cover a broad range of social and economic development issues. *SDG6: Clean Water and Sanitation* wants to ensure availability and sustainable management of water and sanitation for all. SDG6 has eight targets and 11 indicators that will be used to monitor progress toward the targets (Table I). The indicator framework was released in 2016. Out of eight targets six (6.1, 6.2, 6.3, 6.4, 6.5 & 6.A) are to be achieved by 2030 while one by 2020 (6.6) and left one has no target year (6.B).

Table I. SDG6 targets and indicators [1]

Target No.	SDG6 Targets	Indicator No.	SDG6 Indicators
66.1	By 2030, achieve universal and equitable access to safe and affordable drinking water for all	6.1.1	Proportion of population using safely managed drinking water services
66.2	By 2030, achieve access to adequate and equitable sanitation and hygiene for all and end open defecation, paying special attention to the needs of women and girls and those in vulnerable situations	6.2.1	Proportion of population using safely managed sanitation services, including a hand-washing facility with soap and water
66.3	By 2030, improve water quality by reducing pollution, eliminating dumping and minimizing release of hazardous chemicals and materials, halving the proportion of untreated wastewater and substantially increasing recycling and safe reuse globally	6.3.1	Proportion of wastewater safely treated
		6.3.2	Proportion of bodies of water with good ambient water quality
66.4	By 2030, substantially increase water-use efficiency across all sectors and ensure sustainable withdrawals and supply of freshwater to address water scarcity and substantially reduce the number of people suffering from water scarcity	6.4.1	Change in water-use efficiency over time
		6.4.2	Level of water stress: freshwater withdrawal as a proportion of available freshwater resources
66.5	By 2030, implement integrated water resources management at all levels, including through transboundary cooperation as appropriate	6.5.1	Degree of integrated water resources management implementation (0-100)
		6.5.2	Proportion of transboundary basin area with an operational arrangement for water cooperation

66.6	By 2020, protect and restore water-related ecosystems, including mountains, forests, wetlands, rivers, aquifers and lakes	6.61	Change in the extent of water-related ecosystems over time
66.A	By 2030, expand international cooperation and capacity-building support to developing countries in water- and sanitation-related activities and programmes, including water harvesting, desalination, water efficiency, wastewater treatment, recycling and reuse technologies	6.A.1	Amount of water- and sanitation-related official development assistance that is part of a government-coordinated spending plan
66.B	Support and strengthen the participation of local communities in improving water and sanitation management	6.B.1	Proportion of local administrative units with established and operational policies and procedures for participation of local communities in water and sanitation management

Government of India through its Ministry of Drinking Water and Sanitation has set an ambitious target of meeting water for every home by 2030 in line with SDG target 6.1 [2]. The target is popularly called “Har Ghar Jal” and it strives to provide drinking water source at the household premises which will be available when needed and will be free of fecal & priority chemical contamination.

In this paper, atmospheric water will be assessed for its suitability as alternative natural resource for drinking water and how available technologies can be redesigned to suit India’s rural and remote areas to achieve “Har Ghar Jal”. Section 2, provides details of India’s national scenario on purified drinking water and quality of water and its effects on Indian population. Section 3 assesses atmospheric water as drinking water source in terms of available quantity, state wise distribution over a year and provides advantages of using the source. This section also provides assessment of environmental effect under the scenario if all Indian households uses AWG machines simultaneously. Section 4 describes AWG technologies and how cost-effective machines can be designed to suit the needs to “Har Ghar Jal” in rural areas. Section assumes rural and remote areas have identical needs.

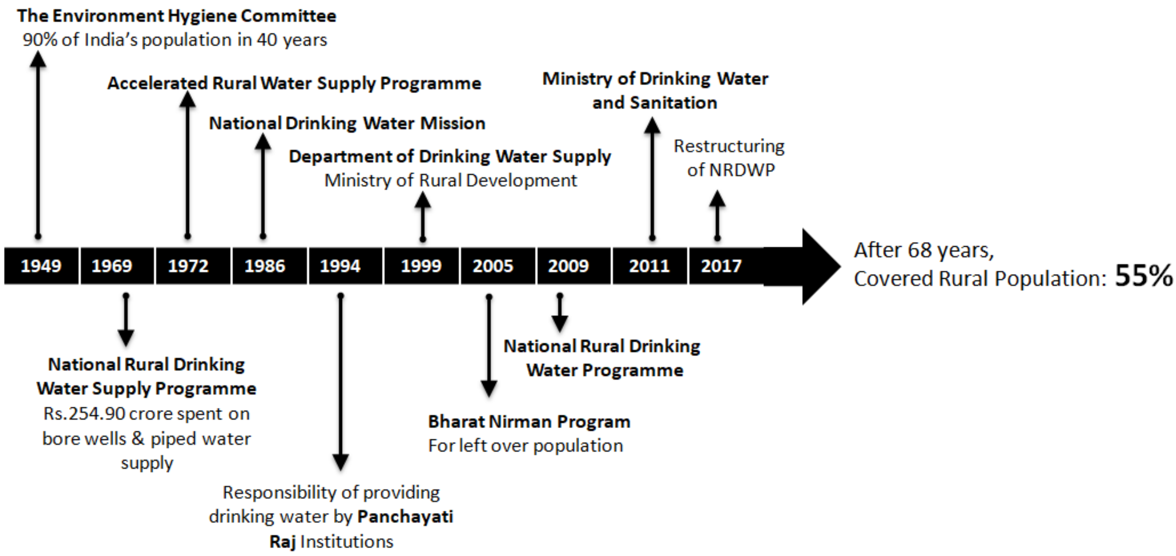


Fig. 1 Brief history of Government of India’s efforts in providing drinking water to its citizens [3].

II. Indian Rural Scenario: Purified Drinking Water

Drinking water efforts were first initiated for its citizen by Government of India in 1949. A brief history of the efforts is provided in Fig. 1. Since 1956, the total spending on account of providing rural piped water to Indian citizens have been ~□ 2,26,888 crores by Government of India and State Governments (Fig. 2) together [3]. These efforts have been successful in providing piped water supply to only 55% of rural populations till 2016 [2] and only 15% of rural population has piped water connections at premises. The major reasons for such low achievement are population growth, strained resources and pilferage.

2.1 Quality of Water

The quality of water is very important for general health of a human being. Microorganism contaminated water can cause water borne diseases like enteric fever, hepatitis, typhoid, cholera etc.; while chemical contamination from pesticides (agricultural and health prevention), industrial pollution (nitrate, sulphate, mercury, cadmium etc.) and natural pollution (arsenic, chloride, fluoride etc.) can cause health issues such as brain retardation, blood toxicity, tissue deformation etc. Thus, safe or purified drinking water which adheres to prevalent standards is essential for minimizing health risks and diseases. Indian piped water supply maintains BIS-IS:10500 standard (Table I) and piped water supply habitations where there is slippage against the standard is provided in Fig. 3. The highest slippage is ~28% of habitations in Tripura and there are five states which are above 10% slippage.

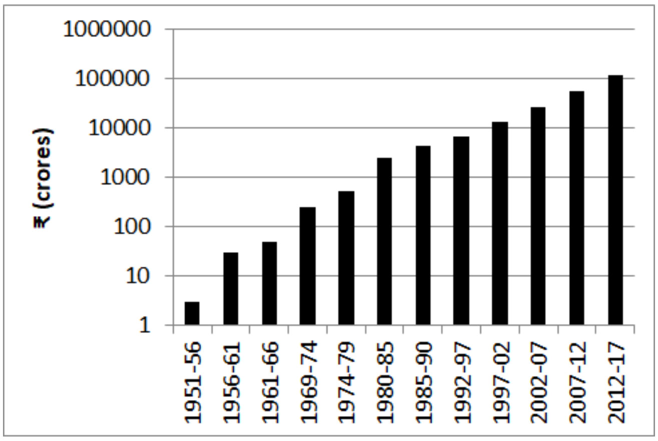


Fig. 2 Non-Purified Water spending in India by Central and State Governments since 1951 [4].

Contamination of water during supply, storage and consumption is unavoidable in piped water infrastructure in India as extensive growth of microorganisms is encouraged by environmental factors such as temperature.

Table I. Indian standard [5] for piped drinking water and comparison with WHO standards [6]. Comprehensive review of the standards is beyond the scope of this work.

Parameter	BIS IS:10500 Permissible limits (mg/l)	World Health Organization Guideline values (mg/l)
Essential Characteristics		
Colour	25 CHU	15 TCU
Odour	Unobjectionable	Free of odours
Taste	agreeable	Free of taste
Turbidity (NTU)	10	< 0.5
pH	6.5-8.5	6.5-8.6
Total Hardness	600 (CaCO3)	100 - 300 (Ca ion)
Iron (Fe)	1	2
Chloride (Cl)	1000	250
Residual Free Chlorine	250	-
Fluoride (F)	1.5	1.5
Desirable Characteristics		
Dissolved Solids	2000	1000
Calcium (Ca)	200	-
Magnesium (Mg)	100	-
Copper (Cu)	1.5	2
Manganese (Mn)	0.3	-
Sulphate (SO4)	400	500
Nitrate (NO3)	100	50
Phenolic compounds	0.002	-
Mercury (Hg)	0.001	0.006
Cadmium (Cd)	0.01	0.003
Selenium (Se)	0.01	0.04
Arsenic (As)	0.05	0.01
Cyanide (CN)	0.05	0.006
Lead (Pb)	0.05	0.01
Zinc (Zn)	15	0.5
Hexavalent Chromium	0.05	0.05
Alkalinity	600	-
Aluminium (Al)	0.2	0.9
Boron (B)	5	2.4
Pesticides	0.001	0.001*

** Guideline value of pesticides used for public health purposes. Additional 31 agricultural pesticide guideline values exist.*

The piped water is generally unfit for consumption and requires purification at point-of-use. This is evident from fecal coliform tests and water borne disease data as shown in Fig. 4, which shows at least four states have failed fecal coliform tests between 2%-10% for 2016-17 and 60% increase in water borne disease cases over a period of recent six years from ~10 million cases to ~16 million cases.

The problem of lack of safe drinking water in India is so acute that one study claimed that India has the highest number of people (758 lakhs) in the world without access to safe or purified drinking water [7]. Purified drinking water is available to Indian citizens through bottled water and water purifiers (point-of-use systems and commercial systems). The current bottled water market in India is expected to be ~14 million cubic meters (MCM) and these waters follow IS:13428:1998 and IS:14543:2004 Indian standards. For point-of-use devices industry lead standards are also available. Water Quality India Association (WQA India) provides one such water quality standards based on ISO/ IEC 17067:2013(E). It is a comprehensive drinking water treatment guide standard for devices that perform microbiological treatment of water. This standard chose bacteria, viruses and disinfectant resistant parasites (cysts) as the key targets and the standard is relevant to water of unknown origin.

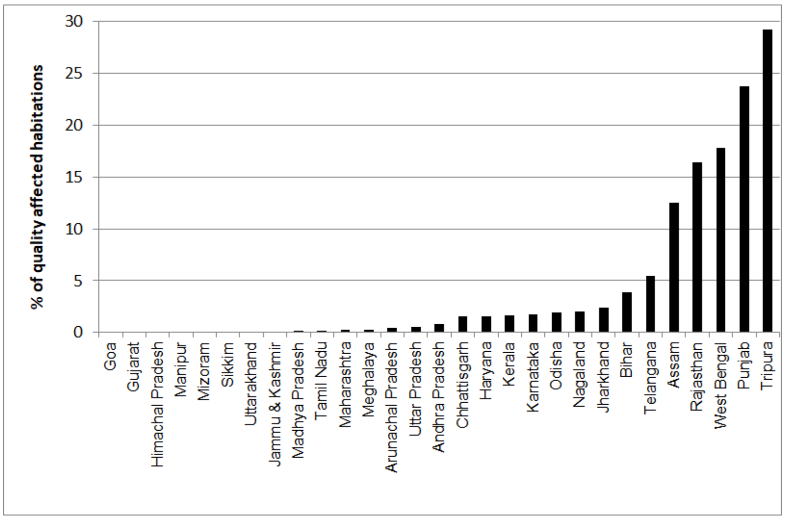
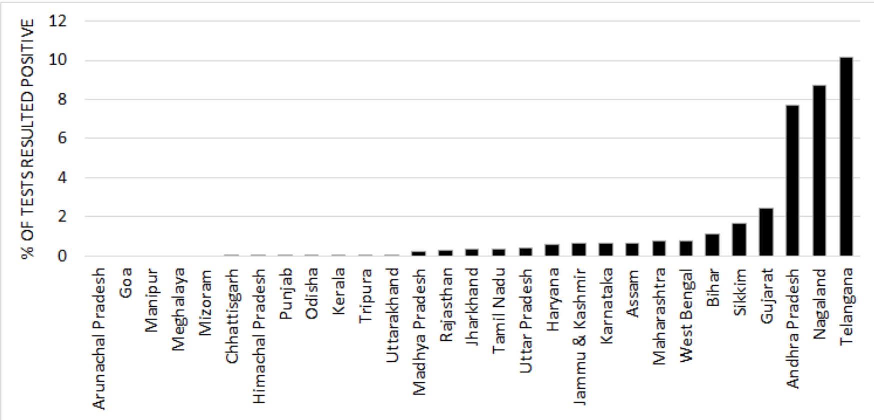


Fig. 3 State-wise quality affected habitations during 2016-17 [3,4].

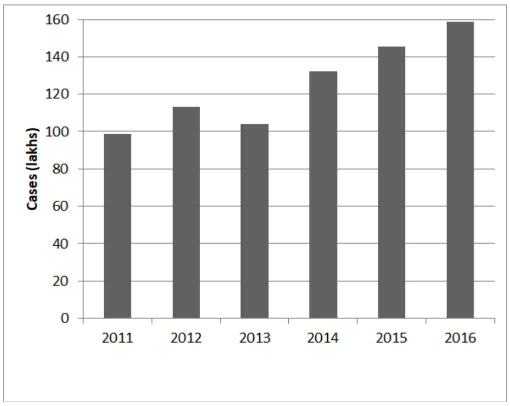
Currently, rural 20 liter bottled water prices are ~93% lower than urban bottled water prices [8]. However, bottled water market has more penetration in urban than rural markets. Similar situation of lack of penetration in rural market also prevails for water purifier market where it is expected to grow at 15.4% CAGR from ~□714 crores to ~□2663 crores during 2016-2022 mostly in urban areas [9]. The current safe drinking water requirement in rural masses is ~1.29 billion cubic meters (BCM). The major challenges for penetration into such a large rural market by purifier or bottled water for “Har Ghar Jal” are: (a) ground/ surface water is considered the only continuous source of water at premises which are at a decline in entire country, (b) affordability of safe drinking water and (c) lack of acceptability of extra spending for safe drinking water by rural population. Description and solutions for issues (a) and (b) are provided in subsequent sections. Acceptability of purified cheap drinking water can be increased by taking up awareness campaigns. One successful model from bottled water industry is Piramal Sarvajal franchise model in India which is extending ~8 touch points every month since last 10 years in rural India [8]. This is possible due to first three months extensive awareness cum advertisement campaign by the company whenever they start a touch point for their 20 liter bottle water at □ 0.30 per liter product. The successful model is serving 4,30,000 consumers daily, through 1000 touch-points across 16 states**.**

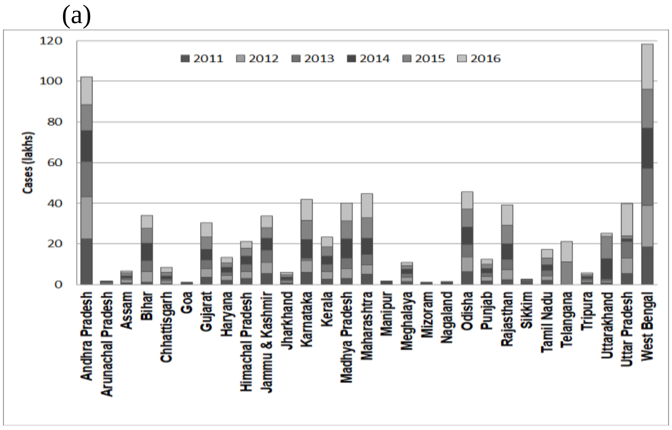
III. Atmospheric water as drinking water source

According to estimates, average annual water availability in India due to precipitation received is 4000 BCM, out of which ~47% has water resource potential and utilizable water resource is only 28.1% (10.8% Ground water & 17.2% surface water) [10]. Approximately 85% of the drinking water source in India is ground water and rest is surface water. Ground water depletion is serious issue in India; ~56% of country is suffering from lowered ground water levels [11]. Thus, additional natural resources which are not ground water or surface water is required.



(a)





(b) (c)

Fig. 4 (a) State-wise percentage of positive fecal coliform test 2016-17, (b) Total number of waterborne disease cases over a period of six years (2011-2016), (c) Sate-wise distribution of number of waterborne disease cases over a period of six years (2011-2016) [12].

Estimates for atmospheric water (when liquified) in India is ~1360 BCM which is close to utilizable water resource of ~1123 BCM (Ground water – 433 BCM and Surface water – 690 BCM). India's current population estimate is 1,324,171,354 (2017) [13] which leads to an estimated requirement of ~2 BCM safe drinking water annually. This estimate includes water for human consumption only and does not include water required for other requirements of daily life like cooking, washing, cleaning etc. Fig. 6 shows the monthly variation of availability of atmospheric water Indian state wise based on measured vapor pressure and averaged over 100 years [14]. Thus, most parts of India have significant atmospheric water content throughout the year. It is evident that around monsoon season (May - October) the atmospheric water content is very high in all states, and north eastern states & costal states have significantly higher atmospheric water content than inland states. State of Jammu and Kashmir is the driest state in India all throughout the year followed by state of Sikkim. Hence, atmospheric water can be considered as one of the natural resources for drinking water in India. Full replacement of ground water as drinking water source with atmospheric water is expected to release 10% pressure on ground water reserves in India (Fig. 7) and additional ~0.15% condensation over 3.3 million sq. Km is not expected to cause any serious environmental issues to hydrologic system. Other advantages of using atmospheric water as drinking water source are provided below:

- Atmospheric water is an alternative natural resource to ground or surface water sources which is untapped currently.
- Atmospheric water is precipitation independent source.
- Atmospheric water is free from fecal contamination as well as natural & manmade contaminations which ground water suffers from. Atmospheric pollution is easily removable with modern technology.
- House hold capacity atmospheric water generators do not require extensive backend infrastructure which is required for piped water supply.
- Atmospheric water generator can be deployed directly to premises which is one of the goals of "Har Ghar Jal" program of Government of India.

- There are ~250 million households [15] in India and based on current lowest market price of atmospheric generators in India the total potential annual economy is □ 4 lakh cores (Rural - □ 2.72 lakh crores) that could potentially provide large additional employment opportunities in entire value chain of such products.

		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
Inland States													
1	Bihar	13	14	14	17	25	31	33	34	32	25	17	14
2	Chattisgarh	13	13	12	13	17	24	31	30	29	23	16	13
3	Delhi	9	9	9	10	14	23	29	30	25	14	10	9
4	Haryana	9	10	10	12	15	23	30	30	25	15	11	10
5	Himachal Pradesh	9	10	11	12	15	22	28	29	24	16	11	10
6	Jammu and Kashmir	5	6	7	9	10	14	19	20	15	10	7	5
7	Jharkhand	13	14	14	17	24	30	31	31	30	23	16	13
8	Madya Pradesh	9	9	8	9	14	25	30	29	26	15	10	10
9	Punjab	9	10	13	14	16	23	30	31	26	18	13	10
10	Rajasthan	8	9	10	12	15	23	28	29	24	15	10	9
11	Uttar Pradesh	9	9	9	10	14	24	30	30	25	15	10	10
12	Uttarakhand	10	10	10	12	16	24	30	30	26	16	11	10
13	Sikkim	7	7	8	11	14	17	18	18	17	14	9	8
Eastern Costal States													
14	Tamil Nadu	21	22	24	28	29	27	27	27	28	27	24	23
15	Andhra Pradesh	14	14	14	19	21	25	25	24	25	20	16	14
16	Orissa	14	16	16	19	22	28	30	30	30	24	17	14
17	West Bengal	15	16	18	23	28	32	33	34	32	27	20	16
Western Coastal States													
18	Gujrat	9	10	11	15	22	28	30	29	27	15	12	10
19	Karnataka	12	12	12	16	18	24	25	24	24	18	14	12
20	Maharashtra	12	12	13	19	22	28	29	27	26	9	15	13
21	Kerala	23	24	26	28	29	29	28	28	28	28	27	24
North Eastern States													
22	Arunachal Pradesh	11	12	13	16	20	23	25	25	24	20	15	12
23	Assam	14	15	17	21	26	30	31	31	30	26	19	16
24	Meghalaya	15	16	18	23	28	32	32	33	32	27	21	16
25	Mizoram	15	16	19	24	27	30	30	31	30	27	21	17
26	Nagaland	12	13	15	18	22	26	27	27	26	22	17	13
27	Tripura	21	22	24	28	29	27	27	27	28	27	24	23
28	Manipur	12	13	15	19	22	26	26	26	26	23	18	14

Fig. 6 Indian State wise monthly availability of atmospheric water based on vapor pressure averaged over 100 years.

IV. Atmospheric water generators: Technologies

Atmospheric water generators (AWG) are machines that extract water from humidity of ambient air. Water vapor in the air is condensed by cooling the air below its dew point, exposing the air to desiccants, or pressurizing the air. Number of different technologies are present for such purpose like cooling condensation using refrigerant circulation with compressor or Peltier cooling and wet desiccation with application of salts. Fuel cells are also capable of producing water from ambient air. Out of these, cooling condensation using refrigerant circulation with compressor is most popular and have diverse product ranges available in the market due to the fact that the technology is similar to already established domestic dehumidifiers, except the condensate is disinfected to manage the quality of drinking water from microbial agents and others which might breed on a moist condenser. Patent landscape for AWG reveals that refrigeration assembly may also be combined with heating and humidity enhancing techniques to enhance liter per unit energy [16]. Cooling coil technology when powered by thermal electricity provides high carbon footprint due to high energy requirement of condensation process using cooling coil. Peltier cooling is an emerging technology in this area and provides lower power and higher liter per energy requirement for similar capacity device [17] and thus is suitable for renewable energy such as solar power. Powering refrigeration cooling technology with solar is possible, however, additional solar panel cost is higher than Peltier technology due to lower power requirement of later. Peltier technology suffers from heating issues which requires expensive packaging technology. In this paper, the focus will be on design challenges of AWG machines with refrigeration-based cooling that will be suitable for rural and remote areas especially affordability wise to help current AWG industry to penetrate Indian rural market. Currently, all commercially available AWG machines in India have high capital cost and running cost. They are even unaffordable to most urban consumers. Hence, to improve rural affordability frugal design with renewable energy will be considered

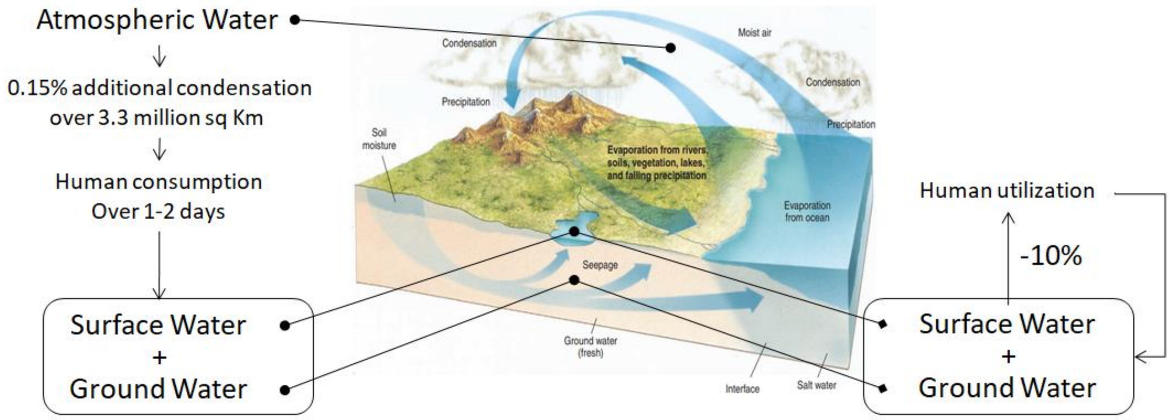
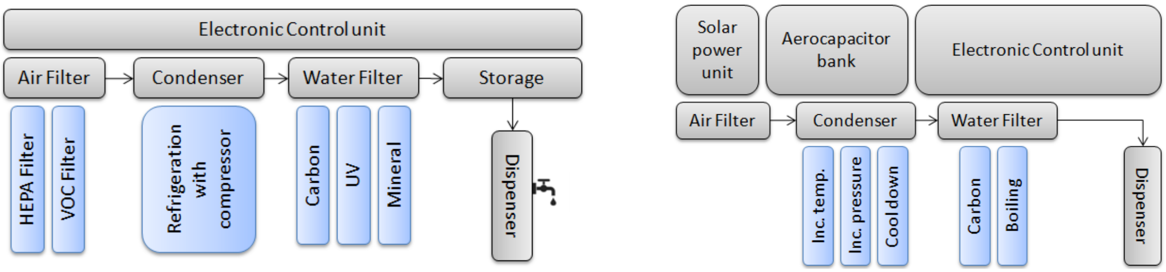


Fig. 7. Expected effects on Hydrologic System due to introduction of atmospheric water as source for drinking water in India.

Schematic diagram of typical AWG machine is shown in Fig. 8(a), in which humid air enters through air filtration system. The air filtration system is comprised of High Efficiency Particulate Air (HEPA) filters to filter out PM2.5 particles and Volatile Organic Chemical (VOC) carbon filters which filters out large organic molecules and odors from the air. Water vapor in the clean air is condensed by cooling the air below its dew point. Cooling is achieved using refrigerant cycling through food grade copper tubing. The refrigerant is cycled by compressor with in the tube. The liquid water condenses on the copper pipes and is filtered (using a combination of carbon and UV filters) and mineralized to achieve water quality standards. The water is stored in storage until dispensed. UV filters are often used in the stored water repeatedly to keep the water microorganism free.



(a) (b)

Fig. 8. (a) Schematic diagram of typical technology for AWG with refrigeration, (b) proposed improvement for lowering cost of AWG machine for penetration of Indian rural market.

An AWG machine suited to "Har Ghar Jal" needs to provide 20 liters/ day at 30% Relative Humidity (based on national average of 4.8 persons per household [15] and 4 liters per person per day requirement of consumable drinking water [3]) at probable price point of current rural bottled water price of □ 0.30 per liter. A typical AWG with such capacity requires ~ 400W or above [18]. To reduce the capital cost and running cost of the machine one needs to target the highest costing parts in bill-of-materials (BOM) and reduce the overall system power requirement from 400W and below. The top three costliest parts in BOM are compressor, carbon filter and mineralization unit. Adopting renewable power source which generates electrical power on site such as solar or wind power sources can reduce the running cost to NIL. However, 400 W solar/ wind power system with battery storage is going increase capital cost of the system. Utilizing indigenous low-cost supercapacitor (which are capable of increased rate of charging [19]) and adopting sequential charging scheme (C/2 scheme, where C is supercapacitor capacity) one can reduce the renewable charging power requirement and reduce the cost the system. Condenser unit is the main power consuming part in the AWG system and reducing compressor capacity will reduce the overall system power requirement and hence capital & running cost. However, this has to be done without reducing rate of water condensation (20 liters per 8 hours). Heating ambient air by 10 ^{o}C followed by cooling below dew point will reduce cooling requirement and hence compressor capacity requirement. Increasing air flow rate (using fan) and heat transfer efficiency of copper surface (by adopting superhydrophobic surface technology [20]) can increase the condensation rate simultaneously. Lowering storage tank capacity or removing storage tank can lower the water volume processed at a time and hence can reduce the capital and running cost drastically as filter sizes can be reduced. Currently, water purifier market's cheapest filter replacements are carried out every 3-5 months and cost range from ₹ 500-700 which is too high for rural market. Reducing size of the filters can help keep affordable price points for rural market. Alternative technologies such as cotton in conjunction with electrostatic air filters can also serve as cheap option where air pollution (PM2.5) is low. However, filter flow rate and quality of water cannot be compromised while looking for cheaper options. Under environmental conditions where humidity remains high, a typical problem is growth of microorganisms in the dispensing tube/ tap. The UV filter cannot disinfect the area and hence the water quality suffers. One of the solution is to boil the water and dispense it to closed lid external storage immediately after boiling. As boiled water is safe to drink for 24 hours, the process can eliminate the problem of growth of microorganisms in the dispensing tube/ tap. Fig. 8(b) sums up the proposed improvement suggested above for improving affordability of the AWG machine for rural and remote India. Technology commercialization also requires understanding of patent landscape dominating Indian market. Indian patent search revealed 26 patents related to extraction of water from humid air since 1999 out of which 15 are industrial, 2 institutional and 9 individual applicants, with latest application in 2016. Indigenous technologies are limited to institutional and individual applications only. This lack of support from Indian industry is providing unfair advantage to foreign companies.

Additional revenue generation through business models such as advertisement and IoT business has the potential to increase affordability of the AWG machines in rural areas in addition to development of frugal technologies.

V. Conclusion

United Nationals SDG6 goal and Government of India's "Har Ghar Jal" target requires additional source of water with sustainable technology to exploit it. Atmospheric water is one such natural resource that can be exploited using Atmospheric Water Generators. Assessment in the paper suggests enough water is available in humid air through out the year in most parts of India and negligible effect on environment will be present if entire India consumes from the source simultaneously. AWG machines which extract water form humid air can be made affordable for rural market using frugal technology and adopting advertising or IoT business models.

Disclaimer

The views reported in this paper are that of author's only and do not reflect Government of India's views on the matter.

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