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1 **Augmentation of Freshwater Productivity in a Single Slope Solar Still Using Ball Marbles**

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9 **Abstract**

10 In the current research, the energy and economic performance in single slope solar still using ball marbles (BMSS)
11 has been investigated and compared the results with conventional solar still (CSS) under the similar weather
12 conditions of Karaikal (10.92°N,79.83°E), India during October 2020. The experiments have been conducted on
13 both sunny and cloudy day to evaluate the performance of solar still. The BMSS has increased the evaporation
14 rate and productivity when compared to CSS due to the sensible heat energy stored by the ball marbles in the
15 absorber basin. The potable water yield of the BMSS is improved by 21.23% and 22.86%, respectively during
16 sunny and cloudy days. The maximum cumulative productivity obtained in the BMSS is 2950 ml/m². day and
17 2150 ml/m². day respectively on sunny and cloudy days. In economic analysis, the payback period (PBP) of the
18 BMSS is 5.7 months whereas the PBP of the CSS is 6.5 months respectively. Furthermore, the cost per litre (CPL)
19 potable water produced by BMSS is 8% lower than the CPL of CSS.

20 **Keywords:** Solar Desalination; Solar Still; Sensible Heat; Ball marbles; Economic Analysis.

21 **1. Introduction**

22 Drinking water and energy are the two crucial needs required to survive on Earth. Owing to the exponential growth
23 in the population around the world, the abundance of freshwater is rapidly increasing day by day. The supply of
24 freshwater is also affected by the rapid rise in industrialization and agricultural practises across the globe. The
25 scarcity of freshwater is also leading to various health problems which adversely affect people's economic
26 prosperity (UN World Water Development Report 2020) The potential way of solving this freshwater crisis is
27 through various desalination approaches by converting the available seawater into drinking water. Solar still is
28 considered as one of the best ways to desalinate seawater effectively and economically. Solar Still is eco-friendly
29 and economical in such a way that everyone can easily implement it for seawater desalination (Arjunan et al.
30 2009; Aybar and Assefi 2009; Manchanda and Kumar 2015; Sharon and Reddy 2015; Dsilva Winfred Rufuss et
31 al. 2016). Nevertheless, the solar still efficiency is comparatively lower than other approaches and many
32 researchers are working to boost solar efficiency through various design improvements and incorporations into
33 the still such as fins/energy storage (Muthu Manokar et al. 2014; Durkaieswaran and Murugavel 2015; El-Sebaai
34 and El-Bialy 2015; Yadav and Sudhakar 2015; Bait and Si-Ameur 2018; Selvaraj and Natarajan 2018; Dhivagar
35 and Sundararaj 2018).

36 In this aspect, Kumar and Tiwari evaluated the internal heat transfer coefficients of solar stills by utilizing various
37 thermal models. It was found that the Kumar and Tiwari Model (KTM) validated the results better when compared
38 with other models. The internal heat transfer coefficients of passive and active solar stills were found to be 0.78

39 and $2.41\text{W/m}^2\cdot\text{K}$ (Kumar and Tiwari 2009). Khalifa and Mahamood evaluated the influence of brine water depth
40 on the freshwater yield of solar still. It was seen that the water depth of the solar still influenced productivity by
41 48% (Khalifa and Hamood 2009). Tanaka and Nakatake analysed the performance of tilted wick solar still
42 theoretically with an inclined flat reflector that attached externally to the system. It was inferred that the yield of
43 solar still was increased by 15% and 27% when the length of the reflector was half and the same of the solar still
44 respectively (Tanaka and Nakatake 2009). Sakthivel et al. studied the regenerative type solar still with jute cloth
45 for better productivity. It was found that the modified solar still had an increase in the yield by 20% and efficiency
46 was improved by 8% compared to CSS (Sakthivel et al. 2010). Dashtban and Tabrizi analysed the performance
47 of solar still with paraffin wax for better yield. It was found from the theoretical analysis, the PCM based solar
48 still achieved 31% higher productivity compared to CSS (Dashtban and Tabrizi 2011).

49 Arunkumar et al. studied the significance of PCM on the yield of solar still. It was found that the inclusion of
50 PCM enhanced the distillate yield by 26% when compared to CSS (Arunkumar et al. 2013). Ziabari et al. assessed
51 the cascade type of solar stills. It was found that the cascade solar still achieved 6.7 L/m^2 which was 26% higher
52 than the CSS (Ziabari et al. 2013). Gad et al. studied the performance of conical type solar still for enhancement
53 of productivity. It was found that the conical solar still attained a yield of 3.38 L/m^2 whereas the CSS attained
54 only 1.93 L/m^2 (Gad et al. 2015). Panchal et al. examined the effect of sandstones and marble pieces on the yield
55 of solar still. It was observed that the solar still with sandstones achieved better yield than the marble pieces and
56 a conventional one (Panchal et al. 2017). Shalaby et al. studied the working of solar still with wax and wicks for
57 better productivity. It was observed that the solar still with PCM achieved a 12% and 11.7% increase in
58 productivity when compared to setup without PCM and setup with PCM using wick material respectively (Shalaby
59 et al. 2016). Sahota and Tiwari studied the impact of Al_2O_3 nanoparticles on the yield of solar still with 35kg and
60 80kg water depth. It was noticed that the yield of solar still with 0.12% concentration of Al_2O_3 nanoparticles
61 enhanced by 12.2% and 8.4% for 35kg and 80kg water depth respectively when compared to CSS (Sahota and
62 Tiwari 2016). Singh et al. estimated the life cycle cost analysis of passive solar stills. It was observed that the kW
63 h per unit cost based on the analysis for a single slope and double slope passive solar stills was about 0.144 kW
64 h/₹ . and 0.137 kW h/₹ respectively. It was concluded from the analysis that the single slope passive solar still
65 performs better than the double slope setup (Singh et al. 2016).

66 Kabeel and Abdelgaid analysed solar still with parabolic concentrator and energy storage for better productivity.
67 It was inferred from the experimental investigation, the yield of modified solar still was improved by 140.4%
68 when compared to CSS (Kabeel and Abdelgaied 2017). Fathy et al. examined the performance of double slope

69 solar still with parabolic trough concentrator system for augmenting the freshwater productivity. It was observed
70 from the results that the solar with tracking concentrator had an improvement in the yield by 28.1% when
71 compared with fixed concentrator coupled solar still. Also, the solar still with tracking concentrator had an
72 increase in productivity by 142.3% when compared to CSS (Fathy et al. 2018). Rufuss et al. studied the
73 nanoparticles enhanced PCM (NPCM) in solar still for better productivity. It was found that there was an increase
74 of 35% yield in the solar still with NPCM compared to the solar still with PCM (Winfred Rufuss et al. 2017).
75 Chamkha et al. investigated the influence of Carbon Nano Tubes doped paraffin wax on the performance of solar
76 still. It was observed that the hybrid PCM had an enhancement in productivity by 41.4% and 26.4% compared to
77 CSS and virgin PCM (Chamkha et al. 2020). Kabeel et al. investigated the influence of sand wrapped in a jute
78 cloth as sensible heat energy storage on the solar still. It was observed that the modified still attained the yield of
79 5.9 kg/m^2 whereas the conventional still achieved only 5 kg/m^2 . Kabeel et al. studied different PCMs for
80 augmenting the productivity of the solar still. It was inferred that the capric-palmitic and PCM A48 had better
81 advantages compared to other PCMs considered in terms of high yield and low cost. Also, found that the thickness
82 of PCM used had no significant effect on the yield (Kabeel et al. 2018a) (Kabeel et al. 2018b). Manokar et al.
83 studied the inclined solar panel basin still in both passive and active modes for enhancement of yield. It was
84 noticed that the active solar still had an increase in freshwater productivity by 44.63% compared to the passive
85 solar still (Manokar et al. 2018). Sathyamurthy and El-Agouz studied the effect of Fresnel lens and blue stones on
86 the performance of solar still. The solar with Fresnel lens and with blue stones achieved 26.64% and 35.55%
87 better yield compared to CSS (Sathyamurthy and El-Agouz 2019). Satish Kumar et al. analysed the performance
88 of fin-type solar still with energy storage media (ESM). It was found that the efficiency was increased by 64%
89 and 94% in solar still with fins alone and solar still with fins cum ESM respectively when compared with the
90 conventional setup (Sathish Kumar et al. 2019).

91 Dhivagar and Sundararaj studied the effect of copper tube heat exchanger in coarse aggregate on the productivity
92 of solar still. It was found that the efficiency was improved by 17% in the modified still compared to CSS
93 (Dhivagar and Sundararaj 2019). Dhivagar et al. investigated the gravel coarse aggregate as energy storage in the
94 solar still for better productivity. It was found that the yield of modified solar still was about 4.21 kg/m^2 (Dhivagar
95 et al. 2020). Sakthivel and Arjunan evaluated solar still with cotton cloth as an energy storage medium. It was
96 noticed that the productivity of modified solar still was increased by 24.1% when compared with traditional solar
97 still without energy storage (Sakthivel and Arjunan 2019). Vigneswaran et al. investigated the effect of multiple
98 PCMs in the solar still for better productivity. It was observed that the solar still with multiple PCMs attained a

99 yield of 4.400 L/m²/day, whereas the solar still with single PCM and CSS yielded about 4.020 L/m²/day and 3.680
100 L/m²/day (Vigneswaran et al. 2019). Dumka et al. investigated the effect of sand filled cotton bags on the
101 productivity of solar still. It was seen that the yield of modified solar still was increased by 28.56% and 30.99%
102 when compared with traditional still at 30kg and 40kg basin water (Dumka et al. 2019). Raj et al. evaluated the
103 influence of metal chips, sandstones and calcium oxide as heat energy storage on the solar desalination system. It
104 was noticed that the solar still with calcium oxide had a 26.98% improvement in the yield when compared to CSS
105 (Raj et al. 2020). Patel et al. investigated the double solar still with reflectors for producing the drinking water
106 from the feed water of Gomti river, India. It was found that there was an increase in the yield by 10.4% and 10.0%
107 during summer and winter respectively with a reflector at an angle of 60° (Patel et al. 2020). Suraparaju and
108 Natarajan studied the impact of the ridge gourd natural fibres on the performance of the single-slope solar still. It
109 was depicted that the more number of natural fibres in the absorber reduced the performance of solar still
110 (Suraparaju and Natarajan 2020). Dumka et al. studied the influence of jute covered plastic balls on the
111 productivity of solar still. It was found that there was an increase in the yield by 64% when compared to
112 conventional still (Dumka et al. 2020)

113 Based on the above literature, it can be outlined that many researchers utilized various approaches like energy
114 storage materials (sensible heat & latent heat), surface enhancers such as fins and wicks in the basin for improving
115 the freshwater productivity of solar still. It was found that there was no particular extensive research on ball
116 marbles as a sensible heat energy storage medium in the solar still basin. In this aspect, the current research aims
117 to investigate the inclusion of the ball marbles into the solar still for enhancing freshwater productivity. Hence,
118 the experiments are conducted with ball marble solar still (BMSS) and compared the productivity improvements
119 with conventional solar still (CSS). The cost-effectiveness of both the solar stills is estimated using economic
120 analysis.

121 **2. Materials and Experimentation**

122 The experiments are carried out with BMSS and CSS at the NIT Puducherry (10.92°N,79.83°E), Karaikal, India
123 during the sunny and cloudy days of October 2020.

124 **2.1. System Description**

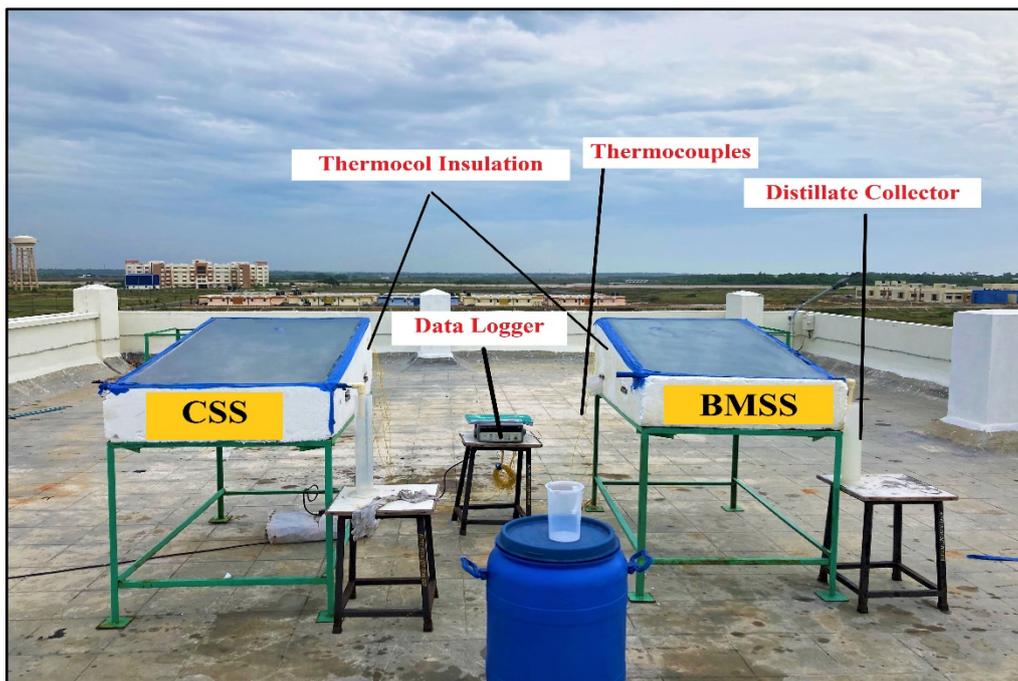
125 In the present investigation, two similar single-slope solar stills are designed and fabricated to examine the effect
126 of ball marbles on the improvement of freshwater productivity in the solar still. The two solar stills that have been
127 developed for analysis are as follows:

- 128 1. Conventional Solar Still (CSS)

129 2. Ball Marble Solar Still (BMSS)

130 **2.2. Materials and Fabrication**

131 The two solar stills are made of durable plywood and the internal structure of the solar still has an aluminium
132 layer of 2 mm thickness, which restricts the direct interaction between water vapour and plywood. Also, the
133 aluminium sheet is coated with standard black paint for absorbing more solar radiation into the system. The
134 absorber basin is made of a 1 mm copper sheet, and the dimensions of the absorber basin are 1000 mm × 600 mm
135 × 50 mm (0.6m² absorber area). The solar still is covered with a transparent and the glass cover is fixed at an angle
136 equal to the latitude of Karaikal for the efficient operation of the system (Singh and Tiwari 2004). The absorber
137 basins of CSS and BMSS are filled with seawater at a particular depth. The black coated marble balls of 25 mm
138 diameter are introduced into the absorber basin of BMSS. The entire absorber area is equipped with black coated
139 marbles to study the impact on the productivity of solar still. The complete outer area of the solar still is insulated
140 with 2 cm thick Thermocol sheets to reduce the heat losses from the system. The photograph of the BMSS and
141 CSS is depicted in Fig. 1.



142
143 **Fig. 1 Photographs of BMSS and CSS**

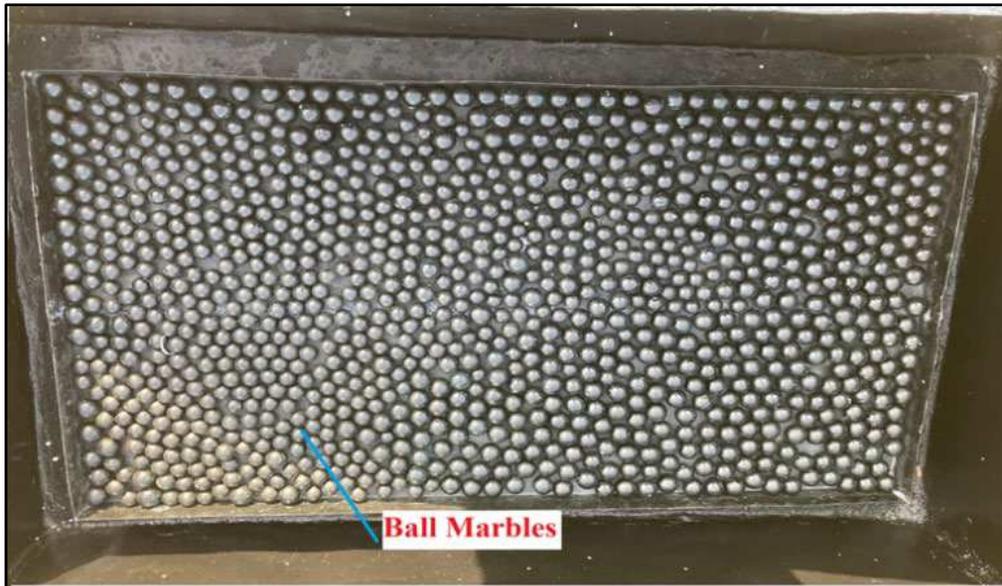
144 **2.3. Preparation of Black Coated Ball Marbles**

145 The study is mainly focused on the use of black-coated ball marbles for augmenting the freshwater production
146 from the solar still. The ball marbles are commercially available in the market and procured from the market for
147 experimental investigation. The marble balls are coated with selective black paint (Thurmalox®) for better
148 absorption of incident global solar radiation. The arrangement of ball marbles in the solar still basin is shown in

149 Fig. 2. The ball marbles have a specific heat capacity of about 850 J/kg. °C which stores and releases the heat
150 energy at the desired temperatures required for operating the solar still with energy storage. Hence, the black-
151 coated ball marbles are chosen for the experimental investigation in the current research.

152 2.4. Experimentation

153 The performance investigation of single slope solar still with and without black coated marble balls is carried out
154 on a sunny day and cloudy day of October 2020 to study the effect of marble balls on freshwater productivity.
155 The feed water for this investigation is collected from the Bay of Bengal sea located adjacent to the NIT
156 Puducherry. The seawater in the absorber basin is filled to a depth of 2 cm and maintained constant throughout
157 the investigation by adding makeup water at regular intervals. The temperatures of the glass cover, seawater,
158 absorber basin, marble balls and ambient temperature are measured using calibrated K- type thermocouples
159 connected to the Data acquisition system (Agilent 34972A). The global radiation of the particular testing day at
160 the testing location is measured using the “Hukseflux Pyranometer”. The experiments are conducted on
161 14.10.2020 (cloudy day) and 15.10.2020 (sunny day), respectively. The readings are recorded from 08:00 am to
162 06:00 pm (Indian Standard Time) for every half an hour.



163

164 **Fig. 2 Arrangement of black coated ball marbles in the solar still**

165

165 3. Uncertainty Analysis

166 The uncertainties in measuring instruments are estimated using the following relations (J. P. Holman 2007)

167
$$w_r = \left[\left(\frac{\partial R}{\partial x_1} w_1 \right)^2 + \left(\frac{\partial R}{\partial x_2} w_2 \right)^2 + \dots + \left(\frac{\partial R}{\partial x_n} w_n \right)^2 \right]^{1/2} \quad (1)$$

168 Here, the total uncertainty is w_r , the function is R , x is called the independent variable and w is also the independent
 169 variable with respect to the uncertainty. The uncertainty of the thermocouple, pyranometer, and measuring
 170 cylindrical jar used in the experimental investigation is tabulated in Table 1.

171 **Table 1 Uncertainties of the Instruments**

S. No	Apparatus	Range	Accuracy	uncertainty
1	Thermocouple – K type	-270 to 1,260 °C	± 0.1 °C	0.058 °C
2	Pyranometer	0 to 1600 W/m ²	± 10 W/m ²	5.774 W/m ²
3	Measuring Cylinder	0 to 1000 ml	±10 ml	5.774 ml

172 The uncertainty in the efficiency and hourly freshwater yield is given by the following formulae; (Suraparaju and
 173 Natarajan 2021)

$$174 \quad u_{\eta} = \left[\left(\frac{\partial \eta_d}{\partial w} \times u_{d_w} \right)^2 + \left(\frac{\partial \eta_d}{\partial I(t)} \times u_{I(t)} \right)^2 \right]^{\frac{1}{2}} \quad (2)$$

175 It was assessed that the error in total potable water yield is ±1.5%. In addition to that, the error in global radiation
 176 and temperature measurement is 0.05% and 0.1%. Hence, the total error is about ±2%

177 4. Energy and Economic Analysis

178 The thermal efficiency of the passive solar still is evaluated by using the following formula (Kabeel and
 179 Abdelgaied 2016)

$$180 \quad \eta_{th} = \frac{P.Y \times \lambda}{A_b \times GR \times \Delta t} \quad (3)$$

181 where P.Y is the overall potable water yield, λ is the latent heat of evaporation of water, A_b is the absorber basin
 182 area in, G is daily overall incident global solar radiation and Δt is the duration of the cumulative readings in sec.

$$183 \quad \text{Here, } \lambda = 3.1615 \times (10^6 - 761.6 * T_a), \text{ if } T_a > 70, \quad (4)$$

$$184 \quad \text{Else, } \lambda = 2.4935 \times (10^6 - 947.79 * T_a + 0.13132 * T_a^2 - 0.0047974 * T_a^3), \quad (5)$$

$$185 \quad T_a = \frac{T_{water} + T_{glass}}{2} \quad (6)$$

186 4.1. Economic Analysis

187 The economic viability of solar stills is evaluated using the following relations (Esfahani et al. 2011)

$$188 \quad FAC = CRF \times CC \quad (7)$$

$$189 \quad CRF = \frac{i(1+i)^n}{(1+i)^n - 1} \quad (8)$$

$$190 \quad ASV = SSF \times S \quad (9)$$

$$191 \quad S = 0.2 \times CC \quad (10)$$

192 $SFF = \frac{i}{(1+i)^n - 1}$ (11)

193 $AMC = 0.15 \times FAC$ (12)

194 $AC = FAC + AMC - ASV$ (13)

195 $CPL = \frac{AC}{P_d}$ (14)

196 $PBP = \frac{\text{Investments}}{\text{Net earnings}}$ (15)

197 $\text{Net Earnings} = \text{Market water price (per L)} \times \text{Productivity (L)/ day m}^2$ (16)

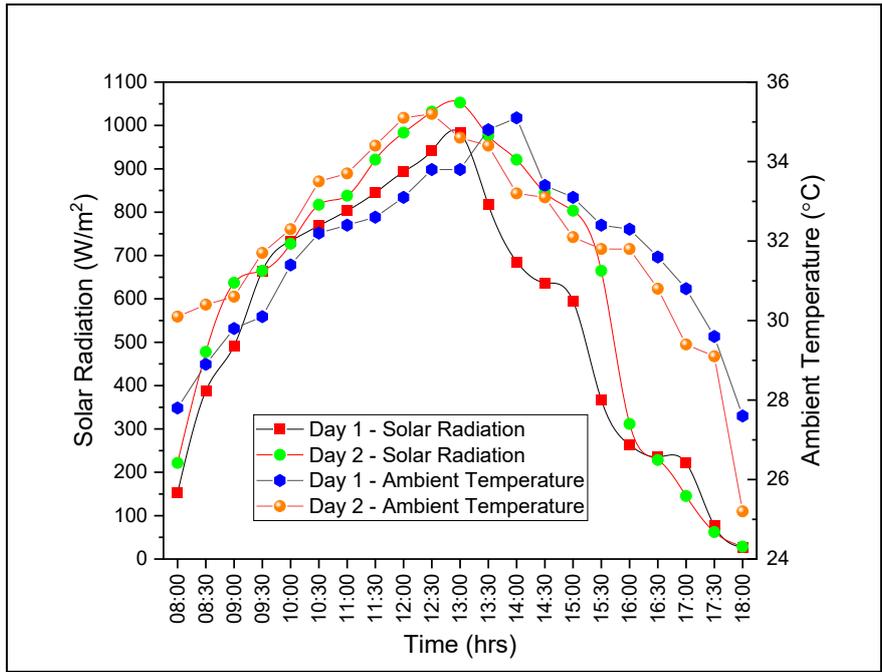
198 Here, the interest rate (i) is 10% and the lifetime (n) of the solar stills (BMSS & CSS) 10 years. The operating days
199 of solar still are considered as 270 days in a year.

200 **5. Results & Discussion**

201 The experimentations have been carried out in both BMSS and CSS during the sunny and cloudy days of October
202 2020 to assess the performance. The results observed in BMSS is compared with CSS under the same climate
203 conditions.

204 **5.1. Experimental observation**

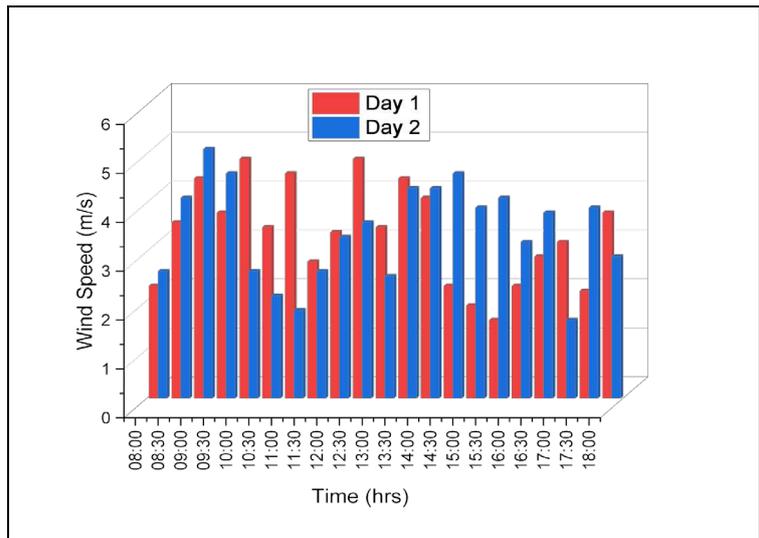
205 The variations of solar irradiation and ambient temperature in both days are illustrated in Fig. 3. On sunny and
206 cloudy days, during morning hours, the solar irradiation was gradually increasing and attained a higher value of
207 about 1052.63 W/m² and 983.38 W/m², respectively. In between, the formation of clouds was reducing the length
208 of sun shines considerably. Hence, during evening hours, the intensity of solar irradiation was reduced slowly and
209 reached to lesser value of about 27 W/m². It was noticed that, during afternoon hours, the maximum ambient
210 temperatures were about 35.2 °C on both testing days. During evening time, it was reduced to about 27.6 °C and
211 25.2 °C, respectively for a sunny day and cloudy day. The phenomenon was due to the reduction in the intensity
212 of solar irradiation. The variations of wind velocity on both days are illustrated in Fig. 4. The wind velocity played
213 a major role during the condensation of water vapour at the bottom of the glass cover. The wind velocity was
214 changing in the range between 1.6 m/s and 5.1 m/s during the experimentation.



215

216

Fig. 3 Variations of solar radiation and ambient temperature with time



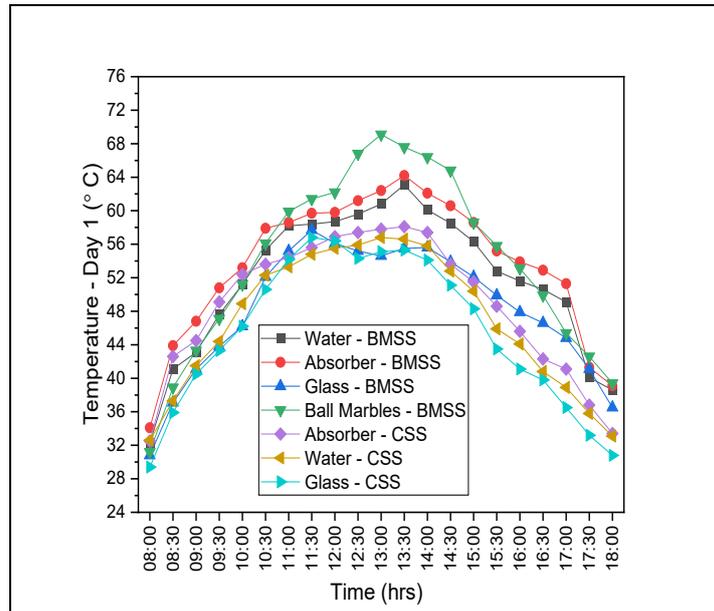
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218

Fig. 4 Variations of wind velocity with time

219 The variations of different temperatures of both BMSS and CSS on day 1 are illustrated in Fig. 5. It was noticed
 220 that the maximum glass temperature of BMSS and CSS were about 57.7 °C and 56.8 °C, respectively and, it was
 221 reduced to about 36.5 °C and 30.8 °C, respectively. The maximum absorber basin temperatures of BMSS and
 222 CSS were reported as 64.2 °C and 58.1 °C respectively. It was observed that the absorber temperature of BMSS
 223 was about 10% higher than CSS. Along with the absorber, the maximum ball marbles temperature was recorded
 224 as 69.9°C in BMSS. Furthermore, it was observed that the maximum water temperature in BMSS and CSS was
 225 63.1 °C and 56.8 °C, respectively. The water temperature was improved significantly in BMSS due to the impact

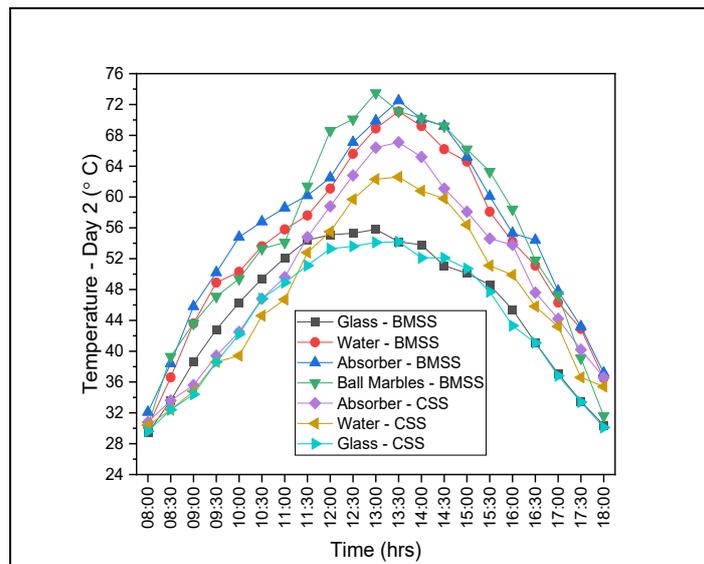
226 of black-coated ball marbles. The observed saline water temperature in BMSS was 12% higher than the saline
 227 water temperature of CSS.



228

229

Fig. 5 Variations of different temperatures of both BMSS and CSS on day 1



230

231

Fig. 6 Variations of different temperatures of both BMSS and CSS on day 2

232 The variations of different temperatures of both BMSS and CSS on day 2 are illustrated in Fig. 6. It was seen that
 233 the maximum glass temperatures of BMSS and CSS were about 55.8 °C and 54.2 °C, respectively and during
 234 evening time, it was reduced to about 30.4 °C and 30.1 °C, respectively. The absorber basin temperatures of
 235 BMSS and CSS were augmented during the morning and attained the maximum value of about 72.5 °C and 67.1
 236 °C, respectively. On day 2, the basin absorber temperature of BMSS was 9% higher than CSS. The maximum ball
 237 marble temperature was 73.5°C in BMSS. Furthermore, the maximum saline water temperature in BMSS and

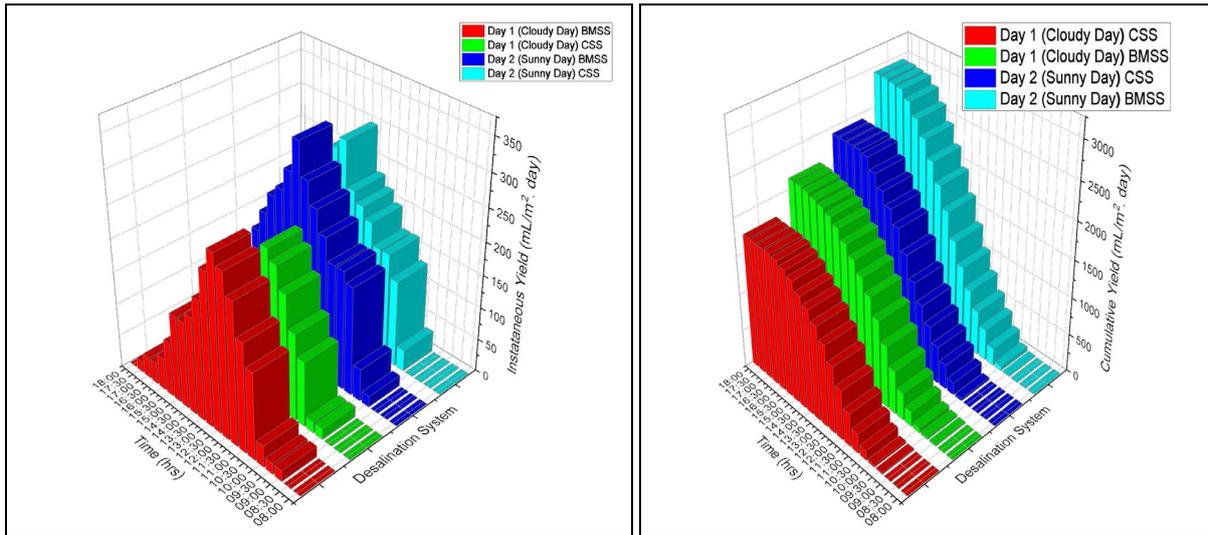
238 CSS were observed to be about 71.1 °C and 65.2 °C, respectively. The observed saline water temperature in BMSS
239 was 14% higher than CSS. Thus, the incorporation of black-coated ball marbles in the sola still effectively
240 increased the absorber and water temperatures to a greater extent compared to CSS. The rise in the difference
241 between water and glass temperatures ($\Delta T = T_{water} - T_{glass}$) lead to enhanced condensation and hence attained
242 more freshwater yield in the BMSS compared to CSS.

243 **5.2. Effect of Ball Marbles on the system temperatures**

244 The inclusion of sensible energy storage into the solar still significantly improved the temperatures of the system.
245 The ball marbles improved the water and absorber temperature enormously. The ball marbles in the absorber
246 basin played a dominant role in heat transfer between absorber and water during diurnal hours. The ball marbles
247 facilitated the solar still to maintain the highest temperatures of water and absorber from 12.00 P.M to 02.30 P.M
248 when compared to CSS. The upsurge in the water temperatures leads to an enhancement in the evaporation rate
249 in BMSS which caused an improvement in freshwater yield compared to CSS. However, the inclusion of ball
250 marbles into the solar still increased the water and absorber temperatures led to an improvement in the freshwater
251 yield of solar still.

252 **5.3. Productivity**

253 The hourly productivity and cumulative productivity for BMSS and CSS on both testing days are depicted in Fig.
254 7 (a) and (b). On day 1, during the morning to afternoon hours (11.00 to 15:00 hours), the hourly productivity of
255 BMSS was significantly improved when compared to CSS. In BMSS, the maximum hourly productivity of about
256 270 ml/m² was observed during 14:00 hours due to the heat energy retained by ball marbles. Similarly, during
257 14:00 hours, improved productivity of about 230 ml/m² was collected in CSS. In BMSS, the observed maximum
258 productivity is 18% higher than CSS. On day 2, the maximum hourly productivity of about 340 ml/m² was
259 observed in BMSS. In CSS, it was observed to be about 300 ml/m². which was 14% lower than BMSS. The
260 productivity of BMSS and CSS on both the testing days is represented as a histogram in Fig. 8. On day 1, it was
261 noticed that the cumulative productivity of BMSS and CSS were about 2150 ml/m².day and 1750 ml/m². day,
262 respectively. On day 2, it was observed as 2950 ml/m².day and 2430 ml/m². day, respectively in both BMSS and
263 CSS. The cumulative production of the BMSS was 22.8 % and 21.3% higher than the productivity collected in
264 CSS for day 1 and day 2, respectively. It was noticed that the average freshwater productivity from the BMSS
265 was 2.7 ml/m². day, whereas the average freshwater productivity from the CSS was 1.9 mL/m². day.



266

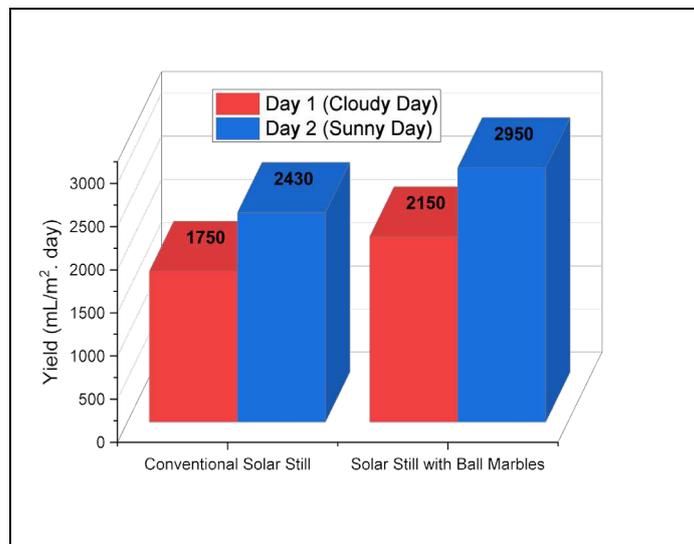
267

268

(a)

(b)

Fig. 7 Variations of (a) hourly productivity & (b) Cumulative productivity of BMSS and CSS



269

270

Fig. 8 Histograms representing the final potable water productivity of CSS and BMSS

271 5.4. Effect of Ball Marbles on the Productivity of Solar Still

272 The freshwater productivity of the solar still was significantly influenced by the ball marbles as thermal energy
 273 storage. The adequate heat-storing capacity of ball marbles allowed the ball marbles to receive and store the
 274 incident solar radiation in the form of heat. The stored heat was the key factor for rising the water and absorber
 275 temperatures during the peak hours of sunshine. Also, when the sunshine was reduced, the stored heat in the ball
 276 marbles got liberated and helped in maintaining the maximum water temperatures for better performance of the
 277 solar still. From the above discussion, it was observed that the inclusion of ball marbles into the desalination
 278 system significantly enhanced the freshwater productivity from the system. Nevertheless, the incorporation of

279 ball marbles in the absorber basin substantially improved the freshwater yield by enhancing the heat transfer
280 between the water, absorber and ball marbles.

281 5.5. Energy Analysis

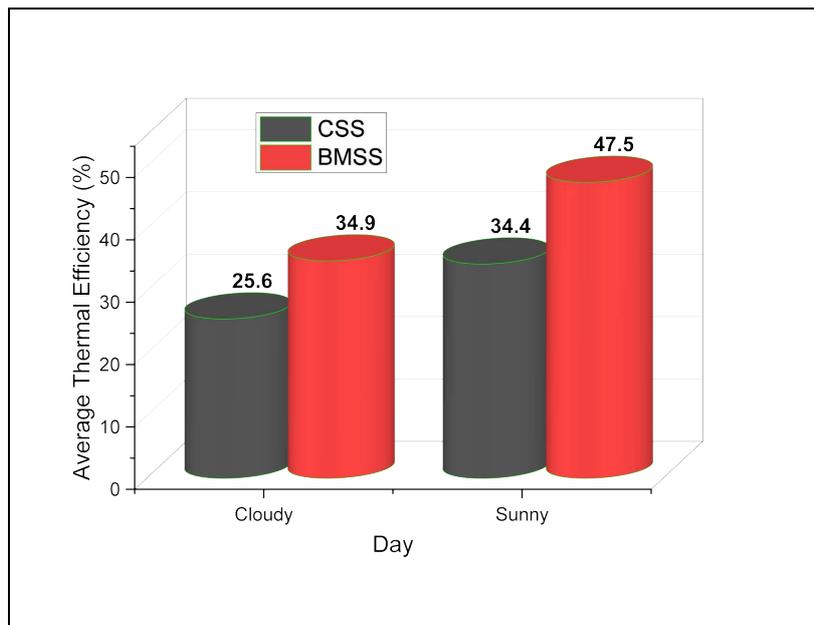
282 The thermal efficiency of the single-slope solar stills was evaluated using equation (3). The average thermal
283 efficiency of the BMSS on a cloudy day was 34.9% whereas the average thermal efficiency of CSS was 25.6%.

284 It was observed that there was an increase of 36.67% in the average thermal efficiency of BMSS on a cloudy day.

285 Besides, the average thermal efficiency of the BMSS on a sunny day was 47.5% whereas the average thermal
286 efficiency of CSS was 34.4%. It was observed that there was an increase of 38.11% in the average thermal

287 efficiency of BMSS on a sunny day. From the above inferences, it was noted that the addition of black-coated
288 ball marbles in the absorber basin as a sensible energy heat storage material significantly increased the
289 performance of single slope solar still by increasing the system temperatures, productivity and energy efficiency.

290 The outcomes of the energy analysis on both testing days is pictorially illustrated in Figure 9 and 10 respectively.



291

292

Fig. 9 Average thermal efficiencies of BMSS and CSS on day 1 & 2



Fig. 9 Increase in the average thermal efficiency of BMSS compared to CSS

5.6. Economic analysis

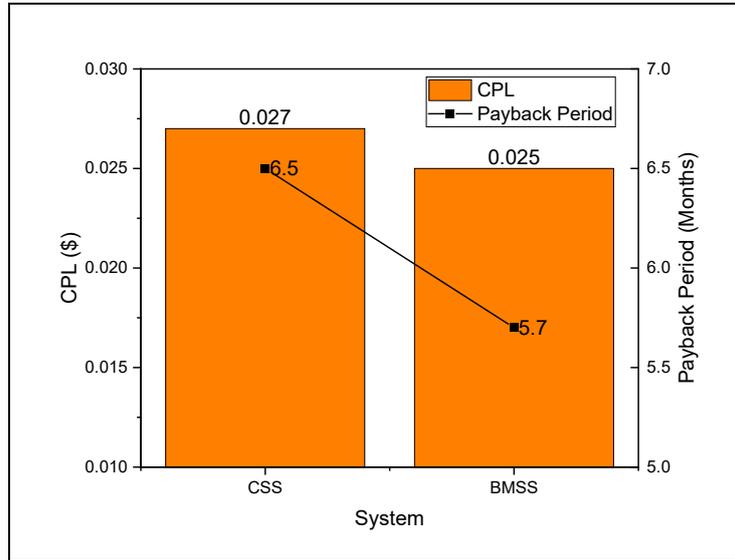
The capital investment was considered by taking the prices of each part of the desalination system assembly, according to the Indian costs. The capital cost was calculated by considering all the fabrication, maintenance and operation costs. The cost-effectiveness of both the solar stills was estimated using economic analysis and listed in Table 2. From table 2, it was observed that the cost per litre (CPL) of BMSS and CSS was 0.025 \$ and 0.027 \$ respectively. Besides, the CPL of BMSS is 8% lower than the CPL estimated in CSS. Furthermore, the PBP of BMSS and CSS was 5.8 months and 6.5 months, respectively. The outcomes of the economic analysis were represented graphically in figure 11. From the outcomes of the economic analysis, it was observed that the inclusion of ball marbles in the absorber basin is economically viable and sustainable.

Table 2 Economic analysis of BMSS and CSS in both sunny and cloudy days

Parameters	BMSS	CSS
CC	\$ 88	\$ 82
CRF	0.177	0.177
FAC	15.57	14.51
S	17.6	16.4
SFF	0.056	0.056
ASV	0.98	0.91
AMC	2.33	2.71

AC	16.92	15.77
P_d	688.5 L/ m ²	564.7 L/ m ²
CPL	\$ 0.025	\$ 0.027
PBP	5.7 months	6.5 months

305



306

307

Fig. 10 Representation of outcomes of economic analysis

308 **6. Conclusion**

309 The experimentations have been conducted in both the BMSS and CSS to assess the effect of ball marbles on the
 310 performance of solar still. The experimental investigation was carried out for two days under the same
 311 meteorological conditions of Karaikal city in India during October 2020. The observed major results are given
 312 below:

- 313 a) The solar still with ball marbles had a better performance compared to CSS.
- 314 b) The water temperature was significantly improved using ball marbles in a solar still basin absorber. On
 315 day 1, the BMSS has 12% improved water temperature when compared to CSS. Similarly, on day 2, it
 316 was improved to about 14% than CSS. The maximum observed ball marbles temperature in BMSS were
 317 69.9 °C and 73.5 °C, respectively during sunny and cloudy days.
- 318 c) The productivity improvement observed on an hourly basis of BMSS was 18% and 14%, respectively
 319 higher than the CSS on both day 1 and day 2. Besides, the cumulative productivity in BMSS was 22.8%
 320 (day 1) and 21.3% (day 2), respectively higher than the cumulative productivity observed in CSS. The
 321 outcomes proved that the usage of ball marbles have enhanced daily productivity considerably.

322 d) The average energy efficiency of BMSS and CSS was about 34.9% and 25.6% on day 1 respectively. It
323 was observed that there was an increase of 36.7% in the energy efficiency of BMSS compared to CSS.
324 Besides, the average energy efficiency of BMSS and CSS was about 47.5% and 38.1% on day 2
325 respectively. It was observed that there was an increase of 38.1% in the energy efficiency of BMSS
326 compared to CSS

327 e) The economic analysis reported that the PBP of the BMSS and CSS was observed as 5.7 months and 6.5
328 months, respectively. Similarly, the CPL of BMSS and CSS was about \$ 0.025 and \$ 0.027, respectively.

329 It has been concluded from the above results that ball marbles had a better heat transfer rate and raised the system
330 temperatures effectively. Also, the productivity from the BMSS was comparatively better than CSS. The
331 economic analysis also proved that the BMSS was sustainable compared to CSS.

332 **Nomenclature**

Abbreviations

<i>AC</i>	—	Annual cost
<i>AMC</i>	—	Annual maintenance cost
<i>ASV</i>	—	Annual salvage value
<i>BMSS</i>	—	Ball Marbles solar still
<i>CC</i>	—	Capital cost
<i>CPL</i>	—	Cost per litre
<i>CRF</i>	—	Capital recovery factor
<i>CSS</i>	—	Conventional solar still
<i>FAC</i>	—	Fixed annual cost
<i>CSS</i>	—	Conventional solar still
<i>FAC</i>	—	Fixed annual cost
<i>PBP</i>	—	Payback period
<i>S</i>	—	Salvage value
<i>SFF</i>	—	Sinking fund factor

333 **Declarations**

334 **Ethics approval and consent to participate:** Not applicable

335 **Consent for Publication:** Not applicable

336 **Availability of data and materials:** The datasets used and/or analysed during the current study are available from
337 the corresponding author on reasonable request

338 **Competing interests:** The authors declare that they have no competing interests.

339 **Funding:** Not applicable

340 **Author Contributions - CRediT author statement**

341 *Subbarama Kousik Suraparaju:* Conceptualization, Formal analysis, Investigation, Data Curation, Writing -
342 Original Draft.

343 *Dhivagar Ramasamy:* Conceptualization, Data Curation, Methodology, Writing – original draft.

344 *Sendhil Kumar Natarajan:* Conceptualization, Validation, Resources, Writing - Review & Editing, Supervision,
345 Project administration.

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Figures

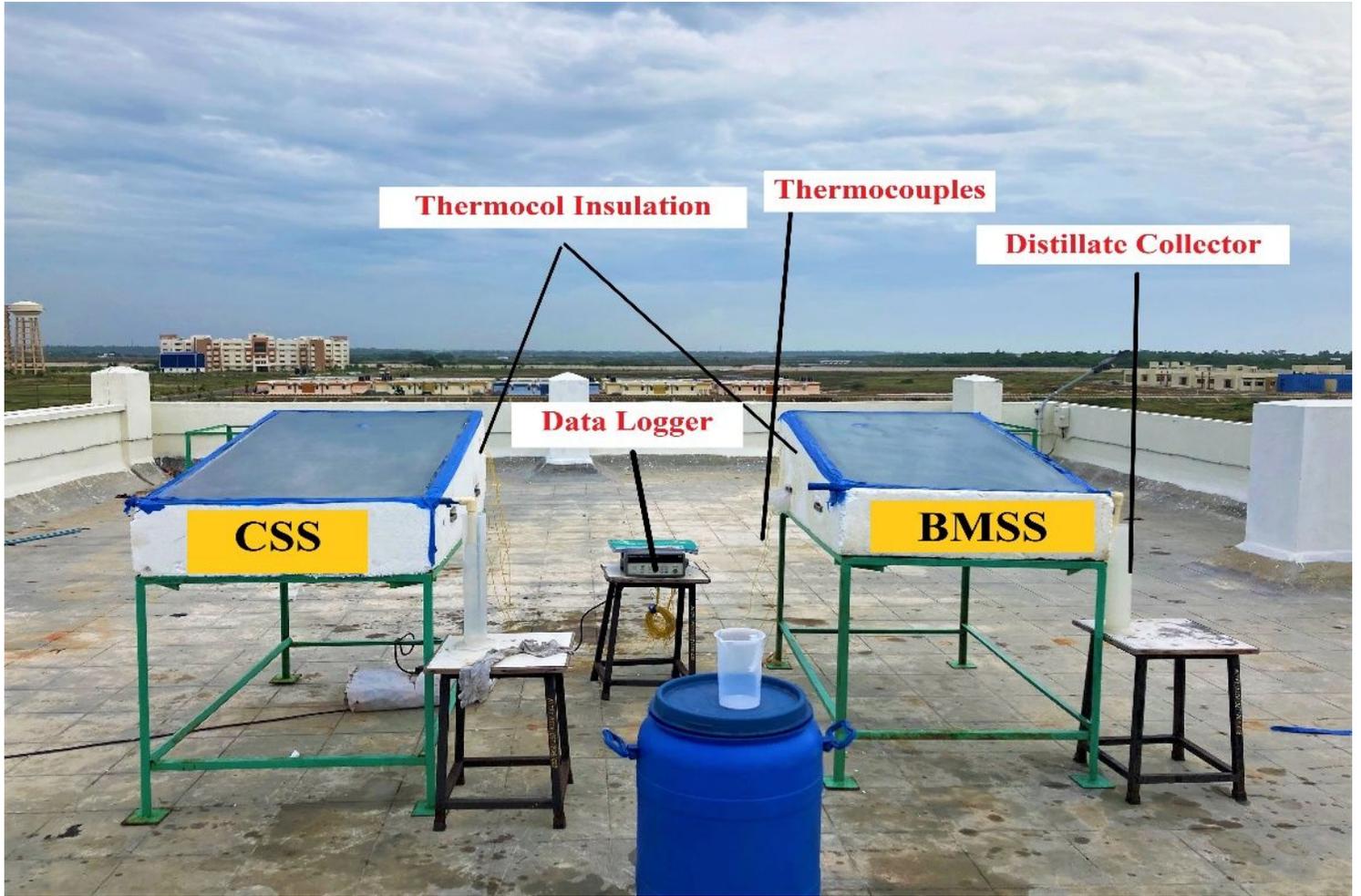


Figure 1

Photographs of BMSS and CSS

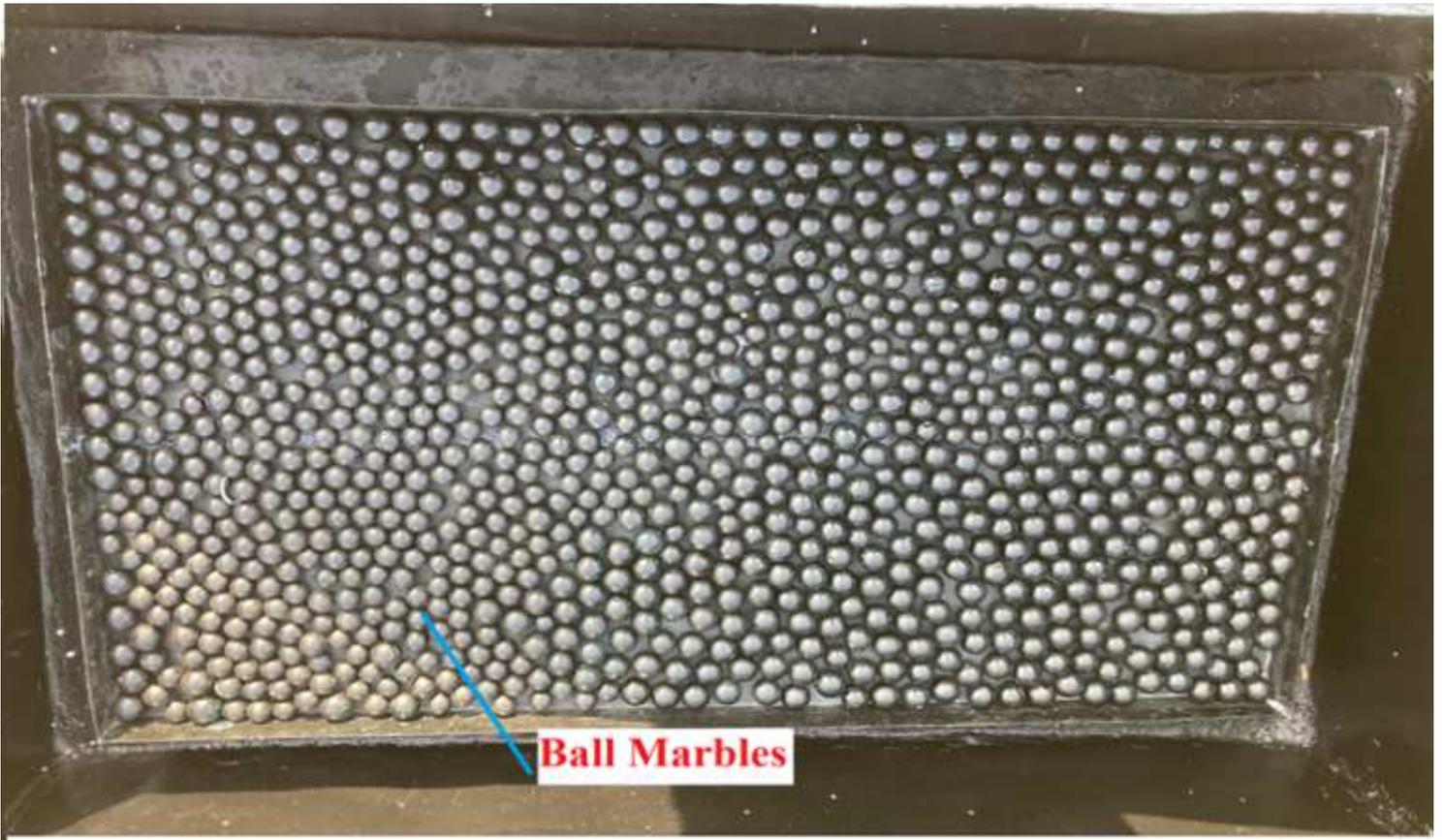


Figure 2

Arrangement of black coated ball marbles in the solar still

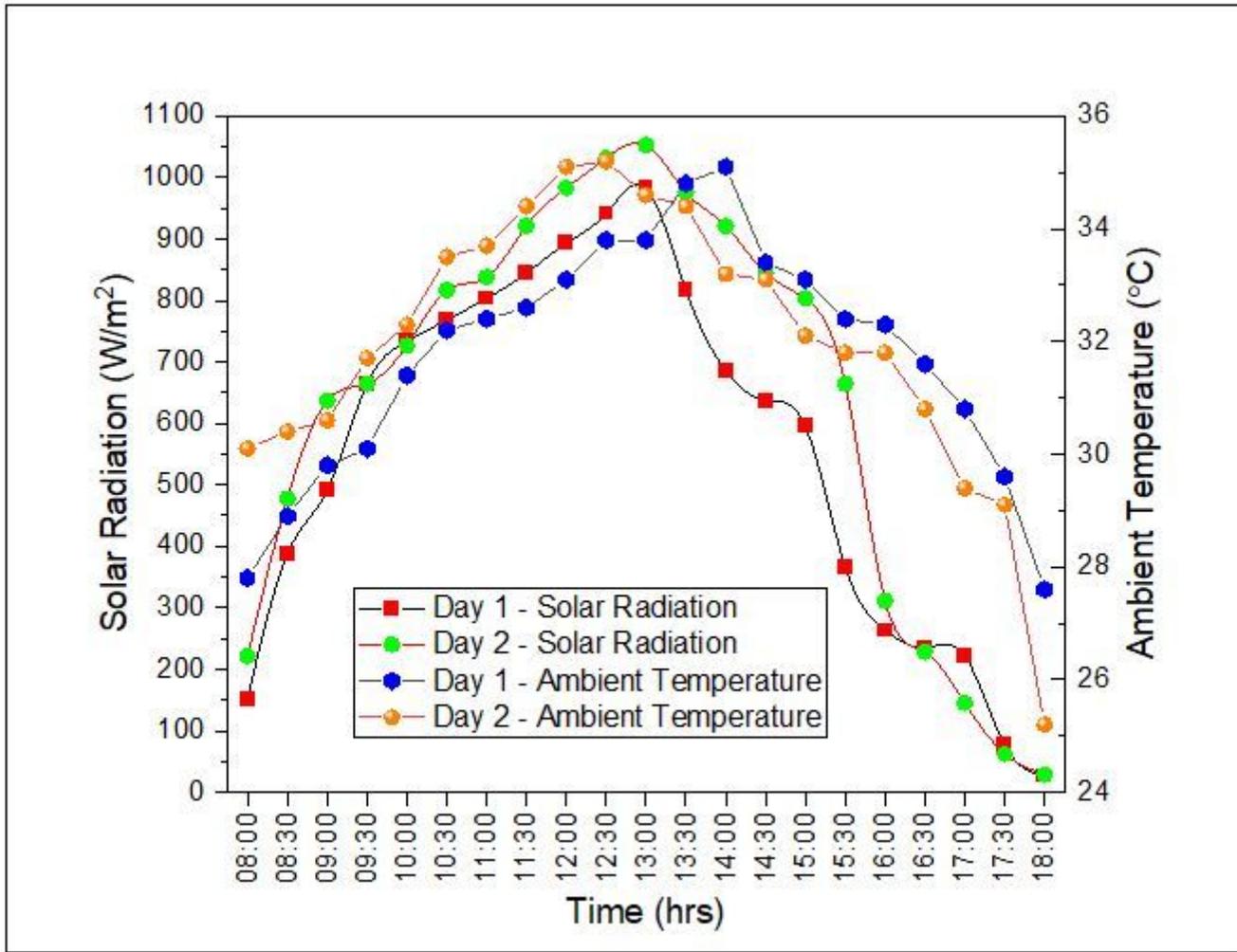


Figure 3

Variations of solar radiation and ambient temperature with time

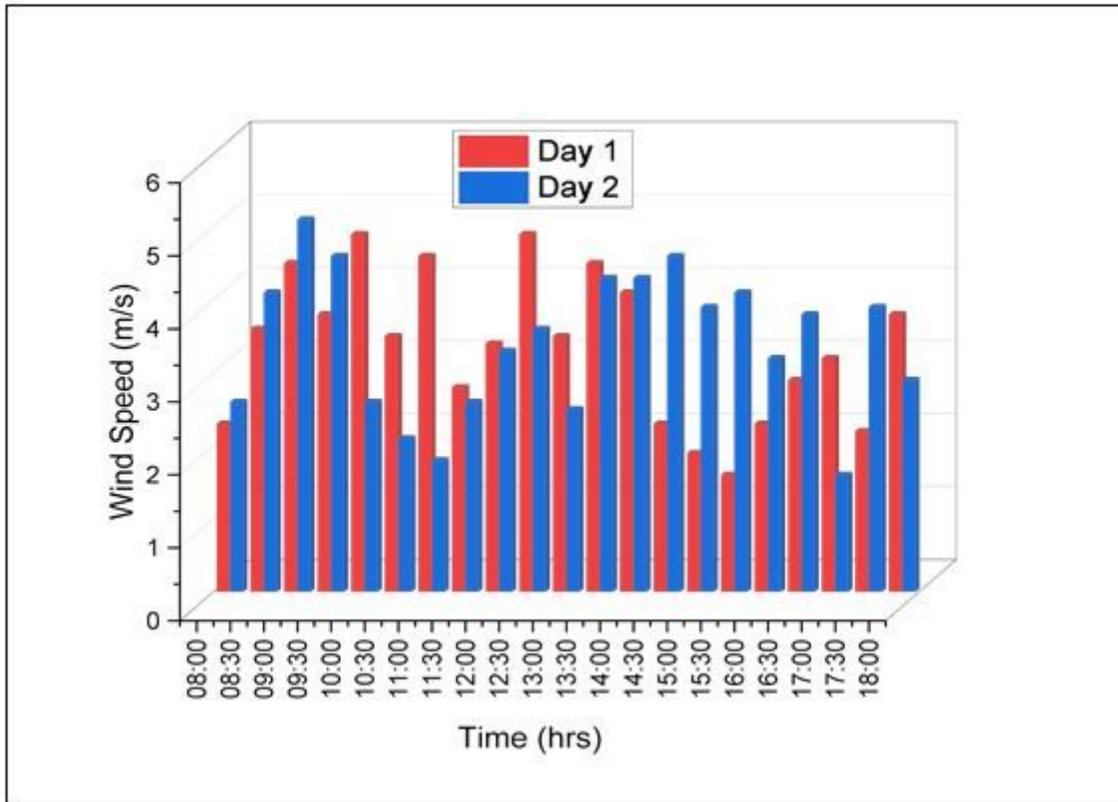


Figure 4

Variations of wind velocity with time

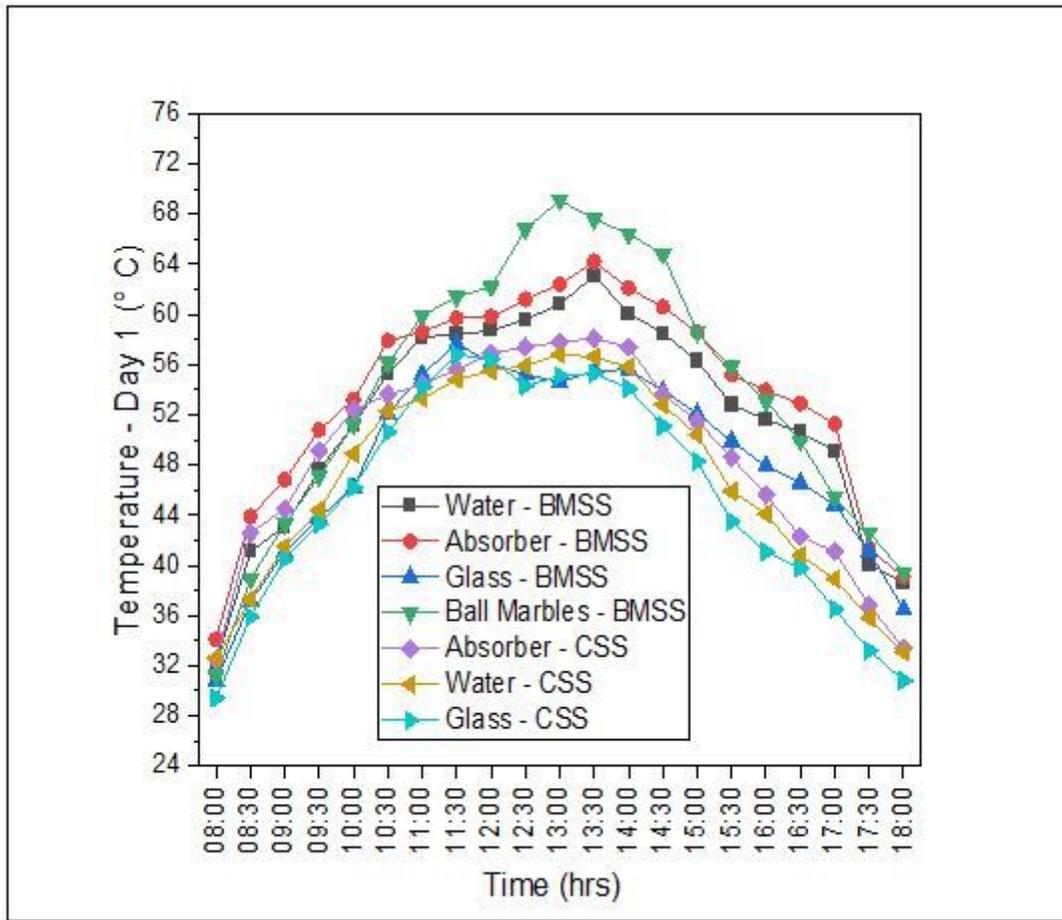


Figure 5

Variations of different temperatures of both BMSS and CSS on day 1

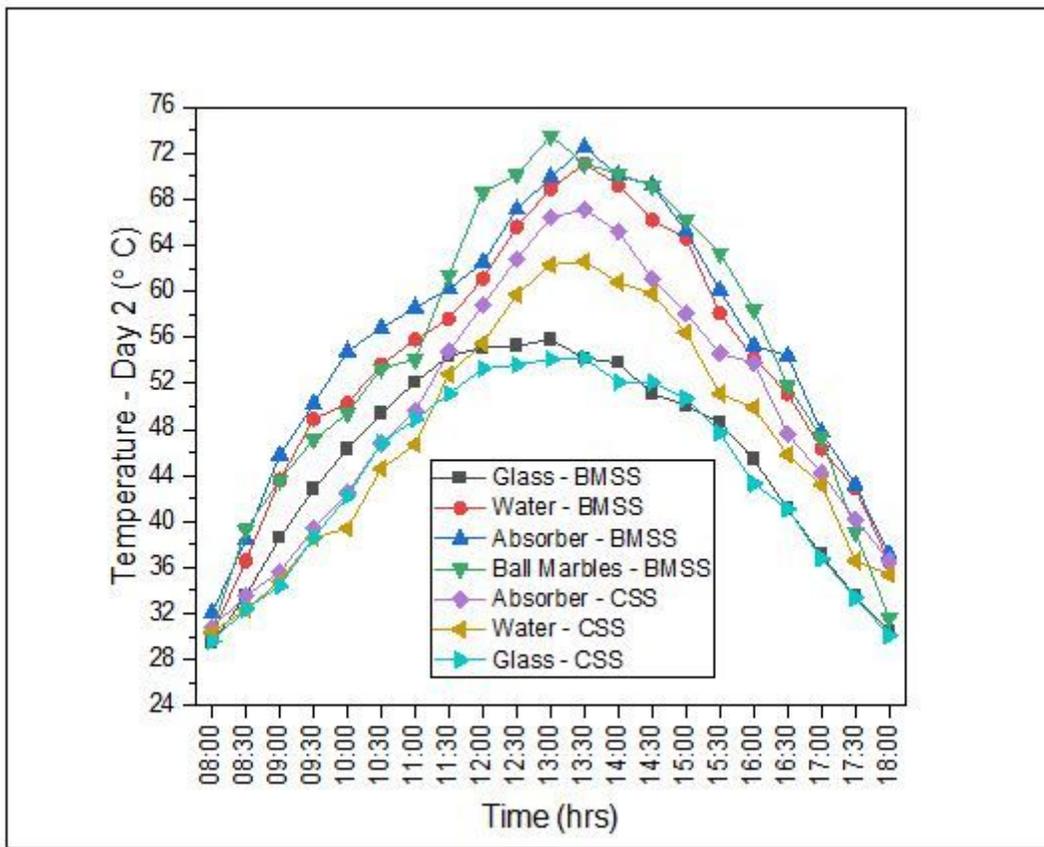
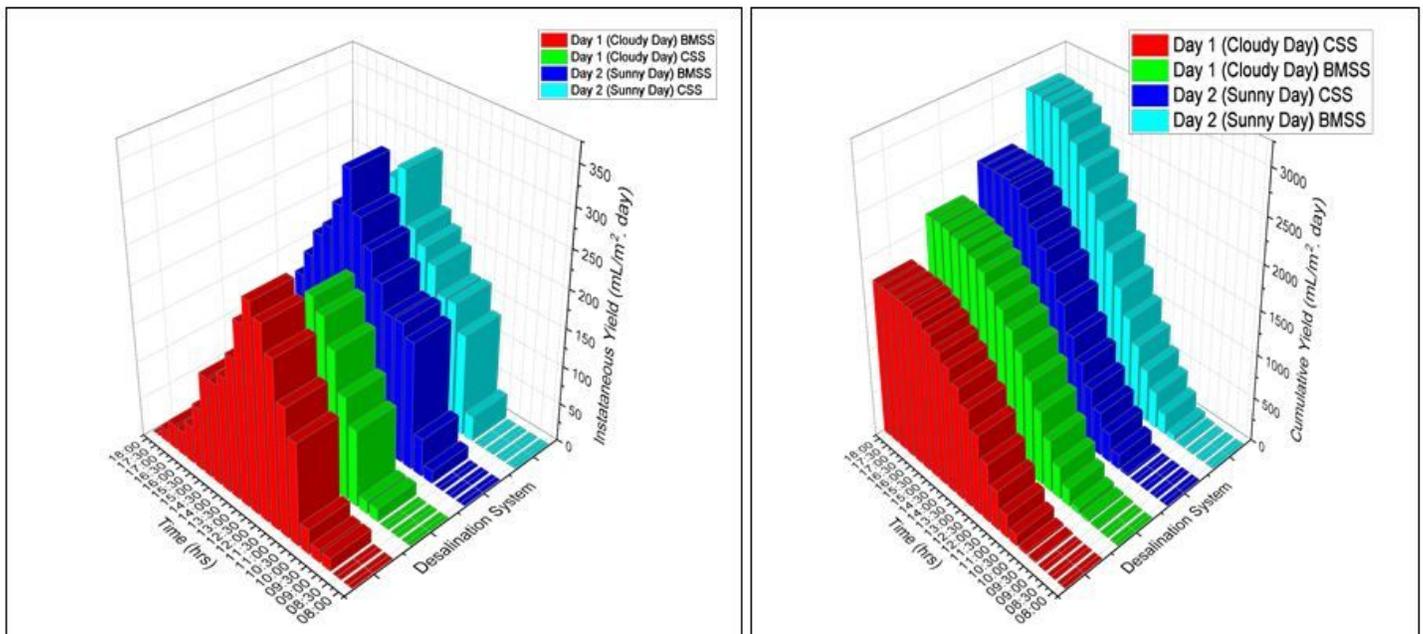


Figure 6

Variations of different temperatures of both BMSS and CSS on day 2



(a)

(b)

Figure 7

Variations of (a) hourly productivity & (b) Cumulative productivity of BMSS and CSS

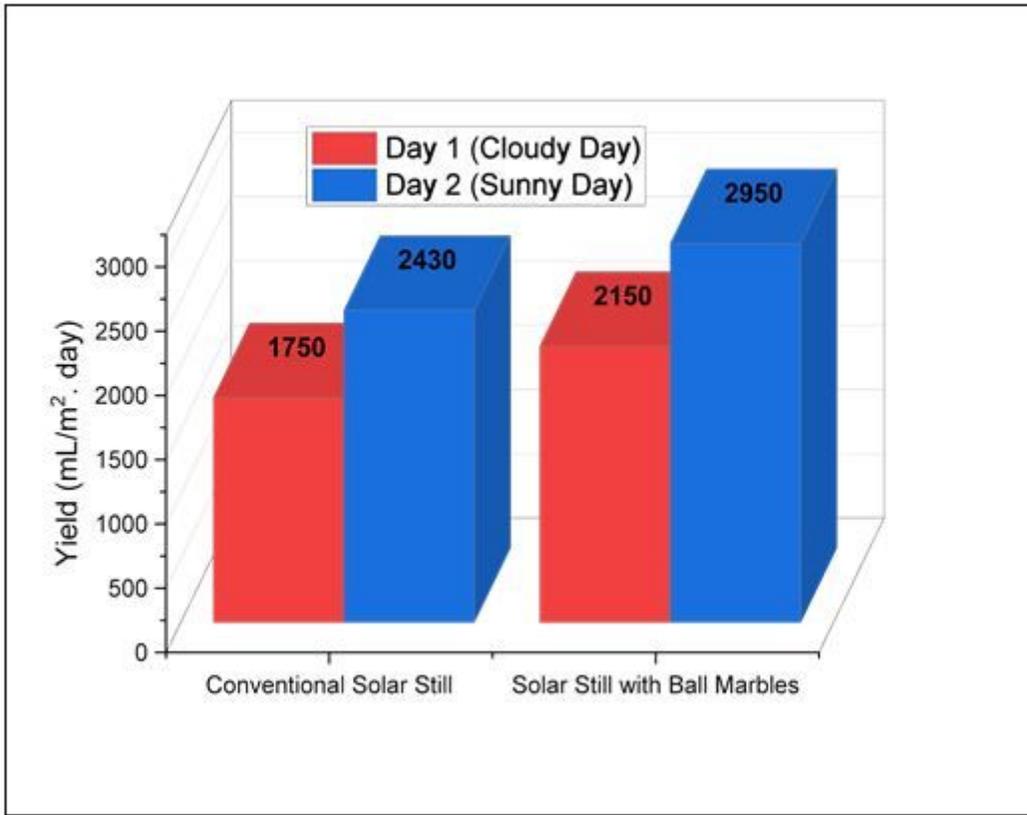


Figure 8

Histograms representing the final potable water productivity of CSS and BMSS

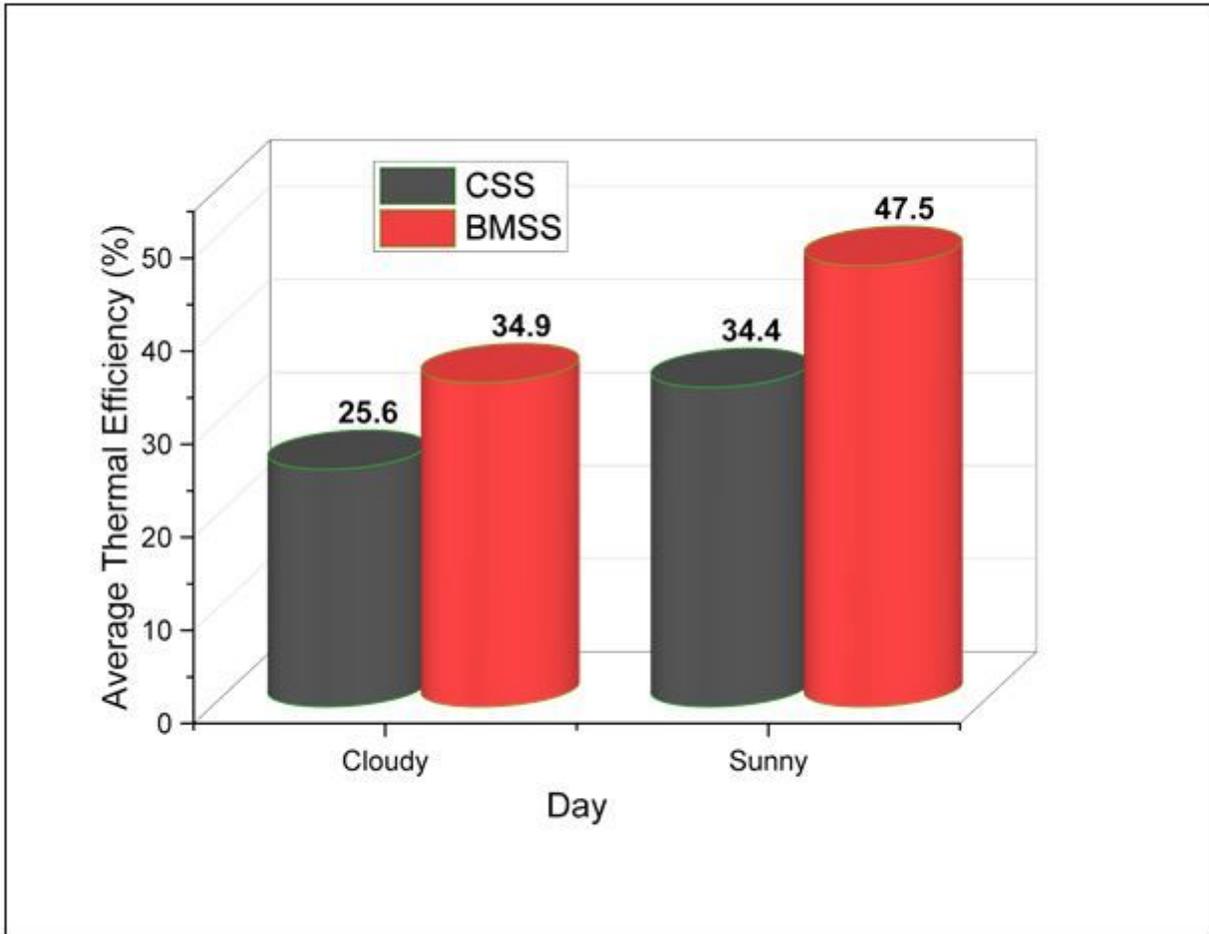


Figure 9

Average thermal efficiencies of BMSS and CSS on day 1 & 2

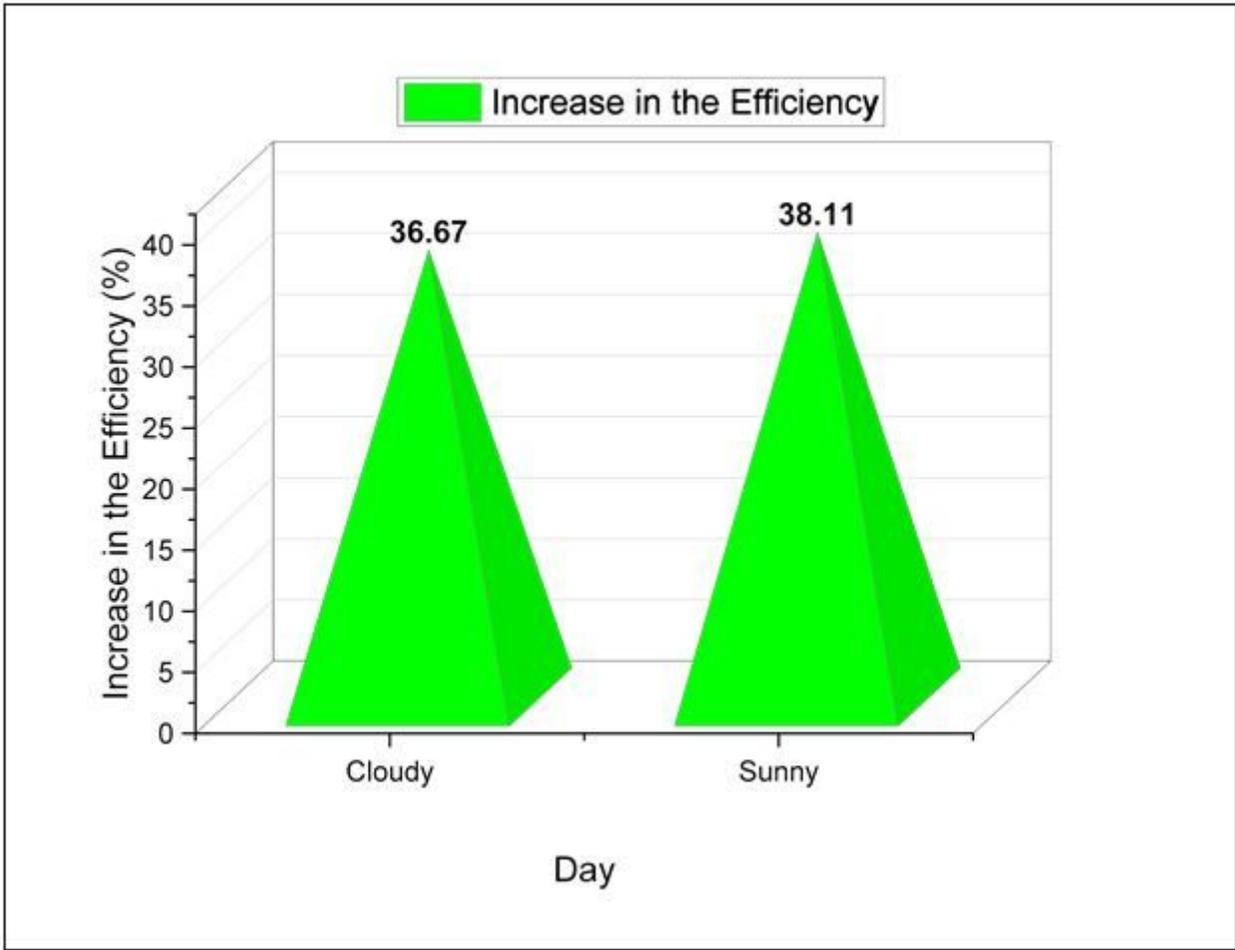


Figure 10

Increase in the average thermal efficiency of BMSS compared to CSS

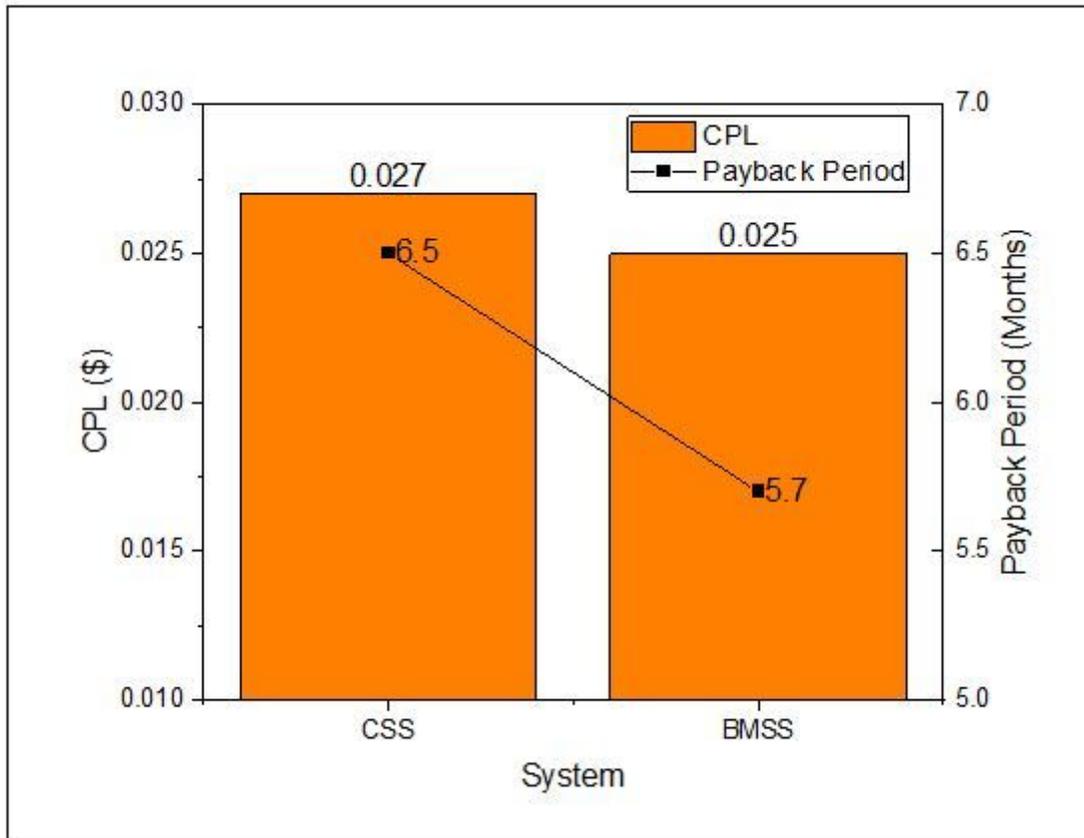


Figure 11

Representation of outcomes of economic analysis

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- [Data.xlsx](#)