

Novel Concept on the Enhancement of Conventional Solar Still Performance via Constant Heat Rate Supply to the Saline Water

Wael M. El-Maghlany (✉ elmaghlany@alexu.edu.eg)

Mechanical Engineering Department, Faculty of Engineering, Alexandria University, Egypt

<https://orcid.org/0000-0002-1315-0054>

enass massoud

Arab Academy for Science Technology and Maritime Transport

mohamed Elhelw

Alexandria University Faculty of Engineering

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Novel Concept on the Enhancement of Conventional Solar Still Performance via Constant Heat Rate Supply to the Saline Water

Wael M. El-Maghlany ^{a,*}, Enass Massoud ^b, Mohamed ElHelw ^a

^a Mechanical Engineering Department, Faculty of Engineering, Alexandria University, Egypt

^b Mechanical Engineering Department, Arab Academy for Science, Technology and Maritime Transport, Alexandria, Egypt

* Corresponding Author: elmaghlany@alexu.edu.eg
elmaghlany@yahoo.com

ABSTRACT

One of most reduction reasons of simple conventional solar still productivity is the coupling between high solar intensity and the high ambient temperature in the same time. The high intensity increases the saline water temperature while the outside temperature increases the glass temperature and consequently reduction in saline water and glass temperature difference leads to reduction in condensation and productivity. The present **theoretical** study focuses on the completion of the absorbed solar energy in the basin to be constant during the day. The basin water will be in high temperature level all day especially at the time of low outside temperature far away the noon. The absorbed heat in the basin is held constant at $\alpha_w I_{max}$ by extra heat from wind turbine power with battery storage system all day hours. The results show that, the solar still productivity with constant heat supply is more than that with same amount of variable energy during sun rise time only (6 AM to 6 PM) by 69.133 %. So, constant absorbed heat in the water basin ($\alpha_w I_{max}$) through the 24 hr of the day enhances the performance with productivity up to 248 % with the hybrid solar and electric power consumption of the wind turbine power. The water in the basin is held constant at 2 cm via makeup water to compensate the evaporation rate.

Keywords: Conventional solar still; constant heat rate; theoretical study

Nomenclature

| | |
|-------|--|
| A | Area, m ² |
| a | Wire cross sectional area, mm ² |
| C_p | Specific heat, J kg ⁻¹ °C ⁻¹ |
| C.O.P | Coefficient of performance |

| | | |
|----|----------|---|
| 33 | F | Radiation shape factor |
| 34 | h_{bw} | Heat transfer coefficient in the saline water, $W m^{-2} ^\circ C^{-1}$ |
| 35 | h_{ca} | Outside air heat transfer coefficient, $W m^{-2} ^\circ C^{-1}$ |
| 36 | h_{cw} | Trapped air heat transfer coefficient in the still, $W m^{-2} ^\circ C^{-1}$ |
| 37 | h_{fg} | Evaporation heat load (latent heat) at atmospheric pressure, $J kg^{-1}$ |
| 38 | I | Solar radiation, $W m^{-2}$ |
| 39 | i | Electric current, Ampere |
| 40 | L | Wire length, m |
| 41 | m | Mass, kg |
| 42 | m_p | Daily productivity, $kg s^{-1}$ |
| 43 | m_{re} | Instantaneous productivity, $kg s^{-1}$ |
| 44 | p | Water vapour pressure, $N m^{-2}$ |
| 45 | R | Resistance, Ω |
| 46 | t | Temperature, $^\circ C$ |
| 47 | V | Volt |
| 48 | U | Heat transfer coefficient from basin and sides to ambient, $W m^{-2} ^\circ C^{-1}$ |
| 49 | W_a | Wind speed, $m s^{-1}$ |

50

51 **Greek letters**

| | | |
|----|---------------|--|
| 52 | α | Absorptive factor |
| 53 | ε | Emissivity |
| 54 | τ | Time, s |
| 55 | σ | Stefan-Boltzmann constant, $W m^{-2} K^{-4}$ |

56 **Subscripts**

| | | |
|----|-------|----------------|
| 57 | a | Ambient |
| 58 | b | Basin |
| 59 | g | Glass |
| 60 | sky | Sky |
| 61 | w | Water in basin |

62 **1. Introduction**

63 The need for freshwater has been dramatically increasing with the rapid increase in the
64 human population all over the earth. The presence of an extreme amount of dissolved salts in

65 the available water on the earth's surface makes the water brackish. In the literature, various
66 methods are available to convert the brackish water into a clean form; however, most of these
67 methods have a negative impact on the environment, need difficult technological inputs and
68 are considered highly energy intensive (Jamil and Akhtar 2014; Safe 2011). In recent years,
69 efficient technologies based on renewable energy sources are being developed mainly to deal
70 with the increasing demands of distilled water. One of the oldest techniques for water
71 purification is the distillation of seawater using solar energy to separate salts and water (El-
72 Maghlany et al. 2020 ; El-Sebaili 2004 ; Li et al. 2013 ; Nayi and Modi 2018; Omara et al.
73 2017; Rajaseenivasan and Murugavel 2013; Sampathkumar and Senthilkumar 2012;
74 Sathyamurthy et al. 2017) . The main advantages of using the solar stills as solar desalination
75 units are their low cost, simple operation, and self-reliant water supply systems (El-Maghlany
76 et al. 2020). The solar still desalination technique uses two main processes: evaporation and
77 condensation phenomenon similar to those occurring in the atmosphere to form rain. The
78 processes involved in the solar stills techniques are the solar radiation for the natural
79 evaporation of water, followed by condensation process. Through the still cavity, the vapors
80 travel to reach the still cover and once the heat is released, a condensation process occurs,
81 where the vapors are condensed back into liquid form. Via the evaporation stage in the still,
82 only water evaporates and all impurities are left to be flushed later via drainage. Thus, the
83 condensed distillate obtained in the solar still is potable. Even though, solar stills could be
84 considered as an appropriate option for the distillation of water with free cost solar energy to
85 fresh water production, but they have low distillate yield and efficiency (Jamil and Akhtar
86 2014). In the literature, a large number of research studies focus on the enhancement of solar
87 still performance aiming to improve its low distillate yield and efficiency. Factors affecting
88 the performance of solar still include the climate condition as the performance of the solar
89 still is very sensitive to climate conditions. The main effective climate conditions parameters
90 are ambient temperature, solar intensity, and the surrounding air velocity around the still
91 (Ahsan et al. 2014; Alfaylakawi and Ahmed 2012; El et al. (2015); Hamdan et al. 1999;
92 Muftah et al. 2014; Omara et al. 2013; Prakash and Velmurugan 2015; Selvaraj and Natarajan
93 2018; Sharshir et al. 2016; Thirugnanasambantham et al. 2013; Tiwari et al. 2009; Kabeel et
94 al. 2019). Other main factors that affect the solar still performance comprises some essential
95 design parameters. These main design parameters include the inclination, type and thickness
96 of glass cover type, orientation of still, absorber plate material and thickness, and the depth of
97 water in basin (Nafey et al. 2000; Omara et al. 2013; Omara et al. 2014; Samee et al. 2007;
98 Velmurugan and Srithar 2011; Khalifa 2011). Research studies show that simple solar still

99 possess low efficiencies and output. Thus, research mainly focuses on new methods to
100 enhance the solar still performance by either internally modifying its existing designs with
101 the incorporation of new technologies or by coupling with external devices to enhance the
102 productivity of solar stills. Regarding the enhancement of the solar still performance by
103 modifying its existing designs, various studies are carried out on different solar still designs,
104 including spherical solar still, pyramid solar still, hemispherical solar still, double basin glass
105 solar still, concentrator coupled single slope solar still, tubular solar still and tubular solar still
106 coupled with pyramid solar still, wicker, stepped, pyramid and “V” type solar stills, (Omara
107 et al. 2013; Abdullah et al. 2019; Saadi et al. 2018; Murugavel and Srithar 201; Kumar et al.
108 2008; Velmurugan et al. 2008; Kabeel et al. 2020; Thirugnanasambantham et al. 2012).
109 Focusing on conventional solar stills, some research focus on improving the production of
110 water by enhancing the yield through the application of energy storage, either latent or
111 sensible heat energy storage (Ansari et al. 2013; Sathish et al. 2020; Shashikanth et al. 2015;
112 Yousef et al. 2019 ; [Gugulothu et al. 2015](#) ; [Sarada et al. 2014](#)). Enhancement to the solar still
113 productivity, yield and performance can also be done by improving the absorbing materials
114 (Abdallah et al. 2009; Gugulothu et al. 2015) . Other studies deal with improvement in the
115 absorber aiming to enhance the solar still performance. Studies using floatable absorbers,
116 baffled absorber, and corrugated absorber are conducted to check their effect on the
117 productivity of solar still (Omara et al. 2011; Srivastava and Agrawal 2013; El-Sebaei et al.
118 2000). It is concluded that water production is increased by changing the absorber type. In
119 addition, another method to enhance the performance of conventional solar still is to add fins
120 in the basin to decrease the preheating time essential for evaporating the still basin water. The
121 fins increase the area of the absorber plate; hence, the absorber plate temperature and saline
122 water temperature increase. The conclusion is that productivity increases as the temperature
123 difference between water and glass increases (Srivastava and Agrawal 2013; Velmurugan et
124 al. 2008). Furthermore, another method to enhance the heat transfer inside the solar basin is
125 by adding Nanofluid that accelerates the water evaporation rate compared with the simple
126 conventional solar still (Gupta et al. 2017; Gupta et al. 2016; Mahian et al. 2013; Kabeel et al.
127 2017). Additionally, other studies show that adding aluminum balls to the solar distillates
128 increase the distillation of distilled water by about around 27.16 % (Attia et al. 2020).
129 Moreover, some studies show that preheating the saline water by passing it over the solar
130 panel front surface before entering the still rises the freshwater yield of the solar desalination
131 system (Abd Elbar and Hassan 2020). (Kabeel et al. 2016) use two main methods to enhance

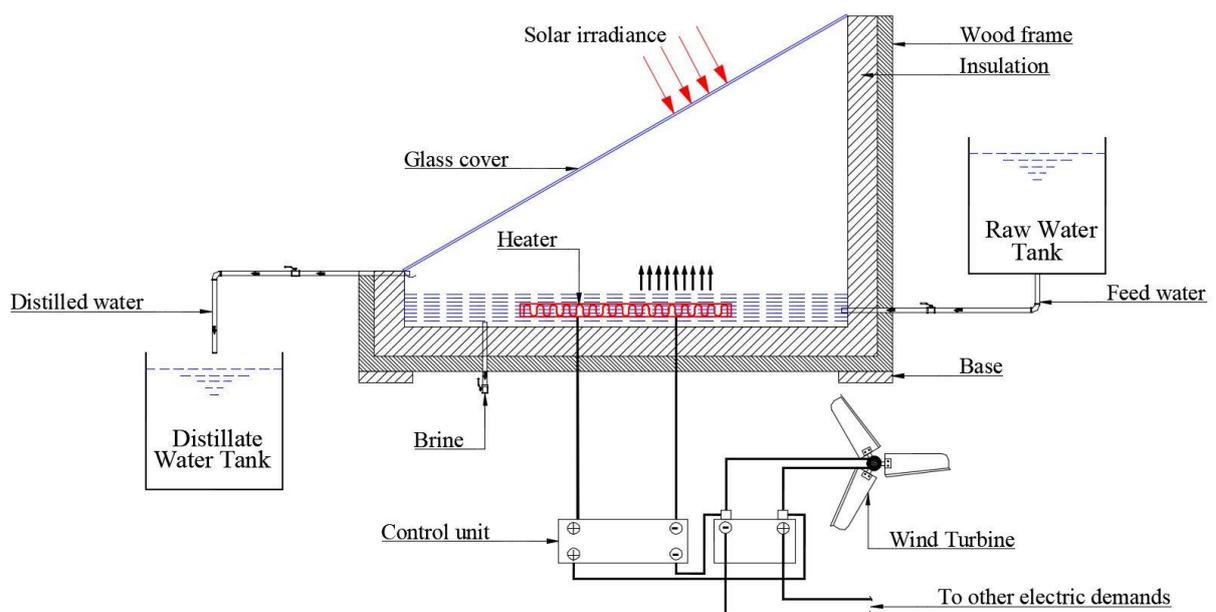
132 freshwater productivity by using hot air injection and PCM. The results show that the
133 developed air bubbles increase the evaporation rate through the modified still with PCM.

134 **3. Aim of the present study**

135 From the previous literature and up to the authors' knowledge, the enhancement of the solar
136 still performance via constant heat rate supply during the day has not been under
137 investigation before. **The novelty of the present study was to prove that the regular constant**
138 **heat supply to saline water takes the solar still to the finest. The results will prove that a**
139 **specified amount of heat to the saline water with constant rate is more effective than the same**
140 **amount of heat in random mode.** Previously, the PCM was used to store energy during the
141 day and release heat in night hours. However, the use of PCM as energy storage in the night
142 period is a random heat supply technique depending on the type of PCM and its amount
143 without any time history to heat absorbed or supply. Therefore, the present study aims to
144 prove that the steady constant heat supply to the solar still is an effective technique to
145 enhance the conventional solar still performance.

146 **4. Mathematical model**

147 The energy balance for water basin, absorber and the glass cover will be applied. Via the
148 solving of the energy equations simultaneously in unsteady mode; the temperatures of basin
149 plate, saline water, and glass cover could be estimated. So, the performance of the solar still
150 will be found. The glass cover is assumed to be un-stored element (thin) without any vapour
151 leakage.



152

153

Fig. 1. Conventional solar still with supplementary heat added

154 The temperature variation of the basin plate could be found from the energy balance as
 155 follow with some brief

$$156 \quad m_b C p_b \frac{dt_b}{d\tau} = (\alpha_b) A_b I - h_{bw} A_b (t_b - t_w) - U_b A_b (t_b - t_a) \quad (1)$$

157 Where:

$$158 \quad h_{bw} = 135 \text{ W/ m}^2 \text{ }^\circ\text{C and } U_b = 14 \text{ W/ m}^2 \text{ }^\circ\text{C} \quad (2)$$

159 In case of constant water thickness, the energy balance for the saline water will be

$$160 \quad C p_w m_w \frac{d}{d\tau} (t_w) = (\alpha_w) A_w I + h_{bw} A_b (t_b - t_w) - \frac{\sigma [(t_w + 273)^4 - (t_g + 273)^4]}{\left(\frac{1-\varepsilon_w}{A_w \varepsilon_w}\right) + \left(\frac{1}{A_g F_{gw}}\right) + \left(\frac{1-\varepsilon_g}{A_g \varepsilon_g}\right)}$$

$$161 \quad - 0.884 \left[t_w - t_g + \frac{(p_w - p_g)(t_w + 273)}{268900 - p_w} \right]^{\frac{1}{3}} A_w (t_w - t_g)$$

$$162 \quad - (16.237 \times 10^{-3}) h_{cw} A_w (p_w - p_g) - m_{re} (C p_w t_w - C p_a t_a) \quad (3)$$

163 Where

$$164 \quad p_w = e^{\left(25.317 - \frac{5144}{t_w + 273}\right)} \quad (4)$$

$$165 \quad p_g = e^{\left(25.317 - \frac{5144}{t_g + 273}\right)} \quad (5)$$

166 Energy balance for the glass cover

$$167 \quad m_g C p_g \frac{dt_g}{d\tau} = (\alpha_g) A_g I + \frac{\sigma [(t_w + 273)^4 - (t_g + 273)^4]}{\left(\frac{1-\varepsilon_w}{A_w \varepsilon_w}\right) + \left(\frac{1}{A_g F_{gw}}\right) + \left(\frac{1-\varepsilon_g}{A_g \varepsilon_g}\right)}$$

$$168 \quad + 0.884 \left[t_w - t_g + \frac{(p_w - p_g)(t_w + 273)}{268900 - p_w} \right]^{\frac{1}{3}} A_w (t_w - t_g)$$

$$169 \quad + (16.237 \times 10^{-3}) h_{cw} A_w (p_w - p_g) - h_{ca} A_g (t_g - t_{sky})$$

$$170 \quad - \varepsilon_g A_g \sigma [(t_g + 273)^4 - (t_{sky} + 273)^4] \quad (6)$$

171 Where

$$172 \quad t_{sky} = t_a - 6.0 \quad (7)$$

$$173 \quad h_{ca} = 5.7 + 3.8 W_a \quad (8)$$

174 The time dependant still productivity is

$$175 \quad m_{re} = \frac{(16.237 \times 10^{-3}) h_{cw} A_w (p_w - p_g)}{h_{fg}} \quad (9)$$

176 The accumulated daily still productivity is

$$177 \quad m_p = \sum_{\tau=0}^{\tau=24hr} m_{re} \quad (10)$$

178 **5. Solution proceeding**

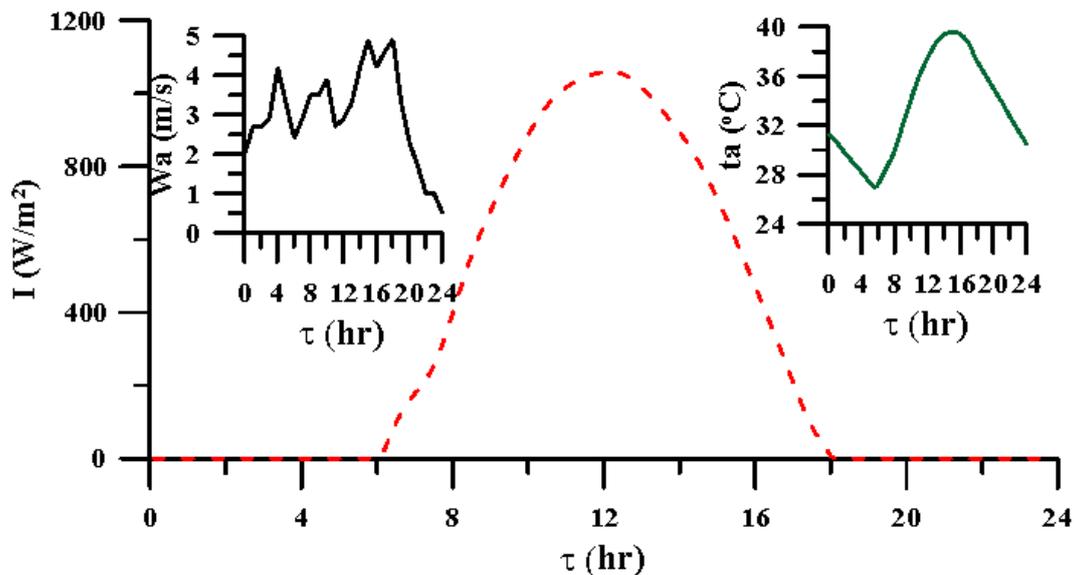
179 Via FORTRAN in house code, the linear differential equations 1, 3 and 6 for the energy
 180 balance are solved numerically with one second time step. Table 1 contains the all thermal
 181 properties and dimensions of the solar still with its contents. The weather data of Alexandria
 182 city in Egypt with average values of August is introduced to the governing equations (solar
 183 intensity, wind speed and ambient temperature). Fig.1 represents the solar still schematic
 184 diagram and the weather data is given in Fig.2 representing solar intensity, wind velocity and
 185 ambient temperature.

186 **Table 1**

187 The thermo-physical and operating parameters of the solar still (El-Maghlany et al. 2020).

| <i>Item</i> | <i>m (kg)</i> | <i>A (m²)</i> | <i>C_p (J/kg K)</i> | <i>α</i> | <i>ε</i> |
|---------------------|---------------|--------------------------|-------------------------------|----------|----------|
| <i>Saline water</i> | 20 | 1.00 | 4190 | 0.05 | 0.95 |
| <i>Glass cover</i> | 9.0 | 1.15 | 840 | 0.05 | 0.85 |
| <i>Basin plate</i> | 14.5 | 1.00 | 460 | 0.95 | ---- |

188 Latent heat for water at atmospheric condition (h_{fg}) = 2335000 J/kg.



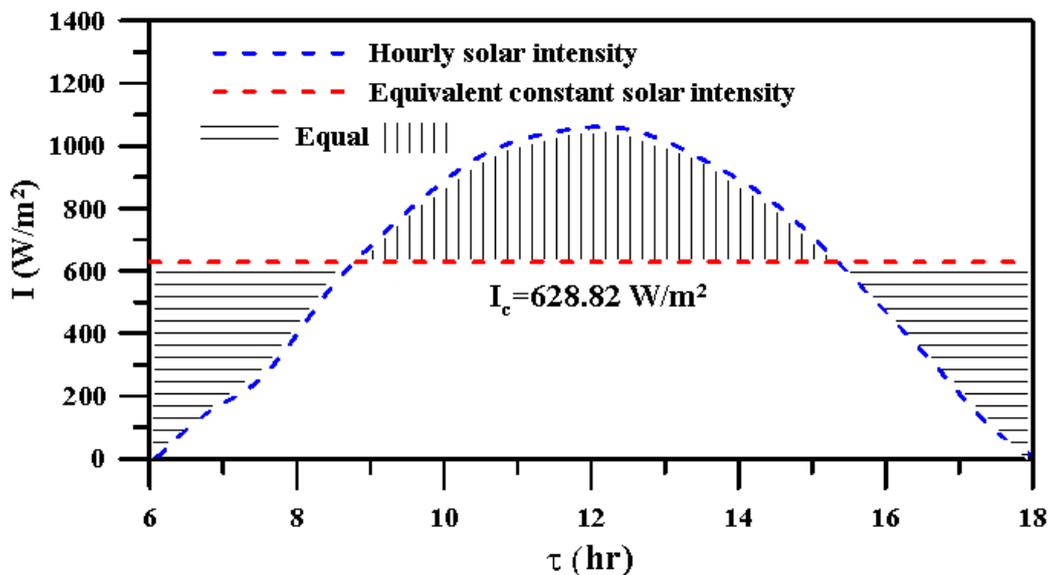
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190 **Fig. 2.** Average daily weather meteorological data of Alexandria in August

191 **6. Results and discussion**

192 As shown in Fig.2 which represents the average daily weather meteorological data of
 193 Alexandria in August, the peak solar intensity takes place around the noon which reflects
 194 high input energy to the saline water. Unfortunately, the outside air temperature is also peak
 195 around the noon. The productivity will be very high in case of the low outside air temperature
 196 which is not found in the actual case. With low outside air temperature, the convection heat

197 transfer inside the trapped air in the still is high due to the less glass temperature. So, the
 198 night hours after the sunset are very important for high productivity. Wind turbine generates
 199 electric power coupled to the storage battery. Electric heater (C.O.P=1) is immersed in the
 200 saline water heated the water in the basin all day by electric energy from the storage battery
 201 less than or equal to the wind turbine power. The power generated from the renewable wind
 202 energy is the peak consumed power in the electric heater. Simple new clarification will be
 203 discussed in Fig.3 which represents the new concept towards the productivity enhancement of
 204 the solar still. The effective solar energy in the still as shown in Fig.2 (red line) is found from
 205 6 AM to 6 PM with value of $0 \leq I \leq 1000 \text{ W/m}^2$ with total energy of $7545.265 \text{ W hr/m}^2$. This
 206 total energy is theoretically replaced by constant solar intensity ($I_c=628.82 \text{ W/m}^2$) for the
 207 same period (6 AM to 6 PM) which gives the same energy of $7545.265 \text{ W hr/m}^2$ in the still.
 208 The equations from 1 to 10 are solved in two cases. The first one with $I = \text{function}(\tau)$, $0 \leq I \leq$
 209 1000 W/m^2 as the actual case, the second one with $I_c=628.82 \text{ W/m}^2$ with value independent
 210 on time.



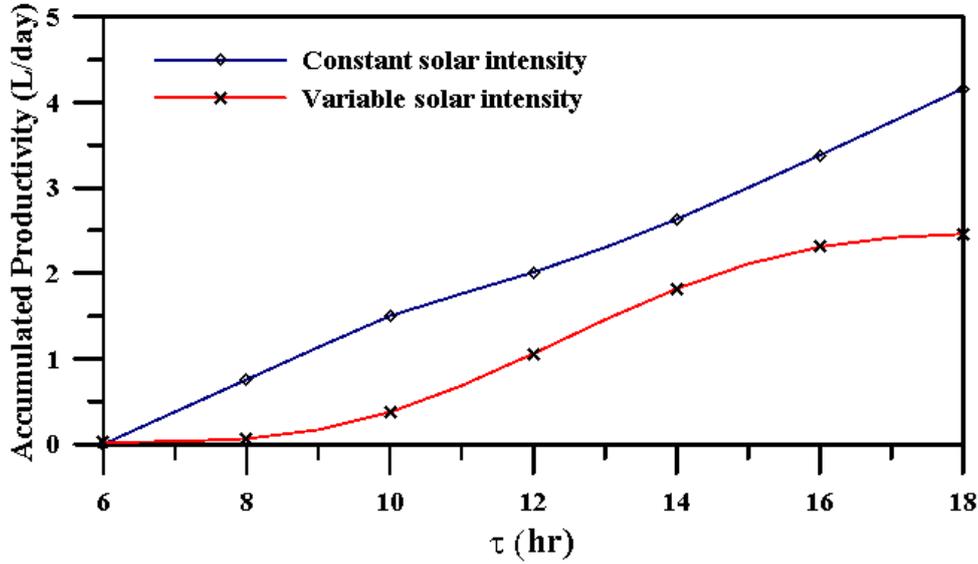
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212

Fig. 3. Average solar intensity and equivalent constant intensity

213 The accumulated productivity at the end of period of 6 AM to 6 PM for the two cases is given
 214 in Fig.4. With constant solar intensity the productivity is 4.16 L/day while with variable solar
 215 intensity the productivity 2.5 L/day. In other words, the constant heat supply is recommended
 216 during the day. This behaviour is due to the large utilized temperature difference between the
 217 saline water and the glass cover due to heating at the time of low outside air temperature. The
 218 previous clarification was to prove that the constant heat rate supply to the basin enhanced
 219 the productivity rather than variable one. However, it is not possible to achieve it actually.

220 There is no control on the solar intensity and the constant heat rate (new concept) will be as
 221 the maximum daily solar intensity with completion from the storage electric power in the
 222 storage battery that has been supplied by the wind turbine.



223

224 **Fig. 4.** Accumulated productivity for both variable and constant solar intensity

225 The linear differential equations 1, 3 and 6 for the energy balance are solved numerically with
 226 one second time step. The solar intensity in Eq.1 for basin plate is the actual solar intensity as
 227 shown in Fig.2 while the basin water will absorb heat from sun as $\alpha_w I$ with addition to the
 228 heat supply from the electric heater to be constant. The absorbed heat in Eq.3 for the water in
 229 the basin ($\alpha_w I$) will be constant at I_c with basin surface area equal unity (Table 1) as

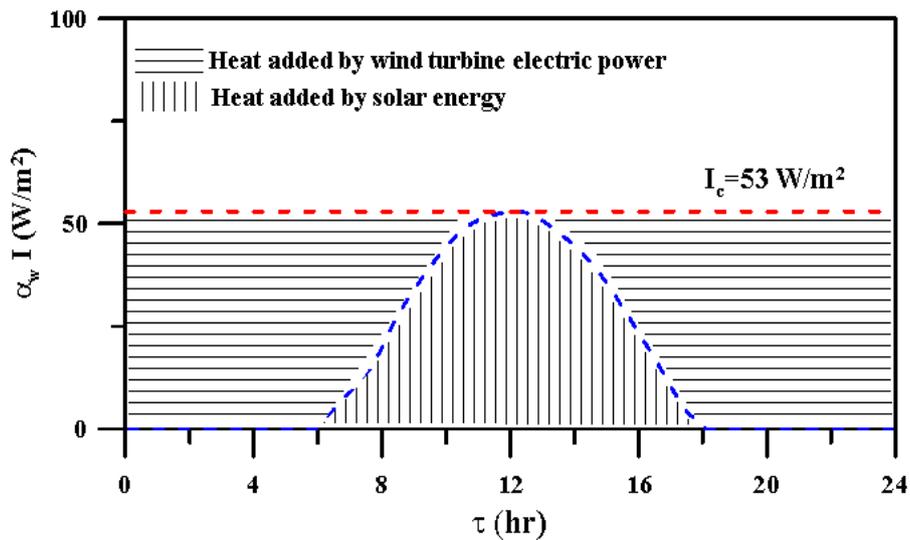
$$\begin{aligned}
 230 \quad C p_w m_w \frac{d}{d\tau}(t_w) = I_c + h_{bw} A_b (t_b - t_w) - \frac{\sigma [(t_w + 273)^4 - (t_g + 273)^4]}{\left(\frac{1-\epsilon_w}{A_w \epsilon_w}\right) + \left(\frac{1}{A_g F_{gw}}\right) + \left(\frac{1-\epsilon_g}{A_g \epsilon_g}\right)} \\
 231 \quad - h_{cw} A_w (t_w - t_g) - 0.884 \left[t_w - t_g + \frac{(p_w - p_g)(t_w + 273)}{268900 - p_w} \right]^{\frac{1}{3}} A_w (t_w - t_g) - (16.237 \times \\
 232 \quad 10^{-3}) h_{cw} A_w (p_w - p_g) - m_{re} (C p_w t_w - C p_a t_a) \quad (11)
 \end{aligned}$$

233 Where

$$234 \quad I_c = \alpha_w I + Q_{electric\ heater} \quad (12)$$

235 As shown in Fig.5, for August month, the required constant heat rate supply to the water
 236 basin should be around 53 W/m² all the day time which is corresponding to the maximum
 237 solar energy peak value. This value corresponding to total energy to the water as 1272 W
 238 hr/m², 377.29 W hr/m² from the solar energy and 894.71 W hr/m² from the electric heater.
 239 The results in Fig.5 could be simply obtained for the eleven months to get the approximate

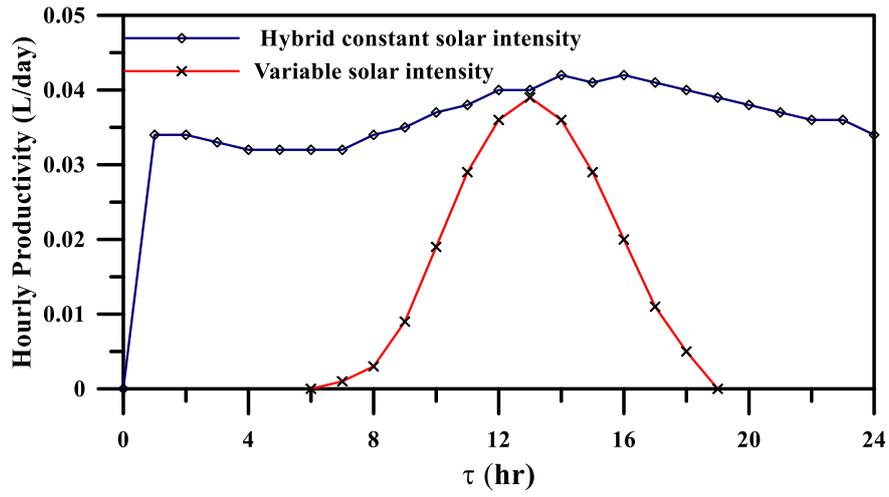
240 required constant heat for the electric heater year around. With very simple control unit fed
 241 by these results, the required time dependent electric current to the solar still electric heater
 242 could be controlled to get maximum productivity of the conventional solar still. Fig.6
 243 represents the **hourly and** accumulated productivity for 24 hr set time for the conventional
 244 solar heated solar still and the constant hybrid heat rate supply from both solar energy and
 245 electric heater energy. The new proposed system has a jump enhancement in the productivity
 246 up to 8.7 L/day in compared to 2.5 L/day for the conventional solar still. The new concept
 247 introduced in this study will be more excellent and professional in winter months. The wind
 248 turbine efficiently operates with high water productivity due to the low outside air
 249 temperature. The required heat supply to the electric heater to keep the heat supply to the
 250 saline water constant during the day is given in Fig.7 (extracted from Fig.5); the peak
 251 required energy to the still from storage energy in the battery is 894.71 W hr (as the basin
 252 area is equal to unity). As mentioned above in Fig.5, the peak electric heater power is 53 W.
 253 So, small wind turbine 1 kW will be used for both electric power generation and the electric
 254 heater capacity, Fig.8.



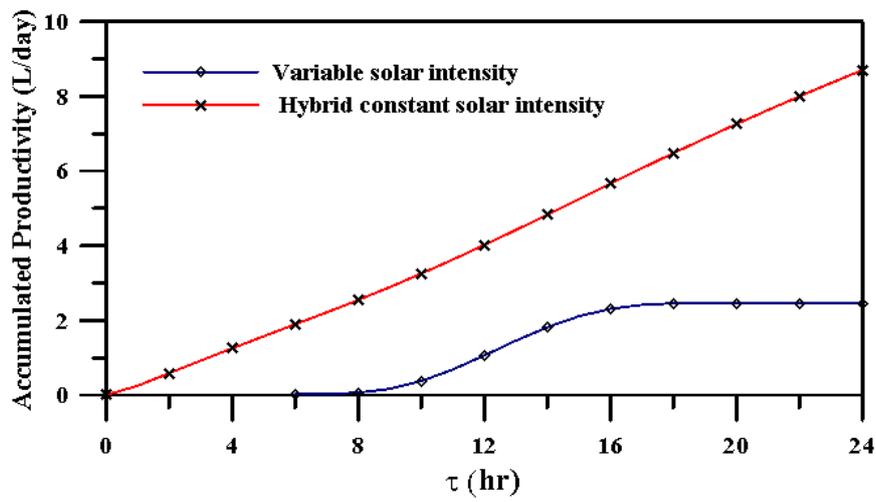
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Fig. 5. Total heat supply to the water in the still during the day hours



257

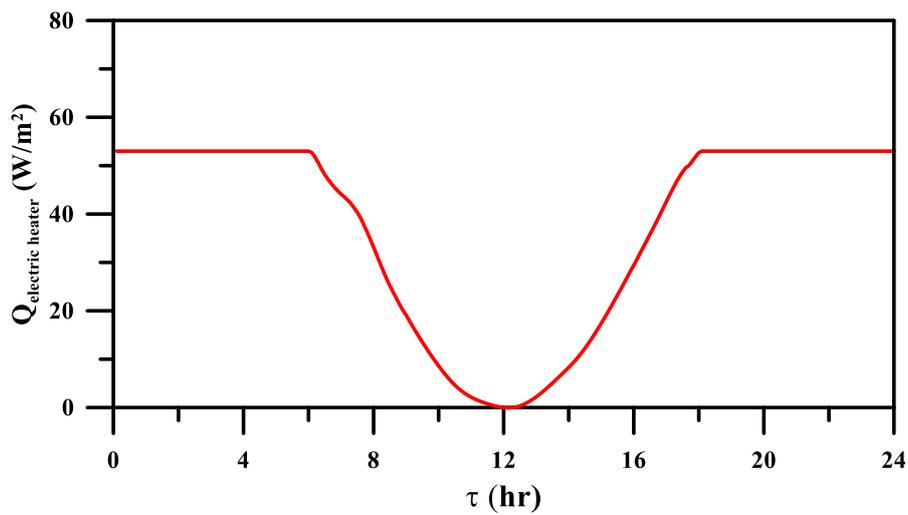


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259

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Fig. 6. Hourly and accumulated productivity for both conventional and hybrid heating solar still

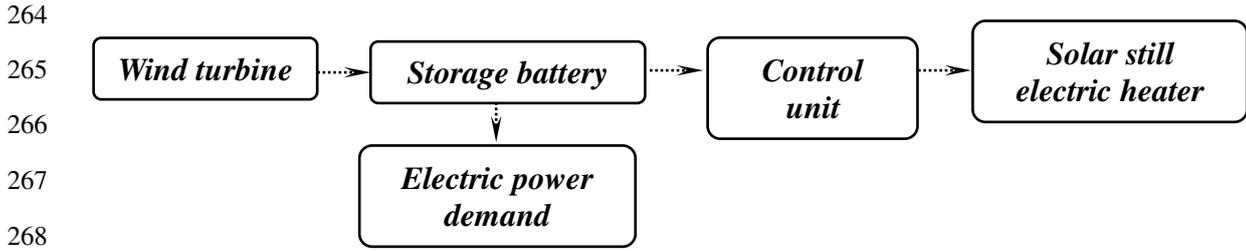


261

262

263

Fig. 7. required supplementary heat supply to the electric heater



269 **Fig. 8.** Wind turbine power storage and electric heater control unit

270 In order to generate the required amount of energy used for the application, it is mandatory to
 271 store the electric energy generated from the wind turbine in an electric battery first and then
 272 re-use it throughout the whole day and night. This is performed through a standard charge
 273 controller from the generator of the wind turbine. The amount of electric energy generated
 274 by the wind turbine (around 1000 W). Once the energy is stored in the 12V-battery, the
 275 normalized loading shown in Fig. 7 can be adopted in order to produce the required heat for
 276 the overall process operation. The minimum and maximum values are 0 and 53 W/m²
 277 respectively. The loading pattern, shown in Fig. 7, spans the whole 24 hours of the day with
 278 peaks during the night and lower values down to zero at noon. The maximum power
 279 dissipation is designed to be 60 W/m² (above 53 W/m²). The resistance of the heating
 280 element is calculated from the following equation.

281
$$R = \frac{V^2}{\text{maximum Power}} = 12.4 \Omega \quad (13)$$

282 The battery voltage is applied to the heating element, which is taken to be a nickel-chrome
 283 wire (of resistivity $\rho = 1.35 \mu \Omega \cdot m$) and cross-sectional area ($a = 1 \text{ mm}^2$). The length (L in
 284 meters) of the wire is calculated as in the following equation.

285
$$L = \frac{R \cdot a}{\rho} = 9.185 \text{ m} \quad (14)$$

286 More details about the control unit is given in appendix B

287

288 **7. Endorsement of the present work**

289 Table 2 presents the current daily productivity of the new proposed system with previous
 290 modified conventional solar still. The selected previous studies are chosen with different
 291 modification technique and both the same current study metrological data of Egypt and other
 292 different weather conditions. The new proposed system philosophy enhances the performance
 293 with high grade. The bulky enhancement in the productivity due to the water productivity in
 294 all day hours with constant peak saline water heat supply.

295 **Table 2**

296 Comparison between the present still performance and previous studies

| Authors | Location (Test year) | Conventional productivity (L/m²/day) | Modified productivity (L/m²/day) | Enhancement (%) |
|--------------------------------|--|--|--|----------------------------|
| (Abdullah et al. 2019) | Alkharj, KSA (May-June 2018) | 2 | 7 | 250 |
| (Yousef et al.2019) | Borg El-Arab city, Egypt (September 2017) | 3.26 | 3.81 | 16.87 |
| (Abd Elbar and Hassan 2020) | Borg El-Arab city, Egypt (September 2019) | 2.334 | 3.534 | 51.41 |
| (Sathish et al. 2020) | Coimbatore, India (Feb- March 2019) | 2.72 | 3.4 | 25 |
| (Kabeel,et al. 2016) | Tanta city, Egypt (June-July 2015) | 4.5 | 9.36 | 108 |
| (Gupta et al.2016) | Jabalpur, India (April 2015) | 2.12 | 2.57 | 21.22 |
| (Kabeel et al. 2017) | Kafrelshikh, Egypt (September 2014) | 3.72 | 4.2 | 12.9 |
| Present study | Alexandria city, Egypt (August 2019) | 2.5 | 8.7 | 248 |

297

298 **8. Conclusions**

299 This **theoretical** study showed that the steady constant heat supply to the solar still is an
300 effective technique to enhance the conventional solar still performance. The absorbed heat in
301 the basin is held constant besides adding the rest from renewable energy for instance wind
302 turbine connected to the storage battery all day. The enhancement of the solar still
303 performance is given in terms of the enhancement of the water productivity all day hours
304 with constant peak saline water heat supply. The results show that, the solar still productivity
305 with constant heat supply is more than that with same amount of variable energy during sun
306 rise time only (6 AM to 6 PM) by 69.133 %. Accordingly, constant absorbed heat in the
307 water basin through the 24 hr of the day enhances the performance with productivity up to

308 248% with the hybrid solar and electric power consumption of the wind turbine power.
309 Finally, the proposed system is applicable not only for one solar still but for more than one
310 with the same storage system (batteries) and the control unit. The proposed system gives high
311 productivity of the common cheap solar distiller units with free supplementary heating from
312 wind turbine in addition to the extra generated electric power for domestic use.

313 **-Ethical Approval**

314 Approved

315 **-Consent to Participate**

316 Approved

317 **-Consent to Publish**

318 Approved

319 **-Authors Contributions**

320 *Wael M. El-Maghlany*: Conceptualization, Methodology and results discussion.

321 *Enass Massoud and Mohamed ElHelw*: Results discussion and paper writing.

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491

492 **Appendix B**

493 The control of the power in order to mimic the exact power requirement curve against time
 494 given in Fig. 7 above is performed using Pulse Width Modulation (PWM) driving a step-
 495 down Buck converter (chopper) MOSFET transistor. The curve above is stored in the
 496 memory of the microcontroller responsible for the PWM in the form of an array of 128
 497 elements (from 0 to 127). In this case, the curve is subdivided into 128 points corresponding
 498 to the time and the corresponding ordinate values are stored in the 128 elements of the array.
 499 The time interval between each two consecutive samples is 11 minutes and 15 seconds. This
 500 array is presented in Table B; the values stored in memory (third column of the array) will
 501 constitute the reference signal for the PWM operation.

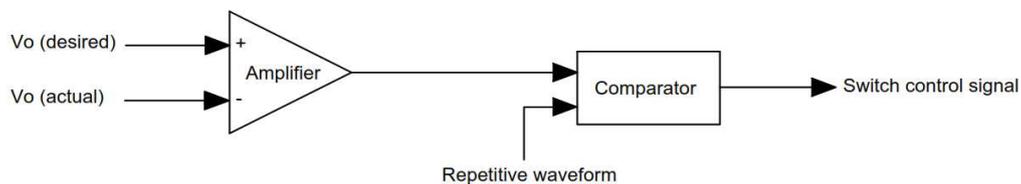
502 **Table B**

503 Sampled data array of the required power

| <i>Time of day (HH:MM:SS)</i> | <i>Memory Address/Sample Number</i> | <i>PWM Reference</i> |
|-------------------------------|-------------------------------------|----------------------|
|-------------------------------|-------------------------------------|----------------------|

| | | |
|----------|-----|-----|
| 00:00:00 | 0 | 53 |
| 00:11:15 | 1 | 53 |
| 00:22:30 | 2 | 53 |
| 00:33:45 | 3 | 53 |
| ... | ... | ... |
| 12:00:00 | 63 | 0 |
| 12:11:15 | 64 | 0 |
| ... | ... | ... |
| 23:37:30 | 126 | 53 |
| 23:48:45 | 127 | 53 |

504 The pulse width will increase in order to accommodate for the large value of required power
505 (53 W/m^2) and it will decrease to zero at noon in order to generate zero output pulse and
506 consequently zero output power. The operation of the PWM controller is depicted in Fig.B1.
507 The microcontroller system employed (An Arduino Mega) is shown in Fig. B2. It is
508 equipped with a Real-Time-Clock (RTC) connected as a shield to the Arduino. The RTC is
509 responsible for generating the time-of-day that will in turn produce the PWM reference signal
510 from the array. The carrier signal of the PWM is assumed to be a saw tooth signal. It is
511 compared to the reference signal generated from the above array. The comparison of the
512 carrier signal (saw tooth) and the modulating signal (reference) yields a binary (High/Low)
513 decision, which is used after proper electronic buffering and isolation to drive the PWM
514 MOSFET transistor responsible for the Buck converter operation. The PWM implemented in
515 this case is performed as a software program inside the microcontroller. This part is denoted
516 by the dotted of Fig. B2.



517
518

519
520

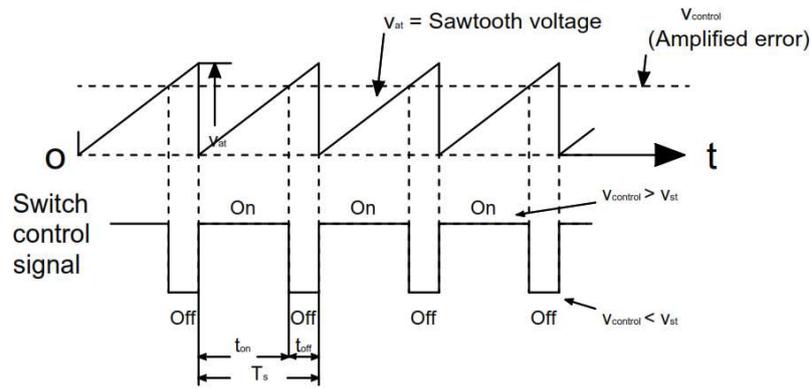
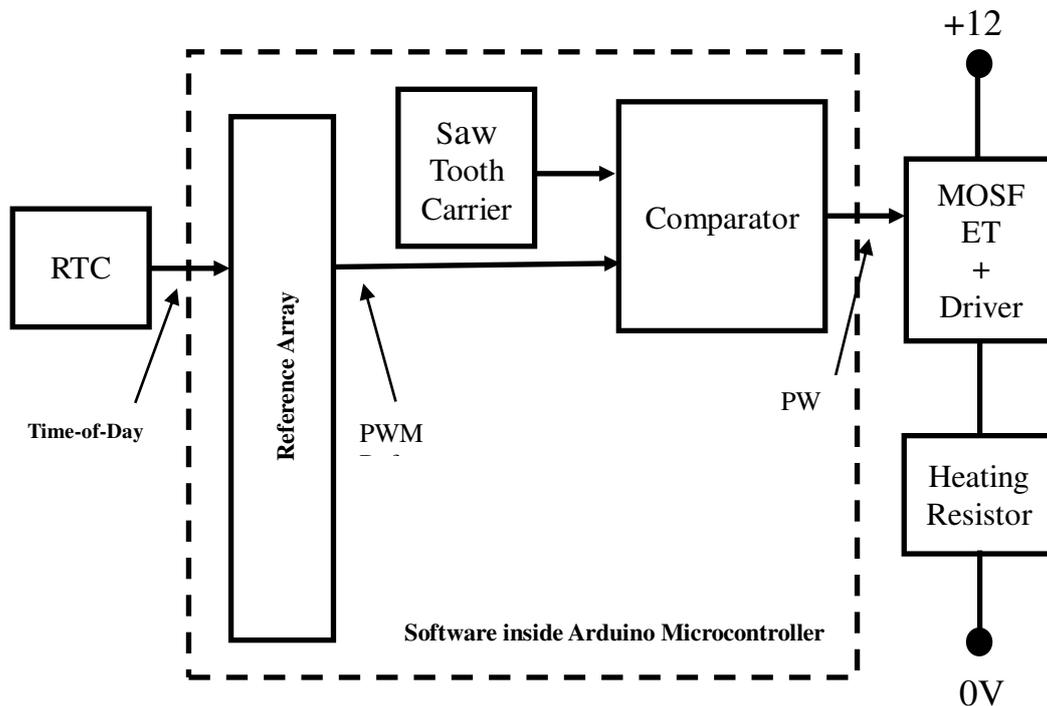


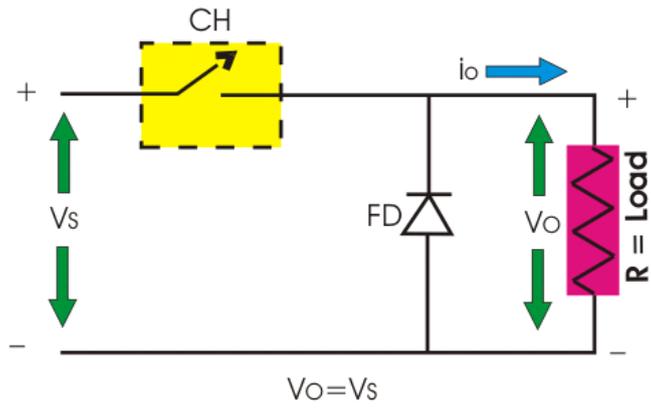
Fig.B1 PWM block diagram and comparator signals



521
522

Fig. B2 Microcontroller system block diagram

523 The DC chopper power circuit of the MOSFET (including the MOSFET, driver circuit and
524 heating resistor) is shown in Fig. B3, where the MOSFET is represented by a switch CH.
525 The freewheeling diode (FD) is used in order to remove the effect of any stray and/or wiring
526 inductances, which would damage the switching circuit. The heating element is represented
527 here by a resistance (R). The output voltage and currents are pulse width modulated signals.
528 The average of the product of these two signals represents the required power from Fig.7.
529 This power will follow the curve desired according to the time of the day as mandated by the
530 heating requirements of the overall system.



531

532

Fig.B3 Power circuit of the MSOFET and heating resistor

Figures

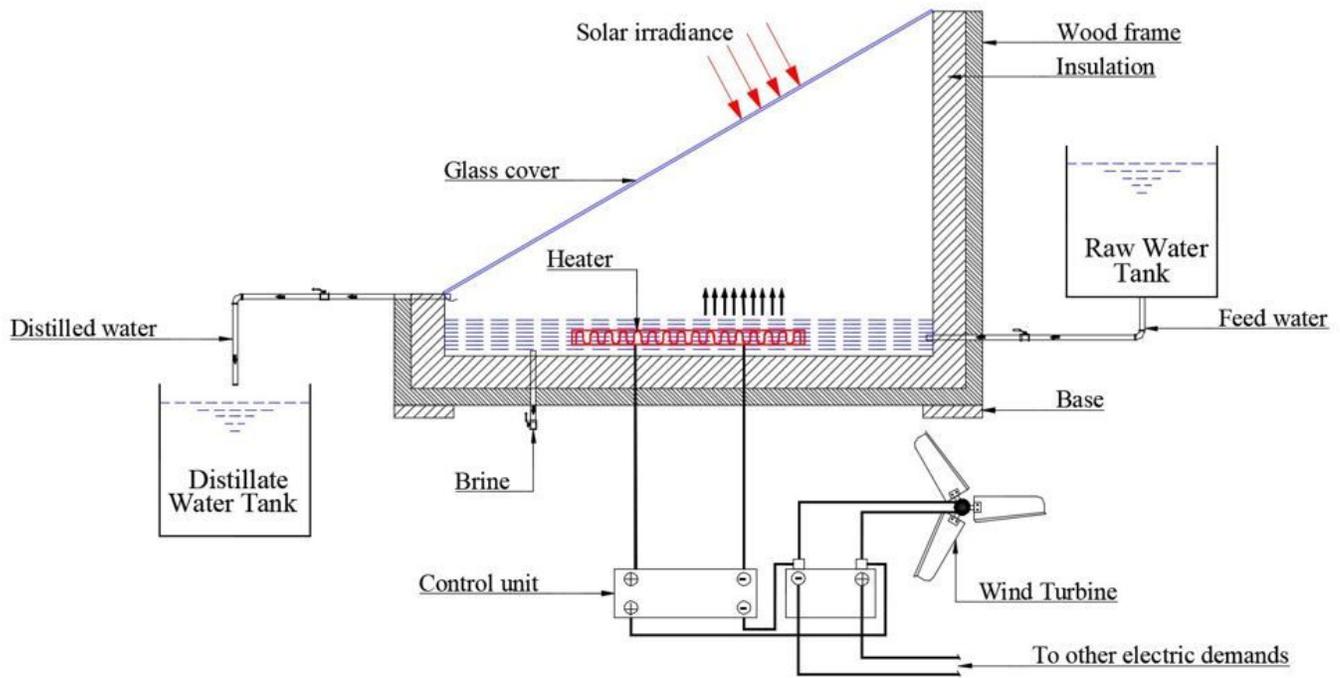


Figure 1

Conventional solar still with supplementary heat added

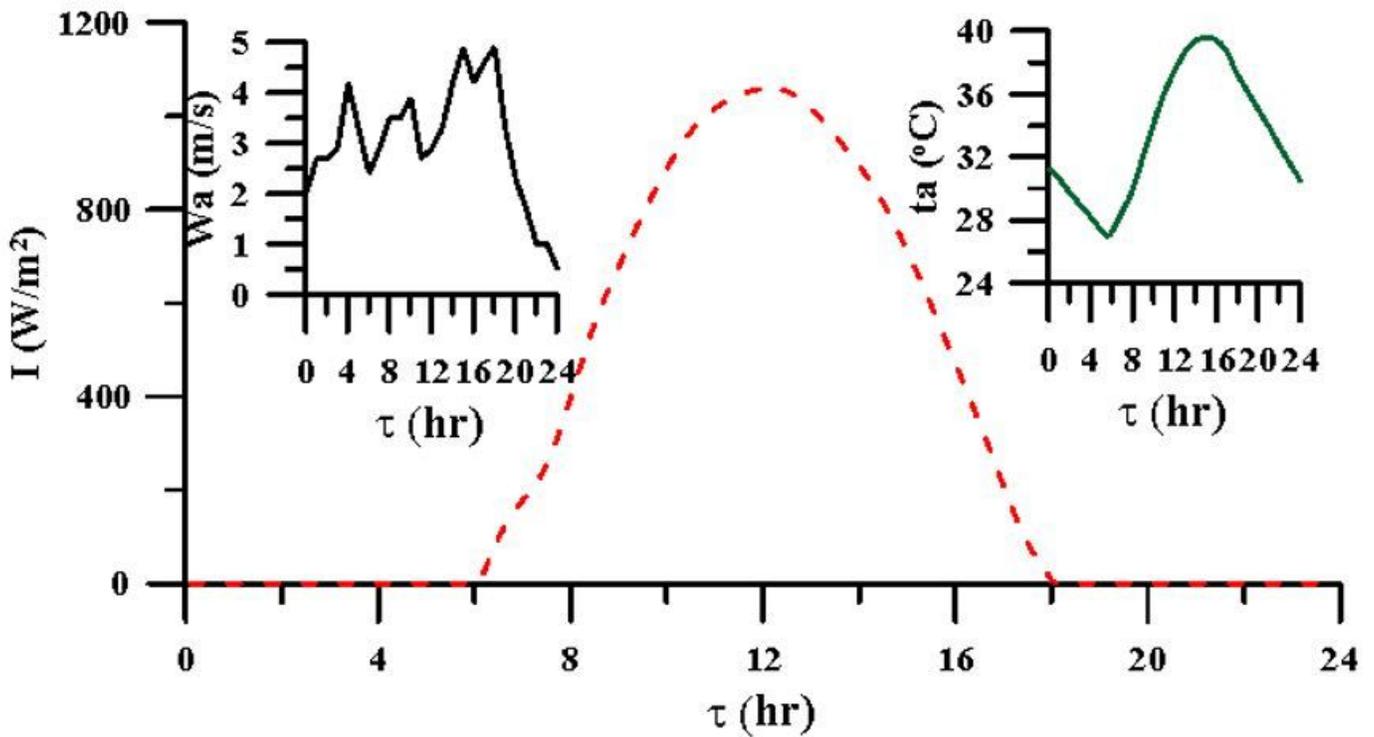


Figure 2

Average daily weather meteorological data of Alexandria in August

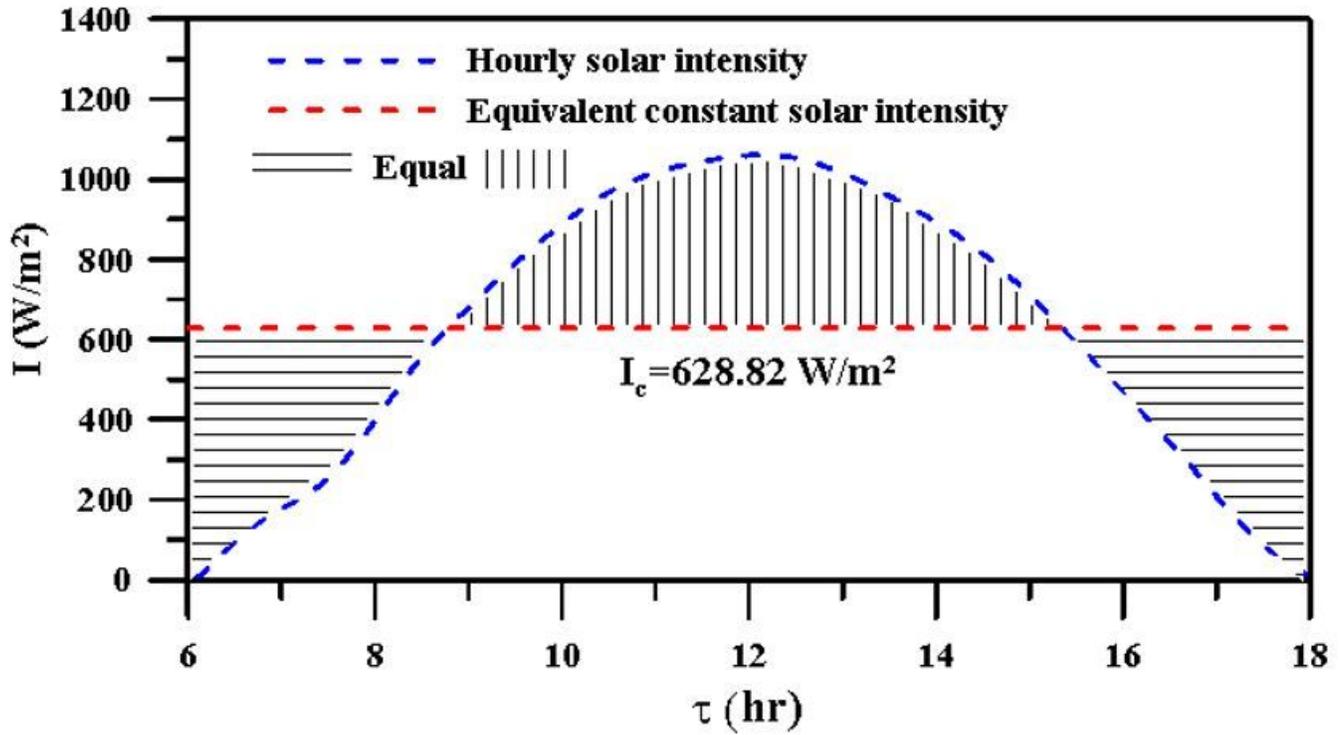


Figure 3

Average solar intensity and equivalent constant intensity

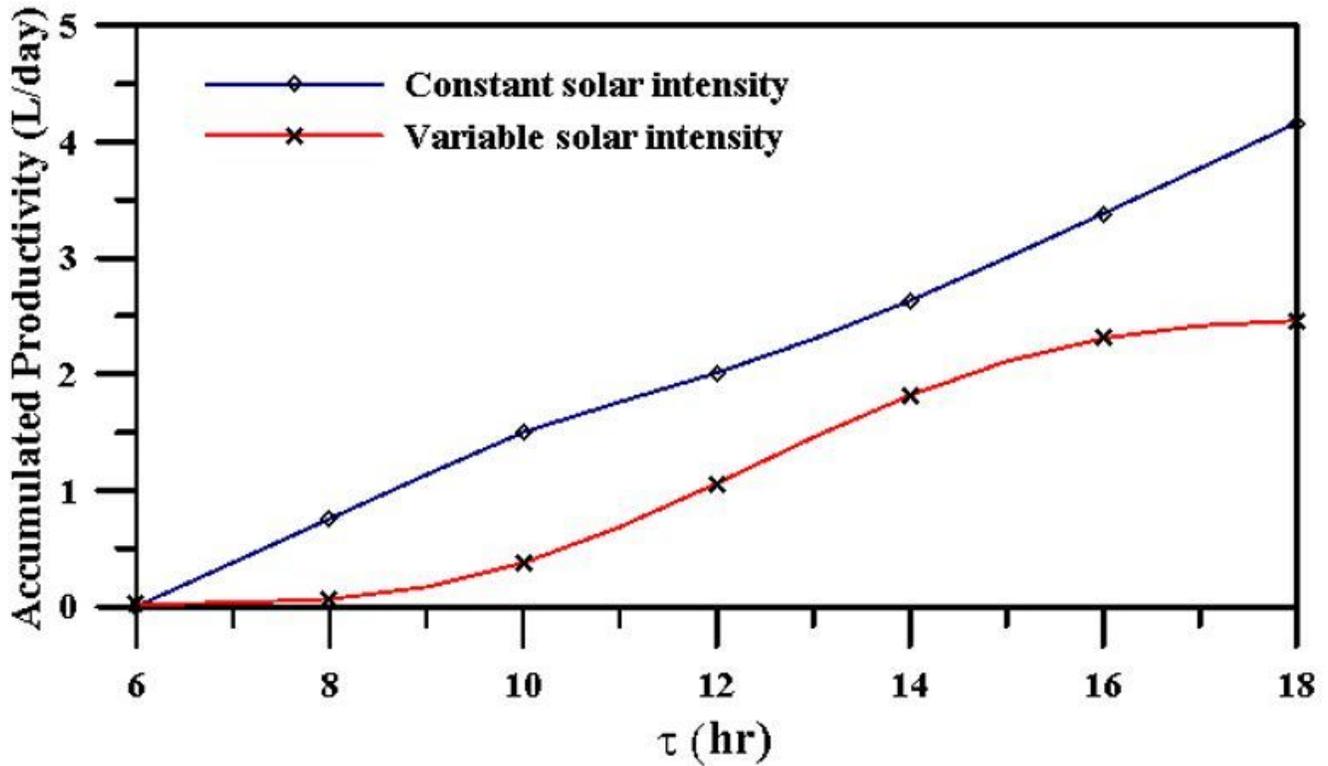


Figure 4

Accumulated productivity for both variable and constant solar intensity

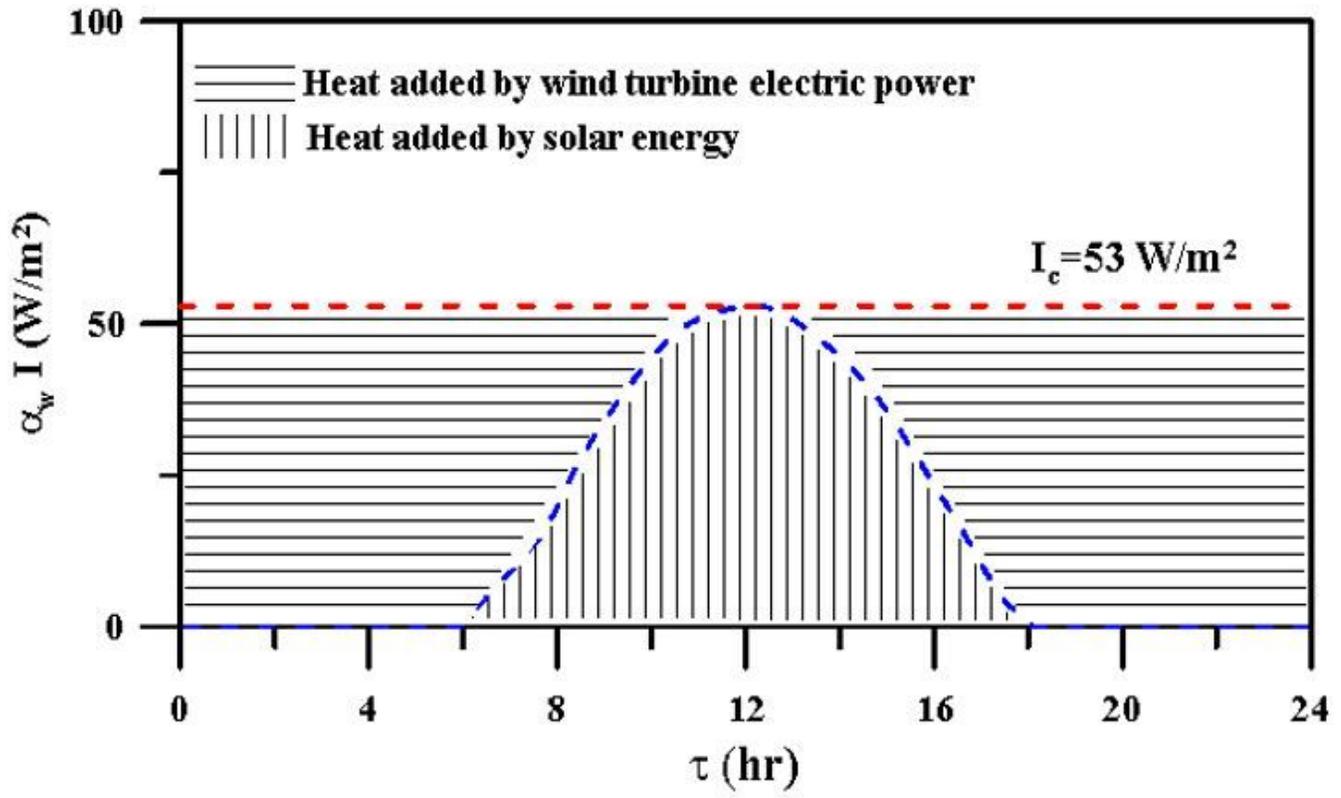


Figure 5

Total heat supply to the water in the still during the day hours

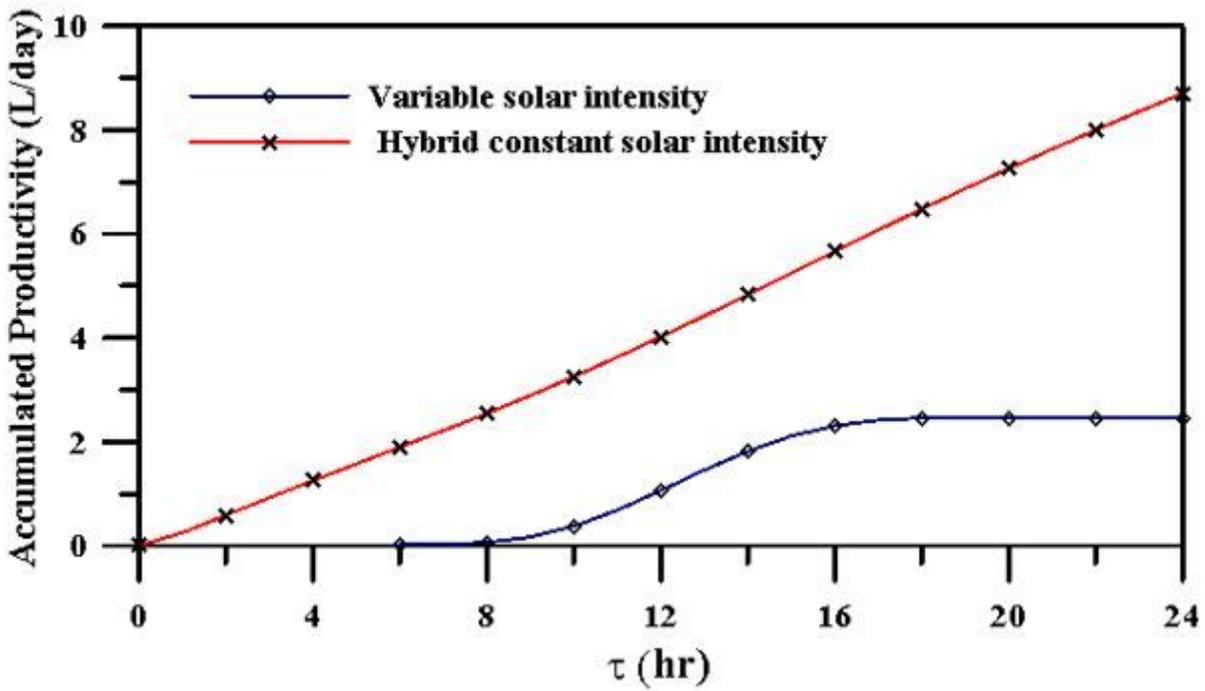
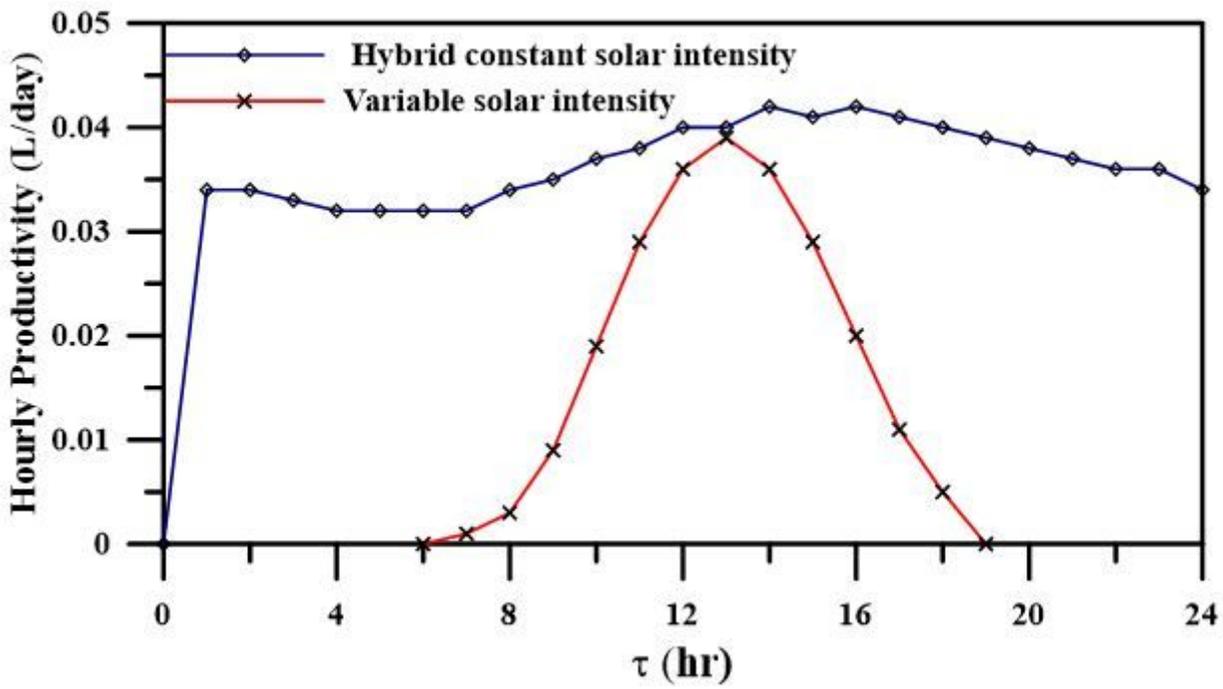


Figure 6

Hourly and accumulated productivity for both conventional and hybrid heating solar still

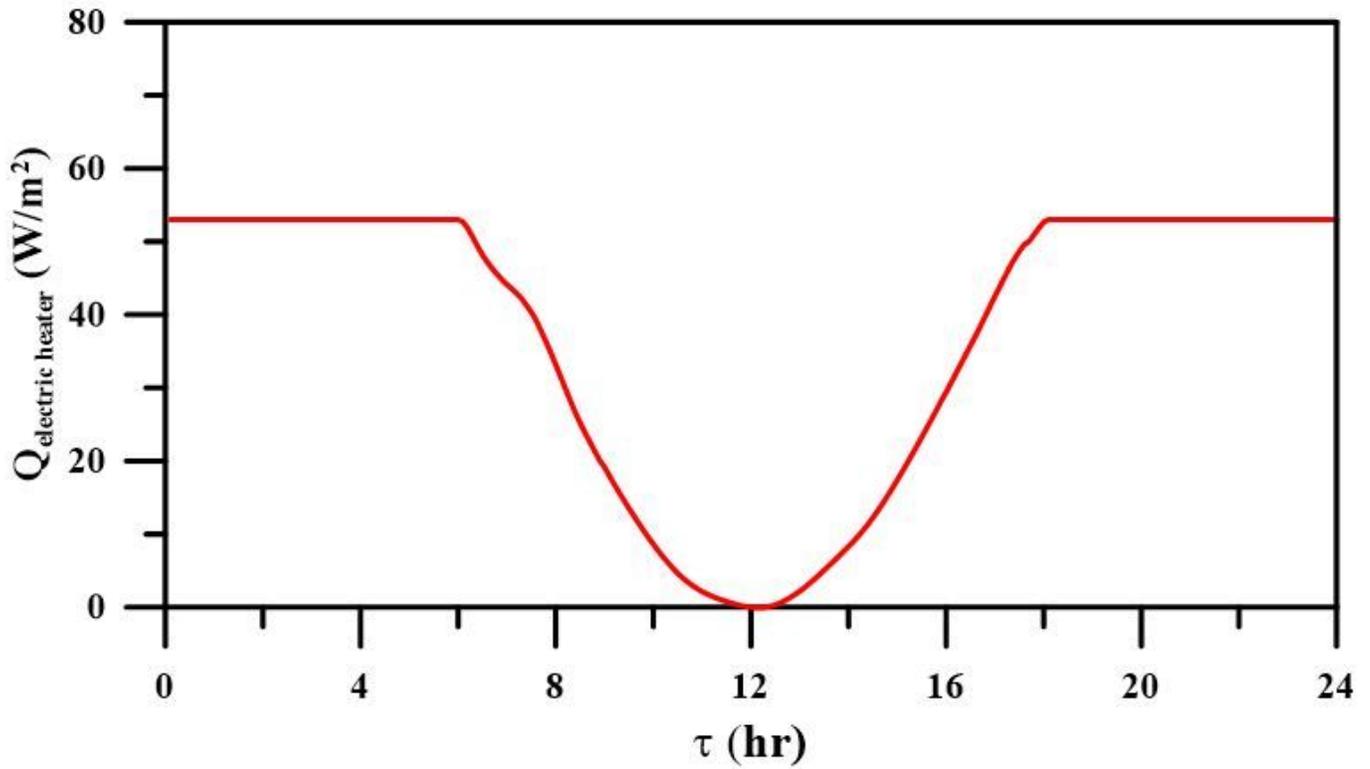


Figure 7

required supplementary heat supply to the electric heater

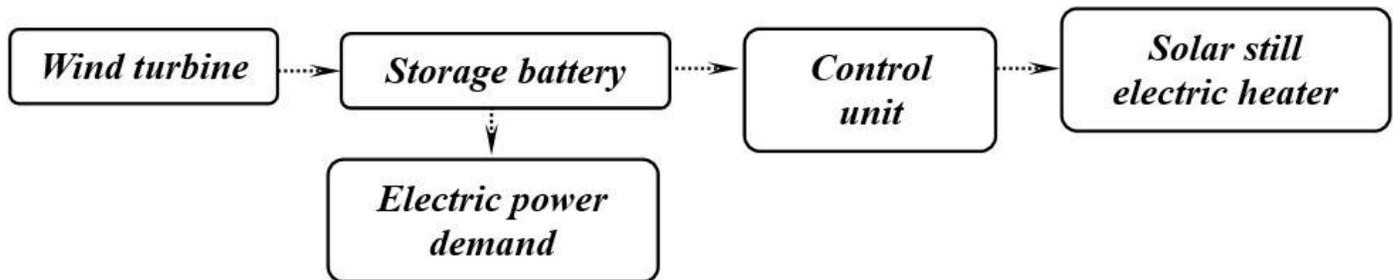


Figure 8

Wind turbine power storage and electric heater control unit

Supplementary Files

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- [AppendixB.docx](#)