A comprehensive review on the productivity enhancement of a solar desalination system through parameters and techniques

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Abstract: Water is an extremely essential life liquid for livings existence. In healthy habitats, hygiene of water is hold up by holy God Sun himself, within the water cycle, in a habitual natural way. In spite of this, inadequate quantity and quality of pure potable water emerge on earth's crust. Water pollution is also producing problems in view of increasing infrastructure and industrialization. So, in this fast-growing era water crisis is a critical consequence. To cope with the clean water scarcity desalination process with solar power is a dynamic steaming process. In this process we have developed synergy with eternal renewable energy from everlasting sun with combination of energy efficient solar stills and other systems. This manuscript meticulously measures a comprehensive review of the classification and impact of various parameters on the still performance such as meteorological, maintenance, and design. It also contains conclusive influence on the yield of distilled water due to different arrangement, coupling with a preheated collector, prototype designs, and economic evaluation. It depicts a comparative analysis which comprises of modification and innovation technique of various designs of solar still and integration of other solar devices, resulting in high productivity, efficiency, and less capital and maintenance cost.

Keywords: Solar still; Solar collector; Desalination; Performance parameters; Productivity.

Abbreviations:
AFC - Annual first cost (INR)
AMC - Annual maintenance cost (INR)
ASC - Annual salvage cost (INR)
CF - Cash flow (INR)
CPC - Parabolic collector (Compound or Concentric)
CRF - Capital recovery factor
CTSS - Concentric tubular solar still
ETC – Evacuated tube collector
EISS- Evacuated tube collector incorporated with solar still
PCM - Phase change material
PV - Photovoltaic
SV - Salvage value (INR)
SFF - Sinking Fund Factor

Nomenclature:
A_c - Glass collector Area (m²)
A_g - Glass cover area (m²)
A_m - PV module area (m²)
D - Distilled water production (l/m². day)
E x e_evap - Instant exergy of evaporation (J/s)


1. Introduction

Water is paramount of life, it covers roughly three fourth of earth's surface in which 97% is saline water and 2% is solidified in ice sheets and polar districts and just 1% of the biosphere's water is potable and this priceless natural resource is available from rivers, lakes, pond, wells, etc. [1].

The demand of drinking water increases dramatically from 1980s due to the population, socio economic & industrial growth [2]. This demand also increases due to water pollution which decreases the quantity and quality of potable water. Worldwide 2.1 billion peoples are in high water stress and by 2025 the demand is expected that half of the world population will scare with fresh water [3]. All over the world drinking water scarcity is a major problem. According to World health organization every year 4,85,000 deaths was recorded due to water borne diseases such as diarrhea, cholera, dysentery, typhoid and polio. Thus, water requires purification through various processes (such as filtration, boiling, and chlorination) to make the water useful for drinking and cooking purpose by removing contaminates from natural available drinking water. However, natural potable water is not enough for fulfilling the demand, so desalting of brackish water or saline water is another method. Vapor compression, Flash distillation, multi-effect distillation, membrane distillation, reverse osmosis, forward osmosis, ion exchange, capacitive deionization, electrodialysis, and seawater greenhouse technologies are used for producing fresh water [4]–[6]. These technologies want huge energy from fossil fuels or renewable energy sources. Since the fossil fuels are limited in earth, and renewable energy is a best possible option for energy source [7]. In earth, solar radiation is cheapest and easily available renewable energy source for desalination process to produce potable water for requirement.

Solar desalination systems are classified into two categories, i.e., Passive and Active systems. In the passive system, a solar still used to produce freshwater through saline or brackish water, whereas in active system, an extra solar thermal collectors are incorporated with solar still [8]–[10].

Solar still is the simplest and economical desalination device that works on water vaporization and condensation. Figure 1 shows a common single slope solar desalination device.
Solar still having a black color coated container held on an insulating frame, where brackish water is fed in to the basin. The container is sealed by a specific inclined glass cover to transmit the solar radiation and reduces the evaporation loss. The inside water in still heats up in presence of solar radiation, when the water temperature increases over its saturation point, evaporation starts. The water vapors start condensing on the internal side of the glass because of temperature difference. This condensed freshwater flows down, collects in a trough through the lower side of the glass and leaves out of the system through a pipe. Performance of system is evaluated by efficiency and production of freshwater. The efficiency of solar still is defined as the ratio of the latent heat energy of the condensed water, to the total amount of solar radiation incident on the still. The productivity of a desalination system is defined as, distilled water quantity collected in a time period.

Solar still possess specific benefits such as simple in construction, less abilities for activity and upkeep, and amicability to nature. The utilization of clean, free energy without degrading the earth’s environment is significant points of interest which bolsters the utilization of solar still. The principal drawback of solar still is the less productivity of freshwater as compared with the other desalination process. The outcome of a conventional type simple solar still was only between 2 to 5 l/m²/day [11-12].

In this review paper, the solar still productivity improvement studied through different parameters and design prospect which affects the system yield, also this manuscript has considered the articles published during the last two decades.
2. Performance Parameters responsible for the yield of solar still

The performance parameters of the solar still are broadly classified based on meteorological, geometrical and miscellaneous parameters as shown in Figure 2.

**Figure 2.** Performance parameters of solar still.

2.1 Meteorological parameters:
The meteorological parameters are belongs to atmospheric conditions/factors, which affects the solar still efficiency. The metrological factors are generated by nature and un-controlled by human, like; Relative Humidity (RH), intensity of solar radiation, ambient temperature, air velocity, Cloudy weather, and geometrical position etc.

2.1.1 Relative Humidity (RH): As per various research, the solar still performance affects by the variation of relative humidity from 40 to 65% [13-14]. Increment in RH at a particular atmospheric temperature decreases the yield of fresh water [15]. RH affects the transmission of solar radiation because moisture absorbs and reflects the sun rays. Due to this the convection coefficient becomes decreases between still and surrounding.

A statistical model represents a relation between quantity of distilled water and RH for different seasons. [16]

\[ D = 4.586 \times R_h^{-0.13} \]  

The analysis of above equation shows that, quantity of distilled water decreases, if RH increases.

2.1.2 Solar Intensity: Solar irradiance is directly affects the efficiency of solar still. More solar intensity increases heating inside solar still which enhance the distillation output. Various experimental and theoretical models were found to evaluate the impact of solar intensity on solar still productivity. [14], [17]

\[ D = 0.037 \times G^{0.705} \]
The analysis of above equation shows that, solar intensity is directly proportional to productivity of solar still. [16]

2.1.3 Ambient Temperature: Different researchers having different views on this factor. Where few investigators found that enhanced yield was attained by decreasing ambient air temperature [18] however other researchers found the favorable impact of increased ambient temperature on the still productivity. [19]

The probability for above controversial conclusion might be, the reduction of ambient temperature or more wind speed, affects the temperature difference between basin water and glass cover. According to that, increment in ambient temperature up to 5 °C increases the solar still performance by 3% [14], [20]. Also, if the temperature increases by 10 °C then productivity enhanced by 8.2% [21]. The highest output was obtained at the maximum ambient temperature of 29.5 °C as shown in Figure 3.

\[ D = 0.263 \times T^{0.783} \]

2.1.4 Air velocity: The flow of air affects the glass temperature, according to the few researchers the maximum efficiency is achieved through lower wind velocity. A result indicates that, if the wind speed augmented from 1m/s to 9 m/s, the total yield diminishes by 13% [19].

However, few researchers claim that productivity improves by increasing wind velocity. Since the convective heat transfer coefficient increases with high air velocity between glass cover and atmospheric air, thus evaporation and condensation increases inside solar still due to temperature change between the basin and glass. Therefore, solar still productivity increases accordingly.
A theoretical and experimental result indicates that, solar still yield increases with the increase in the speed of wind in typical air velocity which is found 10 m/s in summer and 8 m/s in winter. [23] It’s claimed that, the freshwater yield rises up to 50% by increase the air velocity from 0 to 10 m/s. [24]

2.1.5 Cloudy Weather: The Cloudy weather directly affects the direct solar radiation and reduces the solar radiations. This cloudy weather also reduces the ambient temperature, which impact the solar still efficiency and quantity of distilled water reduced. [25]

2.1.6 Geometrical Position: The geometrical position depends on the latitude and longitude of the place. Latitude defines the angular distance of North Pole or South Pole to a point on the globe relative to the equator. Longitude is a point on the globe relative to the prime meridian from east or west direction. As the equator regions get the solar radiation at the perpendicular through the earth, so maximum amount of heat is absorbed at this place and vice versa for polar- regions. Hence, the geometrical position affects the effectiveness of solar still.

2.2 Geometrical Parameters

2.2.1 Design of structures and shapes: The productivity of conventional still is low; this propels the researchers to design different structures to improve the solar still output. Different structures give different yields of solar still, facts; a single slope solar still produced 3.6 l/day, double slope solar still produced 3.95 l/day which is 9.50% more efficient to single slope solar still, the pyramid solar still produced 4.25 l/day, which is 17.50% more efficient than single slope conventional solar still. [26] Hence the output of desalination system increases if the system designed to capture the maximum solar radiations by occupying minimal space.

2.2.2 Absorbing Area and Materials: Absorption surface area and material is directly proportional to the rate of water evaporation in solar still that means productivity [1]. Absorbing material increases the absorbing surface area of the basin which is used to store more quantity of thermal energy and enhance the heat absorption capacity of system. The different absorbing materials are jute cloth [27], charcoal [28], dyes [29], sponges and black rocks [30], nano embedded PCM [31]. The absorbing material’s impact on the productivity of solar still is shown in Table.1.

| S. No | Absorbing Material                          | Increased productivity in % |
|-------|---------------------------------------------|----------------------------|
| 1     | Red Carmoisine (50 mg/l)                    | 7.4                        |
| 2     | Charcoal                                    | 11-18                      |
| 3     | Soot powder                                 | 13-17                      |
| 4     | Dark green dyes (50mg/l)                    | 14.80                      |
| 5     | Sponge cubes                                | 14-18                      |
| 6     | Black granite gravels                        | 17-20                      |
| 7     | Black naphthylamine (172.5 mg/l)            | 17-28.8                    |
| 8     | Red Carmoisine (100 mg/l)                   | 19.9                       |
| 9     | Absorbing black rubber mat                  | 38                         |
| 10    | Black dye                                   | 60                         |
| 11    | Sponges & fins in a stepped still           | 96                         |
2.2.3 Inclination angle of Cover plate: A clean and high trans-missive glass plate used to cover the solar still for condensation of vapors. The angular displacement for glass cover is selected based on the latitude of the place. The extreme yearly productivity of solar still was achieved when the tilt angle of the condensing cover plate is equal to the latitude of the place [13]. The cover tilt angle should be large in winter and small in summer. If the latitude of the site is higher than 20° then conventional single slope solar still is preferred because one side has shadow and another side receives the solar radiation [8], [33].

2.2.4 Cover plate temperature / glass cover temperature: When the solar radiation falls on the desalination device the temperature of transparent glass cover and black absorber plate increases linearly but the quantity of distilled water production is not increased linearly. This circumstance represents that the freshwater quantity is influenced by the cover plate temperature. However, shaded plate reduces the surface temperature of transparent cover to 98°C and absorber plate temperature to 88°C, therefore the distilled water production is increased [34]. Precursory researches govern that the productivity of desalination system was enhanced when difference in temperature is present between saline water and glass plate. Cooling system was used to sustain high temperature difference through fans, condensers, storing materials, reflectors. The glass temperature was diminished by regular supply of air and water. Also, the continuous cooling water layer on the glass cover helps for self-cleaning. A progress in still efficiency and yield was found from 15.5% to 20% by the reduction in glass cover temperature from 6 to 20°C due to the use of glass cover cooling [35]. The daily productivity of stepped still is increased by 8.2% when water is running on the cover plate for cooling and recycling [36].

2.3 Miscellaneous parameters

2.3.1 Depth of water: According to the previous researches, it still shows the highest output and efficiency from solar still produced at lower depth of basin water. The water depth in basin is considered the most affecting parameter for still performance and it is inversely proportional to the yield of still [37]. Table 2 comprises effect of water depth on the productivity of different types of still.

| Water depth variation in cm | Still type | Tilt angle of glass in degree | Productivity in percentage | Conclusion |
|-----------------------------|------------|------------------------------|---------------------------|------------|
| 1 – 10                      | Single slope | 10                           | 34                        | Increased  |
| 1.25 – 30                   | Double slope | 15                           | 30                        | Decreased  |
| 2 – 3.5                     | Single slope | 32                           | 26                        | Decreased  |
| 5-2                         | Single slope | 8 – 13                      | 11                        | Decreased  |
| 7-2                         | Single slope | 32                           | 14                        | Decreased  |
| 8-2                         | Non-insulated double slope | 15                           | 13.8                      | Decreased  |
| 6-3                         | Double slope | 15                           | 13.5                      | Decreased  |

It’s also observed that, the maximum efficiency of 25.3% was recorded at the lowest water depth 2.0 cm in double slope basin type solar still. The graph of productivity against depth shows that the output decreased non-linearly with increasing water depth as per Figure 4. [22]
The maximum instantaneous or daily efficiency ($\eta$) of the solar still is calculated from the data of distillate obtained at depth, using following equation

$$\eta = \frac{Q}{HT}$$

(4)

2.3.2 Dust cover: without any cleaning process, dust is accumulated on the glass surface which restricts the incident solar radiation; hence drop identified in glass tube transmittance and system production. Various authors showed their studies on dust deposition on flat plate collectors [38]–[43]. Measurements of dust accumulation exposure were made on a tilted flat glass plate ranging from 0 to 60° and the transmittance is found reduced from 64% to 17% respectively [40].

The impact of deposited dust on the working of evacuated tube collectors was analyzed by the SOLDES program, where the transmittance decreases from a preliminary value of 0.98 for clean glass to a low value of 0.6 for very dusty glass, production falls from 100% to 40% [44]. 10% to 18% monthly fall in the transmittance of glass was occurred due to the dust deposition. The transmittance fall was found 6 – 16% in the summer months from May to August and 2 –4% in November and December. Outcome represents that, due to less transmittance of glass tube shows a drastic decline in monthly plant production. It was also found that the specific water production (annual average plant fresh water production per unit solar radiation impinging on a tilted surface) 2.7 l/MJ for clean glass falls to 1.8 l/MJ for very dusty glass collectors while the specific power consumption rises by 45% for 0.6 transmittance [45]. It is also observed that the transmittance reduced by 1% at 30° glass tilt angle [8].

![Figure 4. Productivity Vs. water depth [22]](image-url)
3. Performance enhancement technologies
The various performance enhancement techniques reported in the literature are illustrated in the Figure 5

3.1 Solar collectors
Collectors are the sturdy devices that are used primarily for preheating the working fluid or complement heating of a working fluid by collection and concentration of sun rays. These collectors add thermal energy
to a conventional water basin for increasing its temperature. The temperature of traditional still brine solution is 20-50°C, but on the integration of collector, it is increased to 70–80°C for better yield and efficiency.[46]

3.1.1 Flat plate collector: It is a simple box of metal having transparent glazed top cover above the dark-colored absorber plate. This glass cover allows the sun rays which are absorbed by absorber plate and heats up. This hot absorber plate transfers its heat to the basin water which is present in between glazed cover top and black colored absorber plate. Insulation is provided on all the sides except top cover for minimizing the loss of heat. Flat plate collector integrated with conventional still works with two circulation modes either natural or forced. In natural circulation, density difference of water is responsible for flow and in a forced circulation; pump is used for flow of water. Circulation of water through pump produces 5 to 10% more yield as compare to the thermo syphon circulation mode and 30 to 35% yield improvement while connected with simple solar conventional still [47].

From other studies, when an experiment is conducted in solar still which is connected with a series of two flat plate collectors. Author findings says that, the collector combined with solar still gave an average increment of 100% productivity as compared with conventional sun oriented still [49]. At 24.343 MJ/m².day radiation of sun, the maximum value of yield for the simple basin & integrated system was 2.57 L/m² day and 5.18 L/m² day [48]. Figure 6 shows solar still with flat plate collector.

![Figure 6. Solar Still with flat plate collector. [48]](image)

A conventional solar still incorporated with a tubular collector is represented in Figure 7. In this enhancement method, both the still and tubular collector receives the heat. The tubular collector is used for preheating of water; however, still is used for evaporation of preheated feed water, which is present in basin and collection of distilled water droplets that are accumulated under the glass cover plate [50].
3.1.2 Concentrating collectors: This type of collectors concentrates all the incident sun rays at a receiver for increasing the fluid temperature. These systems are costly as a mechanism of tracking is to be incorporated. The distillate productivity of this system was double as compared to single slope solar still. Figure 8 depicts an inverted absorber solar still which absorbs the concentrated sun rays from the base of the still. [51]

The simple solar still was integrated with focal pipe parabolic trough collector (PTC) then distilled water yield of this developed system was approximately 18% more as compared to the simple conventional solar still [52]. A parabolic trough collector was equipped with a small solar desalination unit then the result shows that the maximum solar radiation was obtained at 02.00 PM and at this particular time highest efficiency was achieved due to the more heat transfer area at horizontal position of boiler. [53]

A modified solar desalination system equipped with parabolic concentrator collector, cover cooling, spherical absorber, and continuous flow water circulation through a reservoir tank for yield improvement. In this technology evaporation from basin bottom was increased by the absorption of heat from the parabolic concentrator however, condensation rate was increased by water circulation, above the glass cover. From Table.3 it was clear that the maximum productivity was 3.8 and 3.512 kg/day at highest flow rate of 100 ml/min. [54]
Table 3. Distillate productivity for water flow rate and recorded temperatures [54]

| S. No. | Mass flow rate of water (ml/min) | Fresh water productivity without PCM (ml/day) | Fresh water output having PCM balls (ml/day) |
|--------|---------------------------------|---------------------------------------------|-------------------------------------------|
| 1      | 00                              | 3043                                        | 3557                                      |
| 2      | 40                              | 3063                                        | 3620                                      |
| 3      | 50                              | 3193                                        | 3672                                      |
| 4      | 60                              | 3290                                        | 3725                                      |
| 5      | 80                              | 3300                                        | 3762                                      |
| 6      | 100                             | 3512                                        | 3800                                      |

A receiver tube is placed in parabolic trough collector for absorbing solar radiation. Solar radiation is concentrated on focal line of the parabolic trough. Receiver tube is used to flow brackish water in it. Brackish water gets heated and converted into vapor. Vapor gets condensed in the condenser and collected as a fresh water. The production rate of system was 2 l/m² and efficiency was 12.74%.[55]

Figure 9 shows single slope conventional solar still attached with crescent shaped absorber and compound conical concentrator has been investigated. The performances of this innovative study were analyzed by different approaches such as with and without integration of crescent shaped absorber, with glass cover cooling and shaded top cover. Experimental result showed that the freshwater yield is maximum for conventional single slope solar still with compound conical concentrator and top cover cooling technique is 2.912 l/day. [56]

![Solar desalination system with crescent shaped absorber.](image)

3.2 Hybrid PV (photo voltaic) integrated solar still

3.2.1 PV and flat plate collector integrated solar still: The hybrid PV active still consist of a pump operated by DC motor, single slope solar operated still, two series connected flat plate collector with photo voltaic system of size 1.25×0.55 m². This system is maintained by itself. Operation of this system was started from the preheating of brackish water through flat plate collector and power generation by PV module. Preheated water was injected into still through pump which is operated by DC motor. This experiment concludes that
conventional still gives lesser yield approximately 3.5 times as compared to this active system. It also concludes that the daily productivity of fresh water is approximately same for all the basin water depth when working period of system comes to 5 Hr. from 9 Hr. [57]. The performance of the system consists of PV-integrated flat plate collector, DC motor pump and double slope solar still is experimentally evaluated under thermo syphon and force mode of circulation in both series as well as parallel arrangements. Figure 10 represents the series arrangement of still, PV module and flat plate collector.

![Diagram of Double slope solar still integrated with flat plate collector in series and pump.](image)

**Figure 10.** Double slope solar still integrated with flat plate collector in series and pump. [58]

The energy and exergy efficiency are obtained by Eq. 5 & 6 respectively. The maximum energy and exergy efficiency in parallel forced circulation mode was found 32% and 2.3% respectively. The daily average energy efficiency for parallel forced circulation mode (i.e. 17.4%) was more than series connected forced circulation (i.e. 16.4%) and parallel connected natural circulation (i.e. 16.3) [58].

\[
\eta_{\text{hybrid active system}} = \frac{\sum_{i=1}^{24} m_{\text{ev}} L}{\sum_{i=1}^{24} [I_s(t)_{E} A_{P} + I_s(t)_{W} A_{G} + I_s(t)_{L} (A_e + A_m)] \times 3600} \times 100
\]

\[
\eta_{\text{Ex}} = \frac{E^{*}_{\text{evap}}}{E^{*}_{\text{in}}}
\]

### 3.2.2 PV with evacuated tube collector integrated solar still:

An innovative work was proposed for analysis of this hybrid system in natural mode as shown in Figure 11. Various aspects of performance parameters are investigated for example productivity of distilled water, electrical power production, energy and exergy efficiency considering different photovoltaic module materials, different basin water depth and number of collector tubes.
Figure 11. Conventional solar still with PV module and evacuated tube collector. [59]

The yield of still was affected by increase in number of evacuated tubes and remains almost same fresh water yield for various photovoltaic modules. It was also observed that the 30 collector tubes and 0.07m basin water depth gives maximum distilled water yield i.e., 4.77 kg/m² day. Highest instantaneous power was 70.48 W/m² and daily electrical power output is 483.2 Wh/m² which is achieved by Heterojunction Intrinsic Thin Layer (HIT) photovoltaic module. The comparison of electrical power output from HIT to other PV module was found to be 50 W/m² which is decreases by 23.65% for microcrystalline silicon (m-Si), 40 W/m² which decreases by 34.56% for Poly Crystalline Silicon (p-Si), 30 W/m² which decreases by 55.17% for copper indium selenide (CIS), 29 W/m² which decreases by cadmium- telluride (Cd-Te) and 25 W/m² which decreases by 57.18% for amorphous silicon (a-Si) [59].

3.3 Multi effect active solar still: Figure 12 shows the pictorial presentation of an active solar still with the effect of multi stages of evaporation chamber. Result shows that, when stages are more than production of distilled water was also increased.

Figure 12. Multi-effect active solar still. [60]

Table 4 shows continuous mode of operation gives more distillate output as compare to the non-continuous operation. Single stage of system gives approximate similar output for both the operation modes.
Table 4. Freshwater yield in different modes of operation at each stage of evaporation chamber [60]

| No. of Stages | In 1st stage of evaporation chamber | In 2nd stage of evaporation chamber | In 3rd stage of evaporation chamber | In 4th stage of evaporation chamber | Fresh water yield (kg/m² basin.d) |
|---------------|-------------------------------------|-------------------------------------|-------------------------------------|-------------------------------------|----------------------------------|
|               |                                     |                                     |                                     |                                     | Operation mode: Continuous       |
| 1             | 12.4                                |                                     |                                     |                                     | 12.4                             |
| 2             | 10.24                               | 7.43                                |                                     |                                     | 17.67                            |
| 3             | 9.62                                | 7.17                                | 6.05                                |                                     | 22.84                            |
| 4             | 9.04                                | 6.86                                | 5.94                                | 5.64                                | 27.48                            |
|               |                                     |                                     |                                     |                                     | Operation mode: non-Continuous    |
| 1             | 11.96                               |                                     |                                     |                                     | 11.96                            |
| 2             | 10.04                               | 6.72                                |                                     |                                     | 16.77                            |
| 3             | 8.67                                | 6.53                                | 5.67                                |                                     | 20.87                            |
| 4             | 8.46                                | 5.8                                 | 4.62                                | 4.36                                | 22.81                            |

Result shows that, the first stage of evaporation chamber produces maximum quantity of distilled water while production of fresh water decreases with increasing the number of stages.

\[
D = -0.2539 \times n^2 + 6.1976 \times n + 6.4149 \tag{7}
\]

\[
D = -0.7169 \times n^2 + 7.2516 \times n + 5.3496 \tag{8}
\]

The R² fitness value was 0.9997 and 0.9985 for quadratic equation 7& 8 which is gained by fitting a second degree polynomial over continuous and non-continuous operation data respectively. [60]

3.3.1 Evacuated multi stage solar still: This novel distillation unit was developed by utilizing latent heat. Saline water was feed from water storage tank which is placed on top of solar still to the flat plate collectors for preheating which are connected either in series or parallel for analyzing the fresh water yield. Vacuum pump is used for maintaining the vacuum pressure at all the stages in the evacuated chamber as shown in Figure 13.

![Figure 13. Evacuated Multi stage solar distillation unit coupled with flat plate collector. [61]](image-url)
The outcome of work was reported throughout the year, depends on the parameters such as 4 ideal number of stages, 100 mm space between the stages and 55 kg/m²/day mass flow rate of water were found. Maximum yield was found in the month of March i.e. 53.2 kg/m²/day [61]. A research work in five stage solar still with PCM was also reported for Iran’s climatic condition. Paraffin wax is used on the bottom of the absorber plate for additional heat storage from the solar radiation. This study was done with different thickness of PCM material such as 5 cm, 2.5 cm, & 0 cm. Outcome shows that the 2.5 cm thickness gives 15% increment in distilled water. The mass flow rate of water and freshwater quantity in each stage was also studied. The maximum fresh water is produced with mass flow rate of 1.3 L/min and maximum fresh water is obtained with the first stage out of five stages. [62]

3.4 Distillation with thermoelectric module

3.4.1 TEM with ETC: In this, evacuated tube was used as a basin where evaporation of brackish water takes place and thermoelectric module are placed above the condensation chamber where the colder sideways is linked with the sink whereas the hotter side is attached to the chamber and vapor is condensed by propeller fan (Figure 14).

![Figure 14. Schematic setup of experiment and the process occurred.](image)

The yield for evacuated tube with full and half-filled working fluid in natural mode of convection was found to be 0.97 kg/m².h and 0.74 kg/m².h respectively. However, a highest fresh water output of 1.1 kg/m².h and 68% efficiency was attained by fans in forced convection. It was also found that the more difference in temperature between hot and cold side of TEM was 14.9°C gives maximum power i.e. 1.32 W. [63]

3.4.2 TEM and heat pipe with portable solar still: Generally, vapor condensation depends on glass cover temperature which is affected by wind velocity and cover material. The condensation occurs on an inclined and horizontal surface (Figure 15). They used Plexiglas for condensation surface. To enhance the condensation an aluminum plate (13×26 cm²) cooled with a thermoelectric module is attached in the horizontal roof region. The maximum daily productivity was 7% and it was also perceived that productivity decreased with increasing wind velocity. [17]
3.5 Distillation with tubes

3.5.1 Pulsating Heat Pipes (PHP): Heat pipe technology was introduced in 1990. It is made up of long capillary tube which is consisting of three sections:
(1) Evaporator: in this boiling process increases pressure
(2) Adiabatic section: in this there is no heat loss
(3) Condenser: in this condensation process decreases pressure.
Due to phase change and convective heat transfer, the sensible and latent heat transfer occur simultaneously. [64]

The flat plate collector was used with PHP which is made up of copper with 2 mm dia. and having 24 serpentine turns causes higher rate of heat transfer to the water due to higher amount of absorbed heat. The evaporator section of tubes is fixed on an aluminum sheet and it was filled with water which evaporates due to solar radiation which falls on inclined cover having 35° with horizon (latitude of Tehran). The basin contains the condenser where evaporated heat transfer fluid releases its heat and gets condensed while the latent heat of heat transfer fluid was rejected to the saline water inside the basin was evaporated. In PHP filling ratio (Fw/Fv) is the major factor in the rate of production of fresh water, effect of water depth in basin. The results indicates that the yield of fresh water for the active system was 0.875 kg/m².h with Fw/Fv=40% and 1cm basin water depth. However, the maximum production rate of fresh water was 0.50 kg/m².h with 1cm basin water depth for a passive solar desalination system [65].

3.5.2 Evacuated tubes as basin: This technique does no uses water chamber or copper rods. The brackish water was directly fed into the inner evacuated tubes so the heat is shifted to the water from the inner evacuated wall of glass tube so that saturation temperature is reached, then boiling of water takes place inside the tubes and vaporizes. Water vapor goes into the condensation chamber to release its heat to its cold side walls which was at the atmospheric temperature and condenses. Produced freshwater was collected through the bottom of the condenser. An inclination of 60° with the horizon was made for two evacuated tubes were attached to a shaded galvanized metal box which has five heat sinks on each side for air cooled condensation. Potable water production was influenced by the quantity of filled water and shading. 0.99 l maximum fresh water was produced when tubes were full [66]. A passive solar desalination system in which thermal resistance was virtually excluded between the collector and basin. It is made up of two sections first one is evacuated tube collector and another is condenser (Figure 16). Evacuated tube is worked as a basin as well as collector. Condenser having a connector made up of Teflon poly tetra fluoro ethylene, a tube
made up of steel, and a cap. The yield of fresh water is $0.83 \text{ kg/}(\text{m}^2 \cdot \text{h})$ at an angle of inclination $35^\circ$ with $80\%$ water fill. However, yield is increased up to $1.01 \text{ kg/}(\text{m}^2 \cdot \text{h})$ by using stainless steel wool [67].

![Figure 16. Schematic view of working system. [67]](image)

3.5.3 Heat pipe in Evacuated tubes: In this system an evacuated glass tube collector was integrated with a parabolic trough collector and heat pipe. Brackish water is coming from one side and takes the heat from the condenser section of the heat pipe. Heat pipe is present in the evacuated tube collector. The heat of the heat pipe converts the brackish water into the vapor and it get condensed in the condenser pipe of the system as distilled water. Result shows that the yield was $0.27 \text{ kg/}(\text{m}^2 \cdot \text{h})$ and the efficiency $22.1\%$ when aluminum conducting foils were used in the space between the inner glass evacuated tube and the heat pipe. The space between heat pipe and twin-glass evacuated tube collector is filed by oil, then yield is increased to $0.933 \text{ kg/}(\text{m}^2 \cdot \text{h})$ and efficiency to $65.2\%$. [68]

3.5.4 Evacuated tube solar collector integrated to conventional single slope solar still: Two solar thermal collection systems are arranged in series for distillation of water. The preheating of water occurs in ETC and further this preheated water is feed into the still for distillation. The result indicates that the annual yield of distilled water for an integrated system was $630 \text{ kg/(m}^2 \cdot \text{year})$ however for single slope solar still was $327 \text{ kg/(m}^2 \cdot \text{year})$. $30.1\%$ was the highest overall thermal efficiency and $21.3\%$ was found as annual average thermal efficiency. Annual cost of distilled water was $6.15 \text{ INR/kg}$ while yearly average distillate production of water is $2.5 \text{ kg/m}^2$ at $0.05 \text{ m basin water depth}$. [69]

3.6 Hybrid distillation system

3.6.1 Stepped Solar active desalination system integrated with Solar air heater: Different parameters such as effect of solar radiation, glass cover cooling, underneath heating and thermal energy storage using solar air heater is considered for experiments. The daily productivity of conventional and stepped still at water depth of $5\text{mm}$ was $3.35 \text{ l/m}^2/\text{day}$ & $4.35 \text{ l/m}^2/\text{day}$ respectively i.e. $30\%$ greater than the simple conventional solar still [70]. The daily productivity of fresh water with hot air flow rate $0.13 \text{ kg/s}$ beneath the steps for simple single slope conventional solar still and stepped solar still was $3.4 \text{ l/m}^2/\text{day}$ and $6.3 \text{ l/m}^2/\text{day}$ respectively which was $85\%$ higher than the conventional type solar still. The productivity of conventional and stepped solar still with aluminum filling was $3.5 \text{ l/m}^2/\text{day}$ and $5.4 \text{ l/m}^2/\text{day}$. For this case the productivity of stepped solar still was $53\%$ more than the conventional type still. The productivity with glass cooling in stepped still was $65\%$ higher than the conventional still. When the hot air was supplied to the basin and evaporation rate is more, then yield becomes low due to less difference of temperature between the top glass cover and basin water. For cooling of glass cover a water-cooling system was used. If outlet temperature of cooling water is more as compare to the basin water then it was feed to the basin and productivity was
enhanced by 112% than the simple conventional still [71]. An integrating effect of stepped solar still with a solar air heater is shown in Figure 17.

Figure 17. Stepped solar still coupled with solar air heater. [70]

3.6.2 Active Solar still integrated with solar water heater: The hot saline water through the collector was fed into the conventional desalination device and storage tank. Lower basin water was constantly fed into the ETC for rising the water temperature. Distilled fresh water was accumulated in a measuring jar from the distillate trough. The yield of the active system increased by 77% and the average hot water temperature of the storage tank was 60 °C. The results showed that the yield of the active still integrated with water heater was double [72]. Figure 18 shows a hybrid solar still coupled with evacuated tube collector type solar water heater for enhancement of productivity.

Figure 18. Active solar desalting system with solar water heater. [72]

The correlation between the theoretical and experimental results was calculated using a coefficient of correlation and a root mean square percentage deviation from 0.90 to 0.98 and 16.4 to 39.4% respectively for all the cases [73].

3.6.3 Solar still integrated with solar pond: Salt water pool known as solar pond acting as a solar heat energy collector with integral heat storage. A single slope conventional solar still efficiency was escalated by the integration of shallow solar ponds through insulated storage tank and pump [74]. A spiral tube solar pond as shown in Figure 19 was linked to the insulated storage tank which acts as a heat exchanger where
the heat of solar pond water was transmitted to the inlet water of still for increasing inlet temperature. The thermal performance of the active single basin solar still (ASBS) integrated with shallow solar pond (SSP) was analyzed in closed and open cycle. The minimum monthly average daily productivity of water with and without SSP was 3.0 and 1.570 kg/(m² .day) in December while the maximum monthly average daily productivity of water with and without SSP was 6.68 and 5.29 kg/(m² .day) in July. [75]

Figure 19. Schematic representation of solar still integrated with a solar pond and storage tank. [75]

3.7 Combination of two different type solar stills shallow
3.7.1 Conventional still coupled with concentric tubular still: The aim of connecting the compound parabolic concentrator with concentric tubes and the single slope solar still is to improve the efficiency of the whole system (Figure 20). In this process the concentric tubes are connected with the cold water storage tank. The 10 ml/min fixed mass flow rate of water coming from the cold water storage tank is first passed from concentric tubes. These tubes preheat the water from solar radiation and then supply it to the insulating pipes and these pipes are further connected to solar still and after that the water is evaporated and potable water was accumulated in a jar. The yield of CPC-CTSS was 3.5 l/m²/day however if single slope still was connected with CPC-CTSS then productivity of still was increased by 2.7 l/m²/day. [76]

Figure 20. Pictorial view of single slope solar still integrated with concentric tube solar collector and pipe. [76]

3.7.2 Pyramidal type still connected with concentric tubular solar still: The aim of using the pyramidal type still is to manage the temperature difference between the two sides of the pyramid. In pyramid solar still the cover is in the shape of a pyramid because of this only one side of the cover gains the higher solar radiation
(Figure 21) as compared to the other side and because of this, temperature difference was maintained between two surfaces which enhances the part of condensation that occurs on these sides. Thus, efficiency of the whole system was increased. Pyramidal type solar still productivity was improved by 25% as compared to conventional solar still. The collector area and output of single slope solar still was 0.25 m$^2$ and 2.9 l/(m$^2$.day) respectively. The collector area and output of pyramidal solar still was 1m$^2$ and 2.6 l/(m$^2$.day) respectively. [77]

Figure 21. Pictorial diagram of pyramidal solar still combined with concentric parabolic collector with tubular solar still. [77]

3.7.3 Conventional solar still integrated with stepped solar still with small solar pond: For enhancement of productivity two series arrangements were used. Arrangement for first experiment was tiny solar pond then stepped solar still and conventional solar still were connected (Figure 22) while for another experiment small solar pond then stepped solar still and wick type still were linked (Figure 23).
Figure 22. Pictorial layout for Combination of conventional single slope solar still and stepped solar still with solar pond. [78]

Figure 23. Pictorial layout for Combination of conventional single slope wick type solar still and stepped solar still with solar pond. [78]

For additional enhancement of productivity heat transfer and storage devices were used. For increasing the productivity various modifications were used such as Pebbles, Baffle Plate, fins and sponges. When fins and sponges were used in both the stills then yield was 0.8 kg/m$^2$ however, 0.78 kg/m$^2$ yield was obtained for the second experimental set up when sponges and fins used only in the stepped solar still. For increasing night efficiency pebbles are used as latent heat storage. [78]

Table 5 contains some different enhancement technologies which is also shows the improvement on the productivity.

Table 5: Some other performance enhancement method

| S. No. | Still type and geometry | Still Integrated with | Findings/achievements | Author, year and place of experiment |
|--------|-------------------------|-----------------------|-----------------------|-------------------------------------|
| 1      | Single basin solar still| Air bubbled solar still | • Ambient air bubbling increased the distillation output by 7.1%.<br>• Ambient air bubbling after drying increased the distillation output by 33.5%.<br>• Ambient air bubbling with cooling of glass cover increased the distillation output by 47.5%.<br>• Cooling of glass cover increases the distillation output by 30.5%. | Pandey et al. (1984) New Delhi, India [79] |
| No. | Type of Still | Mode of Operation | Description | References |
|-----|---------------|-------------------|-------------|------------|
| 2   | Conventional single basin solar still | Regenerative effect | • The extreme distillate productivity was 1 kg/ m².h for active regenerative system, 0.7 kg/ m².h for active non-regenerative, 0.3 kg/ m².h for passive regenerative, and 0.02 kg/ m².h for passive non-regenerative at 13h.  
• The productivity of the passive still was more than the active mode of operation. | Tiwari et al. (1993), New Delhi, India [80] |
| 3   | Double effect single basin type | Parabolic concentrator | • 14.684 kg/day was the maximum daily productivity of the system.  
• Higher productivity than flat plate collector | Bhagwan Prasad et al. (1996) New Delhi, India [81] |
| 4   | Multi-effect active | Triple effect | • 73.6 kg/day was the maximum yield which corresponds 9.44 kg/m².day potable water. | Nishikawa et al. (1998) Yokohama, Japan [82] |
| 5   | Greenhouse effect type | Hybrid solar distillation. | • Daily hot water drains amount of 1/4, 1/2 and 1 storage tank volume results decrease the maximum potable water output of 36%, 57% and 75%, respectively, with energy delivered of 1990, 3300 and 5200 MJ respectively.  
• Produce hot & fresh water at the same time. | Voropoulos et al. (2004) Greece [83] |
| 6   | Conventional solar still | Flat plate collector worked in natural flow mode | • The conventional still was 36% less efficient than this active system. Maximum freshwater output was 3.5 l/m². | Bardran et al. (2005) Amman, Jordan [84] |
| 7   | Vertical multiple effect diffusion type solar still | Heat pipe | • 0.1 g/m² was the rate of fresh water production after 5 hr. of the early day. Best solution for higher production but initial cost is also high. | Hiroshi Tanaka et al. (2005) Fukuoka, Japan [85] |
| 8   | Conventional solar still | Packed layer thermal storage of energy, rotating shaft with PV | • Efficiency of the still increases to 7.5% for glass balls packed layer.  
• Efficiency of the still increases to 5.5% for integration of rotating shaft with PV. | Zeinab S. et al. (2005) Cairo, Egypt [86] |
| 9   | Single basin conventional solar still | Evacuated tube collector | • 4kg/m².day was calculated by using theoretical analysis.  
• 17.22% was the total thermal efficiency of the system.  
• Produce hot & fresh water at the same time. | Tiwari et al. (2007) New Delhi, India [87] |
| No. | Type of Solar Still | Description | Additional Information |
|-----|---------------------|-------------|------------------------|
| 10  | Conventional solar still | Flat plate collector with mirror | Yield of solar still with flat plate collector was high as compared to this system. | Badran et. al. (2007) Amman, Jordan [88] |
| 11  | Conventional solar still | Condensing cover material | Daily yield was maximum for copper condensing cover due to high thermal conductivity. Yield increases when absorbing surface of collector increases. | Vimal et al. (2008) Rajasthan, India [89] |
| 12  | Conventional solar still | PV integrated flat plate collector system | Higher yield was attained as compared to conventional solar still. Payback period of the conventional system was 1.1 – 6.2 years. Payback period was calculated for the hybrid PV with flat plate collector integrated active solar still was 3.3 – 23.9 years. | Shiv Kumar et. al. (2009) New Delhi, India [90] |
| 13  | Multistage evacuated solar distillation system. Number of stages = 3 | Pump is used for rotation | 14.2 kg/m².day was maximum production at a vacuum pressure of 0.5 bar and total yield was about three times of the conventional solar still. The cylindrical type was better than the rectangular one in terms of safety factor and maximum deflection. | Ahmed et al. (2009) Kuala Lumpur, Malaysia [91] |
| 14  | Inclined single slope solar still with conventional still | Wind turbine | Daily efficiency for south facing of the conventional main still ranged from 67.21 to 69.59% and for inclined still ranged from 57.77 to 62.01%. | Eltawil et al. (2009) Beijing, China [92] |
| 15  | Multi stage effect heating and humidifying | Cooling tower | 37 l/m².day was the daily productivity of this system. | Hichem et al. (2009) Monastir, Tunisie [93] |
| 16  | Conventional single slope active solar still | Reflectors (external & internal) and thermal storage tank | Increase in productivity with reflectors in winter, spring and summer was 72.8%, 40.33% and 7.54%. Increase in productivity with thermal storage tank in winter, spring and summer was 27.54%, 21% and 23.28%. | Boubekri et al. (2011) Constantine town, Algeria [94] |
| 17  | Conventional single slope solar still | Evacuated tube collector in forced circulation mode | Productivity was 3.9 l/m².day at 0.03 m water depth and 0.06 kg/s was mass flow rate. | Shiv et al. (2014) New Delhi, India [95] |
Double slope solar still

- This system generates potable water when sun is absent.
- It produces approximately 6 to 10 times (5.1 - 5.7 kg/m²) extra fresh water than simple conventional single slope solar still.
- Optimization is required for utilization of energy sources.

Humidification-dehumidification type solar desalination

- System’s initial cost was high as compare to some other active desalination unit.
- Per liter cost of freshwater for a life of 20 years was found to be $0.032 - $0.038 for the six chosen locations.

Solar thermoelectric generator distillation system

- Reported Overall, TEM and distillate yield range of 15-25%, 0.6-1.5% and 1.5-3kg/d respectively.
- Potable water production rate was decreased when wind speed was more while, it increased when ambient temperature increases and condenser temperature decreases.

3. Economic analysis of solar still

The selection of solar still is directly affected by the following factors such as the total requirement of fresh water, availability of brackish water, solar radiation accessibility, installation cost of still, operational and maintenance cost, use of heat energy of residual hot water.

The annual cost of still is obtained by,

\[ \text{Annual still cost} = \text{AFC} + \text{AMC} - \text{ASC} \]  \hspace{2cm} (9)

Where,

\[ \text{AFC} = \text{CRF} \times \text{Initial investment} \]

Where, \( \text{CRF} = \left( \frac{i(1+i)^N}{(1+i)^N-1} \right) \) \hspace{2cm} (10)

So, \( \text{AFC} = \left( \frac{i(1+i)^N}{(1+i)^N-1} \right) \times P \) \hspace{2cm} (11)

The annual maintenance cost is mathematically given by

\[ \text{AMC} = 0.15 \times \text{AFC} \]

The annual salvage cost (ASC) is calculated by:

\[ \text{Annual salvage cost} = \text{Salvage value} \times \text{Sinking fund factor} \]

Where, \( \text{Sinking fund factor} (\text{SFF}) = \frac{i}{(1+i)^N-1} \) \hspace{2cm} (13)

So, \( \text{ASC} = S \times \frac{i}{(1+i)^N-1} \) \hspace{2cm} (14)
The solar still payback period in months is mathematically given by:

\[
N_p = \frac{\ln \left( \frac{C_F}{C_F(A - C)} \right)}{\ln(1+i)}
\]  

(15)

Where, Cash Flow = Yearly Yield x Fresh Water Selling Price  

(16)

The economic analysis in the literature was reported for various types of conventional still powered by solar energy. [99]–[101]. Table 6 represents different solar still designs with their yields and its cost analysis

**Table 6: Different solar still designs with their yields and its cost analysis**

| S. No. | Still Type                                      | Yield of still                                                                 | Per liter cost of distilled water | Remarks                                                                                                                                                                                                 | Author, year of publication, experiment location and reference No. |
|--------|------------------------------------------------|-------------------------------------------------------------------------------|-----------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------|
| 1      | Modified active solar distillation system       | 0.1% Nano heat transfer fluid gave total yield of 12.19 l/m².day with MASDS and 3.48 l/m².day for CSS | 1.54 INR for CSS and 1.41 INR for MASDS | • MASDS consists of a solar still, Fresnel lens concentrator with an evacuated receiver tube and a serpentine type heat exchanger  | M. Murualeedhara ne et.al 2019 Tiruchirappali, India [102] |
| 2      | Multiple tray solar heat collector distillation system | The average output is 148 ml/h for 180 sunny days of the year and 4 hr/ day production period | 16 Algerian Dinars/L (0.15 $/L) for 10 years life of the system | • The performance of solar still was highly affected by Evaporator temperature                                                                                                                                  | Diaf et.al. 2016 Bousmai, Algeria [103] |
| 3      | double basin solar still coupled with Evacuated tube | 0.03 m water depth in basin gives Maximum output of distillate was 11.064 kg and average 8 kg | Yearly cost of distillation was Rs. 0.37/kg. | • The water depth in the lower and upper basin affects the productivity.  
  • In daytime, the distillate output is high at lower depth  
  • In night the distillate output is less at lower depth                                                                                                                                                         | Panchal et.al 2016 Gujrat, India [104] |
| 4      | Solar still combined with heat pipe, evacuated tube and parabolic | Distillation output 0.48 - 1.68 kg/h                                           | 25 years of operation gives average cost of freshwater was 0.0450 $/L/m². | • Rate of production and efficiency is increased when the space between the heat pipe and the inner glass evacuated tube is filled with  | Mosleh et al. Tehran, Iran [68] |
| trough collector | Distillation cost of 0.0485 and 0.066 S/L was reported for an expected life of 10 years. | Various modification increases the yield of developed solar still by 51–148%. | Eltawil et al. 2014 Kafrelsheikh University, Egypt [105] |
|-------------------|-------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------|--------------------------------------------------------------------------------|
| 5. conventional solar still combined with FPC, and solar air collector | - | It was found that the efficiency of the system is reduced when the modified solar still combined with solar air collector. | |
| 6. Solar still integrated with evacuated tube collector | At 0.01 m basin water depth and mass flow rate of 0.006 kg/s. gives yield of 3.47 kg/day. | 1. Cost of potable water was 2.01 Rs./kg. 2. Payback period was 3.7 years when fresh water was sold at 6 Rs./kg | Shiv et al. Delhi, India [95] |
| 7. Wick type solar still combined with solar evacuated water heater | The annual distillate water productivity was 978.4 l/m² for CSS, 2140.75 l/m² for DLSW and 4558.4 l/m² for DLSW with feeding hot raw water during night. | 1 L cost of distilled water from DLSW type solar still with the evacuated SWH was around 0.026 $. The productivity of double layer square wick type still (DLSW) was more than the others. Hot water feeding enhances the productivity by 215% than the CSS. | Omara et al. (2013) Kafrelsheikh University, Egypt[106] |
| 8. Pyramid geometric shaped active and passive solar still | Maximum daily productivity 3.14 l/m² in summer season at 8 cm water depth. Distilled water cost at 8 cm basin water depth for an active and passive solar pyramid type still was 0.039 and 0.042 $/l/m² respectively. | At lower water depth exergy efficiency was found higher for active system. | Kianifar et al. (2012) Mashhad, Iran [107] |
5. Conclusions

On the basis of above discussion, in this elaborated review on various performance parameters and techniques which affects the productivity of solar desalination system are concluded as:

- Productivity of solar desalination system depends on uncontrolled and controlled parameters. The various uncontrolled parameters are solar irradiance, relative humidity, wind velocity, geometrical position, Ambient temperature, inlet temperature of feed water to basin.
- Controlled parameters such as glass cover angle, thickness of glass cover, dust deposition and type of material, and concentration ratio affect the yield of solar still. For maximum yield the inclination angle of single slope solar still must be equal to the latitude of the location. Material which is chosen for the covering of still should have more transmissivity. Daily glass cleaning will improve transmission of solar radiation, hence improve in productivity.
- Water depth and mass flow rate of heat transfer fluid also affects the performance of still.
- Single slope solar still productivity was enhanced in active mode through combination of various collectors.
- Use of thermal energy storage, Nano particles, reflectors, pyramidal structure, incorporating wick, are various techniques reported recently in the literature.
- Nanoparticles can be used as the thermal conductivity is higher leading to higher heat transfer rate and productivity.
- Conventional stills may be integrated with other systems such as evacuated tube collectors, parabolic tube collector, combination of both for preheating the brackish water thereby enhancing distillate yield.
- Various Thermal energy storage materials can be used for increasing the period of operation of solar desalination system.
- Usage of different heat loss from the desalination unit for improving its productivity.

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