PERFORMANCE ANALYSIS OF CONICAL SOLAR STILL BY INCORPORATING ENERGY METRICS AND EFFICIENCY ANALYSIS

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by

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CANDIDATE'S DECLARATION

I Abhishek Kumar hereby certify that the work which is being presented in the thesis entitled "Performance Analysis of Conical Solar Still By Incorporating Energy Metrics And Efficiency Analysis" in partial fulfillment of the requirements for the award of the Degree of Doctor of Philosophy, submitted in the Department of Mechanical Engineering, Delhi Technological University is an authentic record of my own work carried out under the supervision of Prof. Rajesh Kumar.

The matter presented in the thesis has not been submitted by me for the award of any other degree of this or any other Institute.

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This is to certify that the student has incorporated all the corrections suggested by the examiners in the thesis and the statement made by the candidate is correct to the best of our knowledge.

Signature of Supervisor

CERTIFICATE

Certified that **Abhishek Kumar (2K18/PHDME/24)** has carried out their search work presented in this thesis entitled **"Performance Analysis of Conical Solar Still by Incorporating Energy Metrics and Efficiency Analysis"** for the award of **Doctor of Philosophy** from Department of Mechanical Engineering, Delhi Technological University, Delhi, under my supervision. The thesis embodies results of original work, and studies are carried out by the student himself and the contents of the thesis do not form the basis for the award of any other degree to the candidate or to anybody else from this or any other University/Institution.

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ABSTRACT

The design, installation and analysis of solar still is the need of the time as it can fulfil the freshwater need of the population without affecting adversely to the environment. The solar still is made in the form of a box having top surface made up of the glass or other similar materials and it uses the principle of greenhouse effect for its working. It can be easily fabricated using local available materials and works solely on solar energy and hence can be used even in the remote locations for getting freshwater from dirty water. The solar still can be of passive type or active type. In passive type of solar still, no heat is provided from the external heat source. If heat is provided from the external source to passive solar still, then the resulting solar still is active type and it addresses the low output of potable water from the passive type solar still. In the basin type solar still, the freshwater output is lower than the conical solar still (CSS) because of the shading effect in basin type solar still. In CSS, the transparent surface is provided in all the four directions which makes it susceptible to very low shading effect. Due to low shading effect, it has motivated researchers throughout the globe to work upon it. The present deals with the study on CSS analytically by incorporating several identical series connected evacuated tubular collectors (ETCs). The collectors have been connected in series because the series connection provides high temperature at low discharge which helps in increasing the output of potable water from the conical active solar still.

The methodology involves the thermal modelling of NETC-CSS followed by energy, exergy, efficiency, exergy output per unit cost, enviroeconomic and productivity analyses. The thermal modelling means the development of characteristic equations using equations based on balancing heat for various components of NETC-CSS and solving these equations using the concept of mathematics for expressing unknown variables in terms of known variables so that the further analysis can be carried out using MATLAB. The output from MATLAB has been validated with data available in the literature and then further analysis has been carried out.

Concludingly, the optimized value for mass flow rate is determined to be 0.008 kg/s and optimized value for the number of evacuated collectors (N) is determined to be 15. Annual freshwater generation, energy, exergy, thermal efficiency and exergy efficiency for the proposed system are computed to be 2694.91 kg, 1796.61kWh and 170.19 kWh, 38.79% and 3.94% respectively. Annual freshwater yield, energy, exergy and exergy efficiency are higher respectively by 57.94%, 57.94%, 74.14% and 36.55% for the proposed system than the traditional conical solar still. A comparative analysis of results of present system with previously documented research represents that the increase in annual exergy, energy, thermal efficiency and exergy efficiency is 68.03% than modified solar still, 74.14% than conventional conical solar still, 61.12% than modified solar still and 72.59% than solar still with parabolic trough collector.

While the exergoeconomic parameter is found to be 0.080 kWh/₹, the calculated annual productivity comes to 630.80% under optimal conditions with a 2% rate of interest. The production cost of fresh distilled water for NETC-CSS is ₹0.79 per kg, with a payback period of 4.03 years under a 2% rate of interest. The carbon credited for the NETC-CSS is valued at $5181 which corresponds to a carbon mitigation of 103.62 ton. This amount significantly surpasses that of a modified water-cooled solar still by 84.30%. The comparison highlights the superior environmental and economic benefits of the proposed system.

Distilled water generated by use of NETC-CSS will be beneficial for use in batteries, various cosmetic products, as a coolant in automobiles, and in the pharmaceutical industry. In the battery sector, it will be used to maintain the proper chemical composition of battery cells, ensuring efficient performance and longevity. In the cosmetics industry, it will act as a key ingredient in the formulation of skincare products, where purity and pH balance are essential. It can be made suitable for human consumption by reintroducing essential minerals that are removed during distillation process. Small business of distilled water can be set up. It also finds utility in domestic settings, where it serves to purify harvested rainwater for household use.

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NOMENCLATURES

Symbols

a_1	clear day (blue sky)
A_g	area of condensing cover, m^2
A_b	area of basin, m^2
b_1	hazy day (fully)
c_1	hazy and cloudy (partially)
C_w	specific heat capacity of water, J/kg-K
d_1	cloudy day (fully)
$\dot{E}x_{hourly}$	hourly exergy output from the system
$F_{CR,i,n}$	capital recovery factor, fraction
$F_{SR,i,n}$	sinking fund factor, fraction
h_{rwgE}	radiative HTC from water surface to condensing cover facing east, W/m^2-K
h_{rwgW}	radiative HTC from water surface to condensing cover facing west, W/m^2-K
h_{rwgS}	radiative HTC from water surface to condensing cover facing south, W/m^2-K
h_{rwgN}	radiative HTC from water surface to condensing cover facing north, W/m^2-K
h_{cwgE}	convective HTC from water surface to condensing cover facing east, W/m^2-K
h_{cwgW}	convective HTC from water surface to condensing cover facing west, W/m^2-K
h_{cwgS}	convective HTC from water surface to condensing cover facing south, W/m^2-K
h_{cwgN}	convective HTC from water surface to condensing cover facing north, W/m^2-K
h_{ewgE}	evaporative HTC from water surface to condensing cover facing east, W/m^2-K

h_{ewgW}	evaporative HTC from water surface to condensing cover facing west, W/m^2-K
h_{ewgS}	evaporative HTC from water surface to condensing cover facing south, W/m^2-K
h_{ewgN}	evaporative HTC from water surface to condensing cover facing north, W/m^2-K
I_{SE}	solar radiation impinging on glass cover facing east, W/m^2
I_{SW}	solar radiation impinging on glass cover facing west, W/m^2
I_{SN}	solar radiation impinging on glass cover facing north, W/m^2
I_{SS}	solar radiation impinging on glass cover facing south, W/m^2
h_{EW}	radiative HTC between east and west condensing surfaces, W/m^2-K
h_{NS}	radiative HTC between south and north condensing surfaces, W/m^2-K
M_w	mass of water in the basin, kg
mfr	mass flow rate of fuid/water, kg/s
n	number of clear days
NETC-CSS	conical solar still integrated with N identical evacuated collectors
PF_c	penalty factor due to the glass covers for the glazed portion
PF_1	penalty factor first, dimensionless
PF_2	penalty factor second, dimensionless
$\dot{Q}_{u,N}$	useful energy gain for N identical collector connected in series, kWh
R_{o1}	inner radius of outer glass tube of evacuated coaxial glass tube, m
R_{o2}	outer radius of outer glass tube of evacuated coaxial glass tube, m
R_{i2}	outer radius of inner glass tube of evacuated coaxial glass tube, m
r	radius of copper tube
R_g	reflectivity of glass

R_w	reflectivity of water
t	time, s
T_w	temperature of water in the basin, ºC
T_{wo}	temperature of water in the basin at t = 0, ºC
T_a	ambient temperature, ºC
T_{gE}	condensing cover temperature facing east, ºC
T_{gW}	condensing cover temperature facing west, ºC
T_{gS}	condensing cover temperature facing south, ºC
T_{gN}	condensing cover temperature facing north, ºC
$T_{foN.max}$	maximum collector at the outlet of N^{th} collector
r	rate of interest, %
L	latent heat, J/kg
n	number of clear days
N	number of collectors
l	life of the system
$\dot{E}x_{hourly}$	hourly exergy output from conical NETC-CSS, kWh
S	number of sunshine hours
U_L	overall heat transfer coefficient
V	velocity of air

Greek

$\xi_{carbon-di-oxide}$	reduction in the emission of carbon-di-oxide
$\dot{\alpha}_g$	absorptivity of condensing cover, fraction
$\dot{\alpha}_w$	absorptivity of water mass, fraction
$\eta_{p,annual}$	annual productivity, %

η_{therm}	Thermal efficiency for NETC-CSS
η_{exer}	Exergy efficiency
γ	ratio of daily diffuse to daily global irradiation

Abbreviations

CSS	conical solar still
CPSS	conical passive solar still
CF	annual cash flow, Rs.
DPS	double slope passive solar still
EHTC	equivalent heat transfer coefficient, W/m^2-K
HTC	heat transfer coefficient, W/m^2-K
IMD	Indian meteorological department
NETC	N identical evacuated tubular collectors
PSS	passive solar still
SPS	single slope passive solar still
UEC	uniform end-of-year annual cost, Rs.

CHAPTER - I

GENERAL INTRODUCTION

1.1 Introduction

Water and energy are essential for sustaining human life on Earth. Yet, humans can access and utilize less than 1% of the planet's total water resources. Moreover, this limited amount of usable water is increasingly being contaminated as a result of human activities. Hence, there is a need to purify the polluted water in a sustainable way. Solar distillation, powered exclusively by solar energy, offers a sustainable solution to the modern challenge of water scarcity and should be actively promoted. A large population on earth is still dependent on unsafe drinking water which causes many kinds of illness and hence reduces life expectancy. Water contributes nearly 75% of the mass in a human body. Most of the drinking water supplies depend upon underground water which is extremely saline up to 10000 ppm and that of sea water is in the range of 35000 to 45000 ppm. However, salinity up to 1000 ppm is acceptable to human beings according to the World Health Organization (WHO). An allocation of water on the planet earth is presented in Fig. 1.1. As depicted in Fig. 1.1, very low percentage (<1%) is accessible to human being for the use.

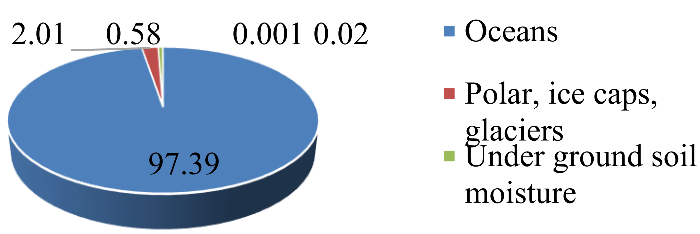

Fig. 1.1: Water distribution on the planet earth

According to the United Nations (UN), more than one billion human beings have not been provided availability to drinkable water. It is expected that 67 % of the global population will project to experience water scarcity by 2025. Furthermore, the rising industrial and urban growth is one of the major causes of damaging the available fresh water and underground water resources. At present, many kinds of water treatment methods, for example chemical, mechanical, membrane based, and thermal treatment are employed to purify the available fresh water for drinking and daily life uses. These available technologies-based water treatment plants need large capital and energy from conventional power plants. Solar distillation offers a renewable, low-cost, eco-friendly, and user-friendly method for producing clean water from available freshwater sources using solar energy. It serves as a viable alternative to reduce reliance on fossil fuel-based energy systems.

As the world's population has grown itself by three times in the 20^{th} century, the potable water production facilities must be expanded accordingly. Also, population growth in addition to considerations like urbanization and industrialization will result in rise in demand for potable water. It will have an adverse impact on the environment and health of people if the demand of safe drinking water is not met. According to UNICEF (2002) survey, more than one out of six people do not have availability to safe drinking water and over two out of six people are struggling with lack of acceptable cleanliness. As per reports of WHO (2004), almost 4000 children die every day all over the world due to the diseases caused by unsuitable drinking water. Most of the population in India depends upon underground water for drinking water. In many regions in India, the underground water is too saline especially in coastal zones. In such areas, the government owned water treatment plants are available only to the urban population or big villages but in small villages and less populated areas; the population is facing severe scarcity of safe drinking water. Nearly 60 to 70 % of rural population in the developing nations is facing the problem of safe drinking water in absence of government owned water treatment plants. Due to this, people go through serious health issues and life expectancy is continuously declining. In these regions, the unavailability of safe drinking water is becoming a prominent reason of human migration to other safer regions.

Large efforts have been made through public distribution system to cover larger population of India under the food security program over last 30 years, still the water treatment facilities have not been expanded in the same proportion. The available freshwater resources like rivers, lakes have already become too much contaminated and are waiting for their revival. The underground water levels have dropped down to all times low due to extreme exploitation by agricultural and urban activities. Hence, economizing the use of water and recycling of used water is becoming the necessity of present society. Hence, with the growing population, industrial growth and economic development, it can be easily concluded that there is a great mismatch between demand and supply of safe drinking water across the entire world. According to the World Water Vision Report (WWVR), the world is facing a water crisis presently. All the depleting freshwater resources get replenished by rain every year but due to poor rainwater management, shortage of water also remains an issue. Hence, it can be concluded that the present drinking water crisis is mainly due to poor management which in turn also impacts the environment. To counter the issue of diminishing freshwater resources, several corrective measures have been taken up especially the rainwater management which have been helping to manage the water crisis up to some extent, but still there is a lot to be done in the same direction. At present time, there is an urgent need to encourage people to be part of saving freshwater resources by running the public awareness drive to counter the issue of depleting freshwater resources and making save water programs a success even on small level. One of the core messages emphasized during the Second World Water Forum was that "Water is everybody's business". Now a days, safe drinking water availability to every family is becoming a top priority issue on national level policy makers list in India. Many state governments have been running many programs to establish water pumping systems for families, at public places and industrial areas with the help of NGOs to permit everyone to have adequate access to safe drinking water for personal and household needs. A sufficient amount of safe drinking water availability is necessary to maintain good health and avoid the danger of water caused diseases.

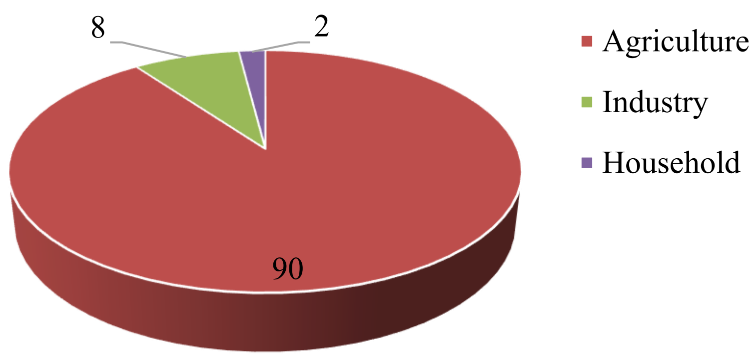

Fig. 1.2: Freshwater distribution in terms of use in low-income countries

Fresh water is necessary mainly for general public uses, industrial processing and agricultural activities. The different nations have variable availability of freshwater resources due to their geographical locations. Fig. 1.2 and Fig. 1.3 show the utilization of fresh water in different activities of low and high per capita income nations. Public in higher per capital income nations utilize larger quantity of potable water for enterprise and domestic purposes with respect to low-per capita income nations. Distilled water can be a good substitute for fresh drinking water but it is 99.90% free from minerals and bacteria. Hence, to make distilled water suitable potable water extra minerals need to be added.

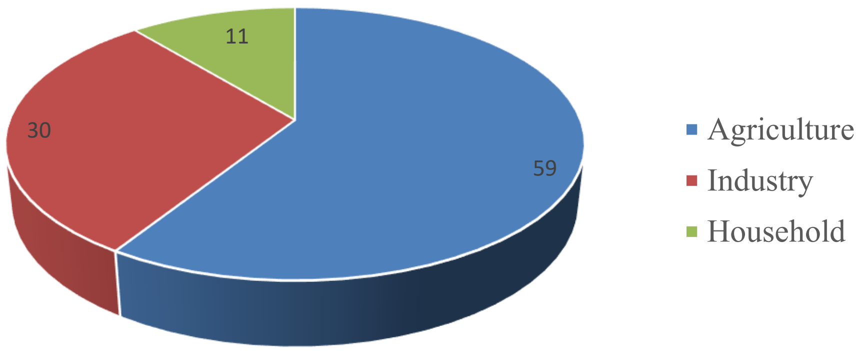

Fig. 1.3: Freshwater distribution in terms of use in high income countries

Distilled water is produced by heating water until it turns to steam, which is then captured on a condenser surface, cooled, and collected. A major limitation of this method is that the high-temperature process may not eliminate certain harmful gases such as chlorine and fluorine. To overcome this limitation solar water distillation is used in which water evaporates at comparatively low temperature and hence distilled water is free from toxic gases. Solar distillation refers to the process of purifying water through distillation powered by solar energy. These systems are effective for generating drinkable water from saline or brackish sources, especially in remote and hard-to-reach regions with warm climates where sunlight is abundant throughout the year.

1.2 Origins of Water Scarcity

The main reason of water scarceness is water contamination, population blast, agriculture, and other related anthropogenic activities. Water contamination is however one more reason of current problem. The bases of water contamination include insecticides and manures that wash-down inattentive from farmsteads, mechanical and hominoid waste that's specifically discarded into channels deprived of treating it inside a water purification unit of large scale. The fast increase in population shared with enormous progress in the industry segment has transformed water biological systems and come around in a disaster of biodiversity. This population blast is really a curse for water scarceness. Agribusiness is another major factor for this problem. However, watering to crops is essential for our survival too. Notably, the pathetic object is that almost 60% of this water gets wasted because of wasteful horticulture policies which cracked watering structure frameworks.

Water is fantastically compulsory to grow crops and care for animal. It has been evaluated that the all-inclusive water utilization for the water scheme and agricultural is approximately 70%, and notably, about 10% is used for household needs. Access to fresh water is crucial to superior living standards or financial development. Colleges, eateries, healing centers, lodgings, and further trades have to persist clean for actions to be active. Eateries and shop centers ought to be reserved hygienic to draw in visitors. Fabricating or mechanical forms, mining exercises, and viable industries all necessitate extensive quantities of water to flourish.

1.3 Solutions to Water Scarcity

Agreeing to a 2012 UN description on The Ecosphere's water, groundwater withdrawal has increased within the last 05 eras since mechanical and agrarian employment. For such motive, administrations and officialdoms can attempt measures to energize underground water by commission ventures pointed at invading or infusing abundant shallow water into underground water bodies. It may incorporate angles, such as the reclamation of watersheds and wetlands.

Water reuse methodologies deliver an aid to ease water shortages in almost living zones or areas. Maximum procedures here integrate a reuse and the utilization of zero-liquid release agendas.

The non-potable water can be used to clean or wash a car, flooding scenes, mechanical preparation, and to flush lavatories. This context allows the squandered water to be a helpful asset. Water reuse can subsequently spare a part of fresh water for consumption in times of water scarceness.

Desalination is the treatment of salty or brackish water. Through this treatment, the saline water can be transformed into drinking water at a quite reduced cost. Around the world, almost countries, especially solar rich nations, are taking benefit of these techniques and making efforts for new developments in this direction to distillate a large amount of water at one distillation plant. This is a simple and economical water treatment technique, and many nations are looking for a sustainable future in this.

Managing water resources through effective regulations and policies can significantly contribute to mitigating water scarcity. Such measures focus on various aspects, including water reuse, resource management, allocation rights, industrial usage, wetland restoration, domestic supply, and pollution control. Essentially, water governance addresses both human activities and natural events, aiming to ensure sustainable water solutions that balance environmental and economic impacts.

Water preservation serves as another driving way to change out of water scarcity. It is an indirect approach to decreasing water requirements and it is a rule elementary in custody up the supply-demand adjustment. Amongst dry spells and in indistinctly inhabited districts, for the occasion, water conservation endeavours assurance there is a supply-demand adjustment. Different approaches can effectively be executed because of including some of the basic customs of sparing water.

Overall, it can be said that the followings are the key issue of water scarcity.

i. Industrial waste
ii. Powerplants discharge
iii. Misuse of water through leakage tapped, overwatering in gardens, during the bath, sanitation, vehicle washing, etc.
iv. Leakage in water supply tank to be supplied in remote areas or hilly areas.
v. Bursting of water pipes under the road due to heavy loads, masonry works, etc.
vi. Overflow in farming lands, flower nurseries, etc.
vii. Animals are often slipped into the well of villages and the entire drinking water has been contaminated.

1.4 Techniques for purifications

It is essential to fulfil the requirements of water or to maintain the water level in a human body to keep fit. But due to limitations of the drinking water availability, it will not an easy task in near future. People (around the world) must have to purify the water to fulfil such demands of the public in near future. Therefore, water purification is our one of the prime sustainable goals. Basically, water purification is the process in which removal of all the objectionable chemicals, organic impurities, adjourned solids, and fumes from the drinking water. Overall, the goal is to obtain water which is appropriate for definite determinations.

Maximum aquatic is disinfected and clean for social drinking (potable), but water decontamination may be done aimed at a diversity of some further resolutions, counting medicinal, pharmacologic, biochemical, and engineering applications. The antiquity of water decontamination comprises an extensive variability of approaches. The techniques used contain physical procedures, such as purification, alluviation, and condensation; organic methods, such as deliberate sand strainers or organically active carbon; biochemical methods, and the usage of electromagnetic radioactivity, such as ultraviolet sunlit. Water decontamination can decrease the attentiveness of particulate matter (PM levels) counting deferred elements, parasites, microorganisms, algae, germs, and yeasts as well as decrease the attentiveness of a variety of liquified and particulate matter (Mara and Horan, 2003).

The standards for drinkable water superiority are characteristically set by higher government administrations/bodies or by intercontinental standards. Such type of standards typically contains least and extreme absorptions of impurities, dependent on the envisioned use of the water. A painterly examination cannot govern if aquatic is of suitable quality. Humble measures, such as scorching, or the usage of a domestic stimulated carbon strainer are not adequate for generous all conceivable pollutants. Even usual spring water well-thought-out safe for all applied determinations in the 19th century which must nowadays be verified before defining what kind of action, if any, is desirable. Biochemical and biological analysis, while exclusive, are the solitary method to attain the info essential for determining on the suitable technique of decontamination (Cheremisinoff, 2002).

Apart from this, the usage of conventional methods, though, would not be exposed without its usefulness to be proved through a suitable investigation. Water decontamination can be conducted at the domestic level and at the communal level. When an individual is speaking about community-based water refinement schemes, matters of ownership and reasonable supply become significant. Communal aspects play a character in decisive access to water. In the instance of community-based water decontamination systems, there should be a mechanism of involvement by the communal, and they can be made accountable for care to ensure sustainability (Cheremisinoff, 2002; Ravindiran et al., 2022).

The assortment of a suitable methodology is administrated by acceptance by users. The usage of up-to-date technologies such as reverse osmosis and ozonation is actual in the treatment of water, but their possibility in a rural location desire to be resolute in relations of principal expenses and work force in functioning and sustaining such systems. There is also a necessity for appropriate field testing before any product is launched, with proper authorization and authentication by prescribed authorities.

The following are few efficient water decontamination approaches:

i. Boiling

ii. Water Purifier

iii. Reverse Osmosis

iv. Water Chlorination

v. Distillation

vi. Iodine Addition

vii. Solar Purification

viii. Clay Vessel Filtration

ix. UV Radiation

x. Desalination

1.5 Solar Energy for water treatment

To compare with water, energy can be generated in numerous ways, through separate water foundation stipulations or outcomes. It structures power-driven by solar radiant heat characterize supportable results to resolve biosphere water calamity and hostile significances of conventional fuels fiery in intelligence of a worldwide water loss and possible power predicament. Solar expertise for water treatment can be chosen relatively. Some familiar methodologies like a solar still, amongst other available methodologies, which are appropriate exclusively for isolated zones in different emerging nations, which requires wide-ranging economic funding, advanced, and capable operative's access. Although, a few of them are not marketable practical, consistency and the technical complexity of unintended distillation methodologies and solar photocatalysis methodologies are increasing as an outcome of both solar and water purification methodologies including some advancements in expertise (Saxena et al., 2022).

The water production rate for solar-based purification is likewise sensibly high associated by means of the conventional fossil fuel-based decontamination large-size units due to an incompetent solar collector and it is a substantial aspect for constraining the stride of commercial availability. In mostly cases, though, non-renewable power environment charges are still ignored unwell. In research for a wealthy globe, the damage of bio-based fuels, GHG emissions, and airborne pollution must have to be considered in the global energy marketplace. In contrast, an anticipated price of significant solar purification units specified financial comparison with outmoded plants, though no definite extensive project was there. In addition, even further research is required to examine the consequence of solar energy and solar-based distillation techniques on a much-improved sustainable life (Saxena et al., 2022; Nashed and Dang, 2022).

Notably, solar energy technology is an extraordinary tool to obtaining water from the earth and making it drinkable through the solar-driven treatments.

1.5.1 Solar distillation

It is a simple method of utilization of solar radiant heat which is directly employed for evaporating water from sea (saline), brackish water or water with certain impurities. The method is still in use for the last several years, typically for moderate applications. Basically, a solar (thermal) purification process of water is an easy method of water distillation commonly used on different scales (from domestic to industrial). The water is purified under a solar still of variable designs according to the demand of drinking water.

History shows that the philosophies elementary to solar distillation acknowledged for several years earlier the 1st noteworthy installation was finished in Chile in 1872. Sited at Las Salinas in (a desert zone), this solar still was defined by Harding (1883) as a glass-covered fitting that enclosed an area of $5x10^4$ square feet and yield a maximum of about $5x10^3$ gpd of distillate for water scuffs. The specific time for such still to be serviced is uncertain to some extent, which has been reported about 40 years. During the 2nd World War, portable systems were considered for usage on life rafts (Telkes, 1945). These were spherical plastic items with subjective conical bottoms and semi-circular at the most and it would drift in the aquatic whenever exaggerated.

A parallel felt sheet beneath the plastic roof was soaked with saline and flexible assemblage exaggerated. The vapour generated beneath the roof condensed partly on the interior side of the transparent cover and partly on the lower cone that was directly in touch with the cold seawater. Subsequent the 2nd World War, numerous trivial tentative glazed stills have been designed and built for USA - Massachusetts (Telkes, 1955) and at the University of California (Macleod and

McCracken, 1961). On the other hand, trials were conducted on a portable plant in the Virgin Islands (Lof, 1955).

In 1954, the OSW of US department of the Central briefed a conceivable custom to utilization of solar energy for distillation (Macleod and McCracken, 1961). The same document is an imperative and elementary report of the field at present. In 1955, a conference focused on solar energy applications was held in Tucson, Arizona, which included presentations on solar distillation research conducted in countries such as Algeria, Australia, and the United States. Small glazed stills were developed in the Algeria (Lof, 1955) and retailed in small figures, in Australia, Cyprus. Throughout the subsequent some years, fast-tracked research was done in the US to be concluded in the building of the big size glasses and plastic-employed plants at Daytona Beach, Florida. Such stills were used for numerous years for obtaining distilled water (Lof, 1954; Gomella, 1958; BMI, 1965). In the intervening time, supplementary investigational research was conducted in Australia, Italy (Nebbia, 1963) including USSR and the USA.

Apart from this, an UN annual Conference organized at Rome in August 1961, which provided further important info on the R&D of solar distillation units in several parts of the globe (Bloemer et al., 1965). Presently, some really large-size installations have been noticed in Australia, Greece, Spain, Tunisia, etc. Compact systems have demonstrated effective results in various countries and numerous islands across the South Pacific, all employing a basin-type configuration.

1.6 Distillation process

When the sunlight passes through surface of brackish/saline water, the temperature of water increases that causes evaporation of water. Water vapor generated during the process condenses to form distilled water as the final product. The conventional distillation process typically follows an open-cycle approach, as illustrated in Fig. 1.4. In contrast, solar distillation systems generally operate using a closed-cycle method, making them more efficient and sustainable.

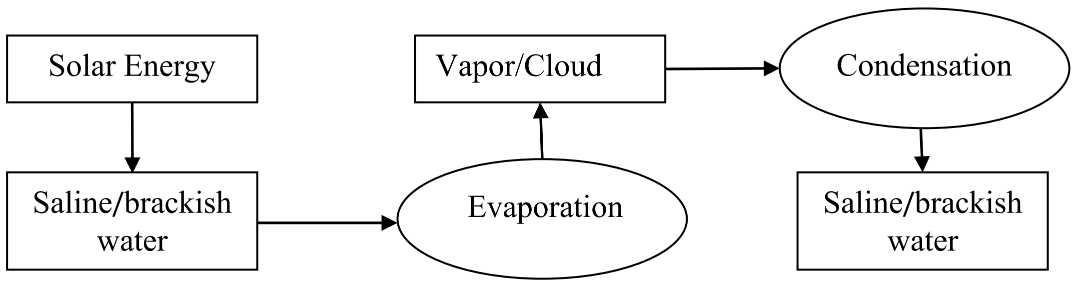

Fig. 1.4: Distillation Process (open cycle)

1.7 Classification of solar distillation system

A solar still, or solar distillation system, is a device that utilizes sunlight to transform saline or brackish water into clean, drinkable water. It replicates the normal distillation process with the difference that it follows in a closed loop. Solar distillation systems are generally classified into two types: passive and active. In passive solar stills, solar radiation directly heats the water in the basin. These systems rely solely on solar energy to raise water temperature and promote evaporation, which often results in lower output efficiency compared to active systems. These types of solar stills are improved conferring to the employed principle for enhancing their productivity by some potential methodologies in the basin design of the tested still. Such modifications are applied only to improve the evaporation rate, condensation, net heat gain and to reduce overall thermal losses from the distillation unit (Kumar and Tiwari, 2009; Tiwari, and Sahota, 2017; Tiwari, and Sahota, 2017a). A few types of passive solar stills discussed below.

The multiple-effect solar still (MESS) comprises of multiple transparent (excluding the last most basin) basins that carried brackish water. This consequence is supported by further associated basins positioned in a perpendicular stake. Notably, vapor produced by the 1st basin condensed on the lowered shallow of 2nd basin. Thus, it transmits latent heat to water inside 2nd basin. Henceforth, transporting latent heat one to another basin positioned overhead is termed a method of multi-effect in distillation units. Such types of stills are distinctive excellent-output distillation units and yield a greater extent of distilled water for a specified irradiance level to compare with a single slope solar still (SSSS) with an equivalent basin area. Multi effect solar still (MESS) is designed to consume extreme utilization of solar radiant energy and decrease the losses from manifold condensing and evaporating process in an individual unit.

Apart from this, a further modification of a SSSS is a reformative still that is alike to the MESS. During this process, the latent heat generated from condensation is conveyed to the water running across the glass cover, which acts as the condensing surface, via conductive and convective heat transfer mechanisms. Thus, flowing water is pre-heated beforehand ingoing the still basin. It is notable that a regenerative based solar distillation unit provides about 35% to 45% increase in distilled output (Tiwari, and Sahota, 2017; Tiwari, and Sahota, 2017a).

Additional modification to a solar still is an inverted absorber (IASS). Basically, it is an advanced concentrating type of SSSS. It comprises of an orthodox SSSS and a curved reflector under its basin collector. A reversed collector obtains the solar radiant heat both from the top and bottom. The additional reflector concentrates sun radiation over the lower surface of its basin. As a result of this additional heat, the water temperature (Tw) in such solar stills increases more rapidly than in a conventional single slope solar still (SSSS).

In passive solar stills, only saline or brackish water is introduced into the basin, relying solely on solar energy for heating. In contrast, active solar stills incorporate an external heat source to raise the water temperature in the basin. This increase in temperature creates a greater difference between the water surface and the condensing surface, thereby enhancing the evaporation rate and improving the overall distillate yield. Generally, passive solar distillation unit faces with the issue of low output which is addressed by many researchers by reporting active solar distillation system. However, one can try to improve the distillate output of passive distiller by changing its design and improving the characteristic of materials used.

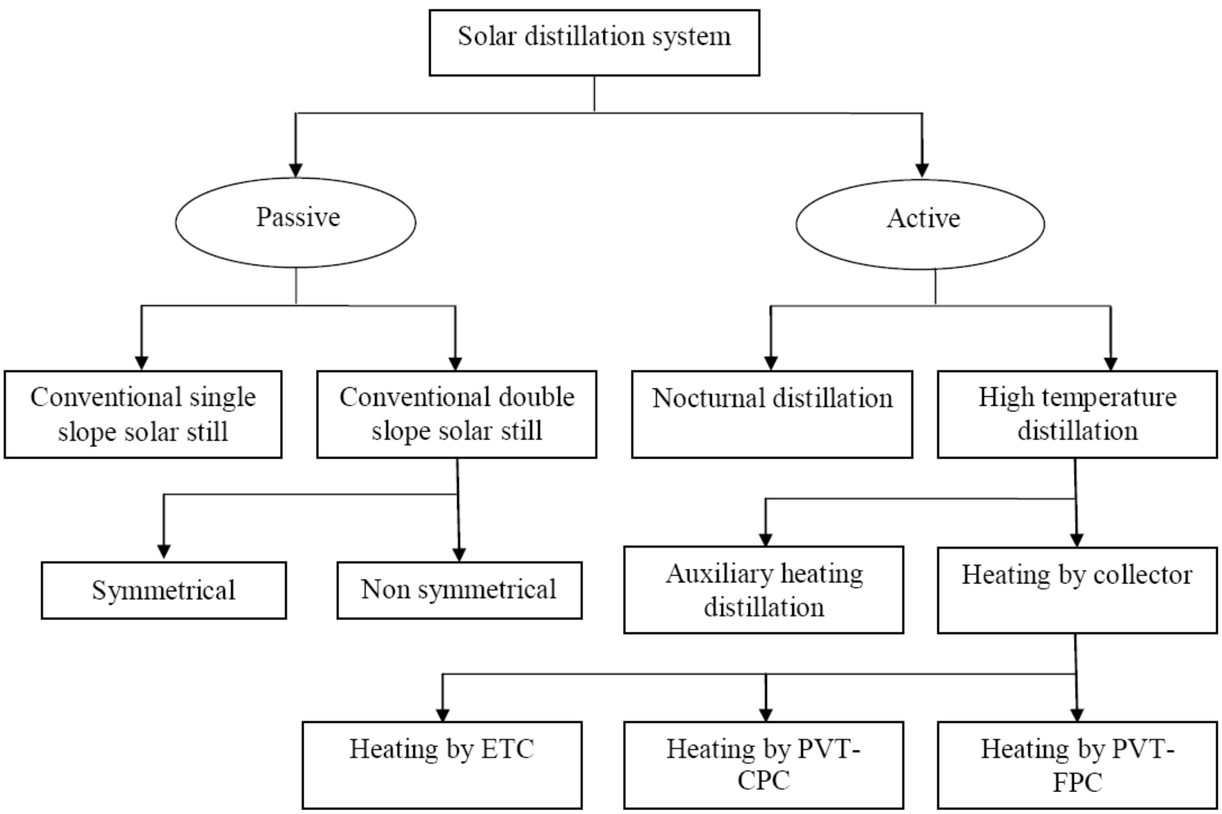

Fig. 1.5: Types of solar still

The low-grade energy/heat to the basin may be supplied from collector/concentrator or low temperature waste heat energy from any industrial plant. Based on design and orientation, solar stills can be categorized into single slope and double slope types. A single slope solar still is typically oriented towards the south to maximize solar radiation capture, while a double slope design positions one glass cover facing east and the other facing west to harness sunlight throughout the day. A detailed classification of solar distillation systems is illustrated in Fig. 1.5.

Double slope passive solar stills can be categorized into symmetrical and unsymmetrical types. In the symmetrical design, both glass covers have identical top surface areas and are inclined at the same angle relative to the horizontal plane, though they face opposite directions. These systems operate without any external energy source. In contrast, the unsymmetrical type features glass covers with differing surface areas and inclination angles.

Active solar stills can be categorized as: nocturnal distillation and high-temperature distillation. Direct sunlight is used nocturnal by distillation during sunny hours while waste low temperature heat from industrial plant is used during non-sunny hours. The low temperature waste heat from industrial plants (food, chemical and textile industry etc.) is circulated through the solar still using heat exchanger.

Further, high temperature distillation systems are classified as auxiliary heating distillation and heating by collectors (PVT). Additionally, a Photovoltaic Thermal Flat Plate Collector (PVT-FPC) can be combined with a parabolic concentrator, forming that is known as a PVT-CPC. While the FPC alone is typically used to generate thermal energy, this heat can be directed to the solar still to support the distillation process. To create a self-sustaining system, the FPC is either partially or entirely integrated with photovoltaic (PV) panels, enabling the simultaneous generation of thermal and electrical energy. Thermal energy is delivered to the solar still, while a portion of the generated electrical energy is utilized to operate the water circulation pump. The remaining electrical energy can be stored or used for other applications. In this setup, the PVT-FPC is coupled with a parabolic concentrator, which reflects solar beam radiation onto the receiver area to enhance energy capture. The present research work focuses on heating by PVT-FPC, PVT-CPC and evacuated tubular collector (ETC).

1.8 Material requirement of solar still

A solar still can be fabricated using substandard material which is easily available in local market at much cheaper price but such a solar still will have poor performance and the material will degrade in a few years and system will breakdown itself. Therefore, when selecting materials for constructing various components of a solar still, factors such as cost-effectiveness, system durability, and thermal efficiency should be carefully considered. A high-quality standard material is recommended to be used. While the initial fabrication cost of the solar still relatively high but such a solar still will have longer life span and high performance with a little maintenance. Such a system will produce distilled water at cheaper investment in the long run.

The material chosen for constructing a solar still should be affordable and wear environmental conditions for a long life. Also, if some parts of the system are to be replaced after some period of its service, they should also be affordable. The material should survive the sunlight, strong wind loads and earthquakes. Components selected for constructing solar still should be chemically inert with water. The solar still material and water should not produce any kind of toxic solution, toxic gas or vapors or give out any unpleasant smells within the operating conditions of temperatures and humidity. The material should defend against corrosion from saline water and distilled water and also easy to handle for local transportation.

In the distillation process, condensation on the inner surface of the glass cover should ideally occur as a thin film. If water droplets form instead, they can reflect a portion of the sunlight incident on the outer surface of the transparent cover, thereby reducing the solar radiation reaching the water surface. Solar stills can be constructed using materials such as concrete or cement, galvanized iron (GI) sheets, or fiber-reinforced plastic, with the top cover made from transparent materials like glass or plastic.

1.9 Quality of water from solar still

The distillation of water is basically based on boiling the water to generate water vapors followed by its condensation to obtain pure water. In a solar distillation unit, the water temperature typically remains well below its boiling point. As a result, evaporation occurs at sub-boiling temperatures within the still. The distilled water produced has a pH of around 7, indicating its neutral and pure nature. Therefore, the water quality obtained from a solar still is often superior to that produced by many conventional purification methods. Solar distillation systems can remove the arsenic and harmful bacteria also. From the studies carried by El Paso Energy Association (EPSEA), it has been found that those people who consume water obtained from solar distillation unit, stay healthier than rest of the people. From the above study, it is evident that water obtained from solar distillation systems is free from all the contaminations and it is suitable for drinking.

1.10 Performance parameters for solar distillation

Several parameters influence the performance of a solar still, including solar radiation, the inclination angle of the glazing surface, water temperature, condensing cover temperature, the temperature gradient between the water and the condensing surface, vapor leakage, and heat losses through the basin liner and side walls to the surroundings. Increased solar radiation on the glazing surface typically leads to higher distilled water output from the system. An appropriate inclination angle of the glazing surface allows a greater amount of solar energy to penetrate and reach the water inside the solar still. However, the angle of inclination of glazing surface does not have any affect the condensation rate of the distillate that flows down the inner surface into the collection trough. When the condensing glass surface is clean, water vapor tends to condense in the form of a thin film on the inner surface, allowing the condensate to flow down even at a slight slope of around 1°. It is generally preferred to keep the inclination of the glass cover as low as possible due to the following reasons:

i. The large value of inclination of glass cover will increase the amount of material required to fabricate the glass cover for a given area of the basin.
ii. A greater inclination angle of the glass cover increases the overall size and weight of the solar still, leading to higher transportation and shipping costs.
iii. For the large value of inclination of the glass covers, larger will be the volume of air inside the still and lower will be the thermal efficiency of solar still.

In a solar still, the water in the basin typically reaches a much higher temperature than the condensing glass cover. This significant temperature difference between the warm basin water and the cooler glass surface enhances the evaporation rate and promotes more efficient condensation of the vapor. Minimizing vapor leakage and reducing heat loss through the basin’s bottom and side walls leads to higher distillate output. The temperature of the basin water rises more quickly when it absorbs a greater portion of the incoming solar radiation. To achieve this, low-absorptivity glazing and a highly absorptive basin liner are used. Additionally, maintaining a shallow water depth in the basin helps increase the water temperature. A large temperature difference between the water surface and the condensing glass can also be achieved by selecting a condensing surface material with low absorptivity, which enables quicker heat removal through convection, evaporation, and radiation.

1.11 Application of distilled water

The sun light is freely available everyday which can produce distilled water. The primary expense in producing distilled water through a solar distillation system lies in the fabrication cost of the solar still using available materials, which makes the final cost of distilled water relatively high. As a result, generating large volumes of distilled water for large-scale applications such as agriculture or waste disposal in households and industries can be economically unfeasible. Hence, solar stills are mainly employed for specific purposes like drinking water purification, medical use, laboratory needs, industrial processes, and greenhouse applications.

In everyday life, distilled water is commonly used for drinking, cooking, bathing, and cleaning purposes. There is significant demand for use in research laboratories for scientific investigations. In hospitals and dispensaries, it can be used for sterilization. It can be used as make up water in back up battery connected with inverters and telephone exchange maintenance. It can also be used in industry for preparing different kinds of solvents, paints. It can be applied in agriculture sector for making dilute solutions of pesticides and insecticides and other purposes; however, one will have to consider the economy before such use. The use of distilled water may be economical for farming in greenhouses. As per Gordes and McCracken, a properly designed water-based nutrient system, as opposed to traditional soil methods, can yield 8 to 10 times more food per unit of water used compared to conventional field-grown crops.

A solar still can be used for obtaining salt from sea water; however, the cost of produced salt will be quite high because salt is a cheap material. Recovery of pure water from sewage can be possible with the help of solar still. One of the major limitations of using sewage water in solar distillation is the possibility that foul-smelling gases present in the feed water may evaporate, condense, and contaminate the distilled output. Despite this, solar distillation holds considerable potential in food processing industries, particularly in the production of energy drinks and beverages.

In the next chapter, literature review on solar still has been presented. From the literature review, the research gap and objectives have been stated. The motivation of the proposed research has also been discussed.

CHAPTER - II

LITERATURE REVIEW

2.1 Introduction

The key objective of this chapter is to write the literature review to convey all the readers that what knowledge and basic philosophies including concepts are well-known on the water distillation units, and what are their potentials, weaknesses, challenges and the advancements. This has been done through an in-depth study of available research work reports, magazines, books and research articles especially during the last ten years.

2.2 Literature reviews

The literature assessment must be distinct by a guiding concept. It is not only an expressive list of the materials/facts available. Table 1.2 focuses on the recent developments on the design, productivity, nocturnal use, performance enhancement, hybrid mode of solar stills, around the world.

Table 2.1 Previous research work on solar distillation systems

Reference	**Design of distillation unit**	**Results of research work**
Shatar et al. (2023)	An SSSS type distillation unit integrated with a TEC module for different cover materials	Total of 03 different cover materials, such as glass, polycarbonate, and acrylic, have been experimentally investigated for the tested SSSB. The output yield of the unit productivity with glass cover, polycarbonate and acrylic has been found improved about

		76% 48% and 82%, respectively, while the maximum η_{energy} has been found about 23.6%, 2.5%, and 7.2%, respectively. The minimum cost/litre of yield has been attained by glass cover i.e., 0.042$.
Angappan et al. (2023)	An SSSB type distillation system integrated with a hot box solar cooker	The integrated SBC augmented the unit's captivation area and improved the T_w inside SSSB. Results showed that the passive and active type solar still provided about 3.9 and 5.5 L/m^2/day, correspondingly. Apart from this, the yield has improved by 41% through the applied modification compared with the passive type.
Abdullah et al. (2023)	A pyramid solar still with dissimilar wick materials operated on an electric heater	Results exposed that the tested unit can produce about 8000 mL/m^2.day to compare with a conventional solar still which produced about 3550 mL/m^2.day. thus, the percentage increase was about 125%. Moreover, the highest output yield was about 125% for jute, about 115% for cotton, about 88% for plush, and about 60% for silk. Besides this, the daily productivity of still with heaters

		was about 10750 mL/m^2.day, with a net productivity enhancement of about 195%. The tested still had an η_{exergy} of about 6.1%.
Sambare et al. (2023)	A tubular type solar still to be operated on different SHS materials, such as jute cloth, iron fragments and wire mesh.	Experiments have been conducted under Indian climate at a specific basin depth of about 2 cm. To compare with a conservative tubular still, the tested still had the η_{therm} and η_{exergy} by about 35% and 88%, respectively. Results exposed that wire mesh had the peak output among the tested SHS materials. The fresh water cost/liter was found approximately 0.00499 \$/m^2.
Shatar et al. (2023a)	A passive designed still was used with a moderately treated condensation cover. A varying TEC technique was applied (12W - 36W) to enhance the productivity.	Experiments were carried out under Malaysian climate. The performance analysis was done on drinking water yield, energy, exergy, ecological and financial characteristics. The productivity improvement was found possible up to 126% on a 36W TEC potential. The η_{energy} was enhanced about 44%, and the η_{exergy} was reduced about 25% compared with a reference unit. The CO_2 mitigated through the

		tested still was about 2.97 tonnes of CO_2 in its expected lifetime. The lowermost cost/litre was approximately $0.036 with TEC (36W).
Rabishokr and Daghig (2023)	A newly designed portable-size multi-slope still was experimentally studied with a magnetic stirrer and TEC module.	This research was carried out in Iran. The potable yield was observed about 1550 ml/m^2·d that was increased about 143.14% compared with a conventional still. Moreover, the η_{energy} and η_{exergy} of the tested distillation unit was found about 28% and 1.67%. The estimated cost was calculated to be approximately 0.081 $/l/$m^2$.
Wei et al. (2023)	A tubular type solar still	A stepping up still for vaporization with reducing pop and uplifting T_w were studied. At T_w = 60°C, average vapor flow under 40 kPa was about 66.6 mm/s, augmented about 151%. A relationship was developed of 12-22% accuracy. Through this relationship, a new model to predict daily productivity from the distillation unit was discussed.
Dwivedi et al. (2023)	A simply designed solar evaporative still (SES)	A total of 03 processing mills have been considered from diverse sites in an urban area, and sewer water samples

		were attained. Individual sample was preserved for 08 hours in day. The parameters, such as pH value, TDS, CL contents, TH, TA, and Ph content of the sewer and drinking water were evaluated. The results showed that SES had a yield about 4.6 l/day.
Alsaiari et al. (2023)	A unique software was developed to assess the output yield of a conventional, stepped, pyramid, and tubular solar stills. Flowchart is below	The accurateness of an advanced system associated with 03 other MLP models improved with orthodox optimizers. All tested units found proficient and established by using the investigational statistics of the 04 different still under climatic conditions of different locations of Saudi Arabia. The performance investigation was done through some dissimilar numerical events for all examined configurations. The MLP-ARO outclassed further 03 models. The calculated RMS deviation standards for all the tested stills were found satisfactorily.
Shoeibi et al. (2023)	An SSSS combined with a PV, heat pipes and TEG was studied for the performance improvement.	The outcomes of this research work demonstrated the maximum power output PV-integrated still (CSS), still

		integrated with TEG, still integrated with heat pipes and the entire combined unit was about 68W, 69W, 73W and 75W, respectively. The daily yield for the same order units was about 748, 832, 1058 and 1162 ml/m^2, respectively. Furthermore, cost/litre for the same order units is approximately 0.042, 0.098, 0.077, 0.084 $/L, respectively.
Beggas et al. (2023)	A hemispherical solar still with *Al* waste as a energy storage material.	The outcomes showed that *Al* waste inside the tested still was helpful to obtain the drinking water of about 6.15 kg/m^2/day. While a reference still produced about 4.15 kg/m^2/day only. The usage of waste aluminium improved productivity by about 49%. After from this, this metallic waste also improved the η_{therm} from 36% to 52%. The usage of *Al* waste was suggested in different solar stills due to its high thermal conductivity.
Attia et al. (2023)	Total of 04 hemispherical solar stills was tested with reflective *Al* foils, metal sheets, and phosphate granules to enhance their daily yield and η_{therm}.	It has been noted that the daily $\boldsymbol{P}_{yield}$ of the improved stills was as 1. The daily $\boldsymbol{P}_{yield}$ of model-1 (with *Al*

		foil and PO_4 granules) was about 8.7% and the net improvement was about 31%. 2. The daily yield of solar still-2 (Zn metal sheets and PO_4 granules) was about 29% and the net improvement was about 50%. 3. The daily yield of solar still-3 (Cu metal sheets and PO_4 granules) was about 43% and the net improvement was about 63%.
Kanchana et al. (2023)	A solar desalting type still was used for distillation of underground water of Tamil Nadu’s eastern coastline in India.	Different factors relating to the water quality were investigated with a total of 08 samples, and the outcomes demonstrate that the invasion of salt-water is main for the saltiness of the underground water in this region. Formerly, the physiochemical constraints and SDS treated samples were investigated.
Liu et al. (2023)	A pyramid type solar still was integrated with ETC and US foggers	Notably, a full thermo-economic assessment was carried out including η_{energ}, η_{exerg} and potable cost/liter. The outcomes of improved stills have been compared with a conventional model.

		Model DPSS-III enhanced the drinking water yield, η_{energ} and η_{exerg} about of 84%, 19% and 39%, respectively. However, the productivity cost was decreased about of 12%. The results exposed the pertinency, sustainability, and viability of the anticipated additives in solar distillation.
Tuly et al. (2022)	An active type double slope solar distillation unit integrated with internal reflector, hollow-circular fins, and nano-PCM.	The outcomes focused on the attainment of a distillation output of about 1853 mL/day through the modified still with internal reflector, extended fins, and nano enhanced PCM (paraffin wax+Al_2O_3). Notably, distillate accumulation was noted to exceed the conservative case by about 62% (pure PCM) and 92% (nano-PCM). Furthermore, the peak η_{energ} of about 22% was attained with the mutual effect of the applied performance boosters. The drinking water cost was found about 0.02-0.022$/L.
Alqsair et al. (2022)	A drum type solar still integrated with transparent walls, PSC, PCM, nanoparticles' coating and outward	The outcomes specified that the $\boldsymbol{T}_{boil}$ of brackish water in the modified still was achieved that led to a noteworthy rise in

	condenser.	evaporation. Furthermore, the peak $\boldsymbol{P}_{\text{yield}}$ was observed by using NC, PSC and outward condenser and productivity improved was about 320% while η_{energ} was estimated at about 72%.
Sonker et al. (2022)	A frugal solar still was developed with PCM-cylinders and nano particles.	The productivity yield was improved by about 44% by using PCM compared with no PCM. Notably, the $\boldsymbol{P}_{\text{yield}}$ was noticed to be improved by 33% by using nano-PCM. The evaporative HTC was improved in NPCM operated still. The innovative frugal still reduced the cost of potable water from ₹/L to ₹ 3/L. The PBP for the innovative model was about 4.3 years.
Tuly et al. (2022)	The 4E and sustainability metrics analysis was performed for a DSSS.	The outcomes explored that the PCM (Case-2) increased the output about 59% compared with a conventional model (Case-1). Notably, there was a further improvement of about 26% in Case-3, when nano-PCM was used. Besides this, nano-PCM induced approximately 02% additional cost-saving/unit of water purification. The

		tested unit can be used for a long duration.
Essa et al. (2022)	A tubular type still integrated with a spinning drum, nanoparticles' coating, PSC, and the PCM.	The outcomes expressed that the rotating cylinder enhanced $\boldsymbol{P}_{\text{yield}}$ of modified still. Notably, the still with nanoparticles' coating produced about 6650 mL/m^2.day compared with 2800 mL/m^2.day for a conventional still with a net increase of about 137%. The peak productivity of modified with PSC and PCM was about of 195% and 218%, respectively. The η_{therm} of CSS was found about 34%. The maximum η_{therm} of the modified still with PCM was at about 69%. The PBP was approximately 5 months.
Sangeetha et al. (2022)	A dual-slope U-shaped stepped basin type still with carbon nanoparticles as shown here.	The newly designed still improved the daily yield at about 15 l/m^{2}day with an average η_{daily} by about 39%. The results also showed that water quality is quite safe to drink. Notably, some small-size steel balls have been used inside the still (over the basin) for improving convection.

Selimefendigil et al. (2022)	An SSSS was experimentally studied for an impact of combined effect of CuO nanoparticles.	The outcomes exposed that mutual effect of nanoparticles improved the output yield by about 27% compared to a conventional unit. Apart from this, η_{ener} and η_{exer} were improved by about 20% and 2.01%, respectively, through the combined effect of nano-PCM.
Abdelgaied et al. (2022)	An improved hemispherical solar still with nano-PCM (CuO- nanoparticles + paraffin wax.	The results showed that the CuO based nanofluid and pure paraffin enhanced yield by about 61% and 29%, respectively. The PCM and CuO based combined nanofluid further improved $\boldsymbol{P}_{yield}$ by about 80% compared to conventional system. Furthermore, the daily η_{ener} of the modified distillers were observed at about 36%, 46%, 56%, and 64%, respectively, for model 1,2,3 and 4.

Gad et al. (2015) experimented with conical passive solar still (CPSS) and concluded that the heat transfer coefficient of CPSS was increased by 51.51% over the conventional solar still. Tiwari et al. (2020) investigated the effect of input parameters on the performance of conical solar still incorporated with concentrators and concluded that the distillate output increases with the diminish in the value of packing factor of photovoltaic thermal collector due to increase in heat gain by the collector. Kabeel et al. (2023) experimented with conical solar still for obtaining the best and most favorable inclination of condensing surface and concluded that 30° is the optimum angle of inclination for the condensing surface considering the cumulative distillate output and efficiency. Attia et al. (2023) investigated conical solar still with heat storage materials and concluded that the distillate output was increased by 39.47% over the conical solar still without heat storage. Wang (2023) experimented with solar thermal evaporator for producing freshwater and salt simultaneously and concluded that the concept introduced will start a new direction for solar evaporator development. Abdallah and Aldarabseh (2024) experimented with conical solar still having hexagonal base and concluded that the reported system produces 221.5% higher distillate over the conventional solar still. Table 1.2 summarizes the key papers.

A summary of key papers on conical solar still has been provided in Table 2.

Table 2: A glimpse of work on conical solar still

Author	**System**	**Parameters**	**Remarks**
Gad et al. (2016)	Conical passive solar still	Distillate output	The distillate output of conical solar still was higher than the traditional solar still due to the reduces shading.
Tiwari et al. (2020)	Conical solar still with concentrator	Distillate output	Increasing the mass flow rate diminished the distillate output

			because of lower heat addition to the basin.
Mishra et al. (2020)	Active conical solar still consisting of concentrator collectors	Effects of parameters on output	To get improved output, high absorptivity of basin liner and lower water depth were recommended.
Kabeel et al. (2023)	Conical passive solar still	Conical angle	The experimental study on the conical solar still was done and the optimum conical angle was reported as 30 degree.
Singh et al. (2023, 2024)	Conical solar still of passive type	Analyses from energy, exergy, economic, environmental, and energy performance metrics perspectives.	superior performance compared to the conventional solar still when evaluated from exergetic, environmental, and economic perspectives. Specifically, improvements of 44.25% and 25.68% were observed over the traditional design.
Abdallah and Aldarabseh	Conical solar still with some	Distillate output	There was an increase in the distillate output with the

(2024)	modification		decrease in volume flow rate of saline water.
Kumar et al. (2024)	Conical solar still with/without PVT integrated concentrators	Thermal modelling	Concludingly, the instantaneous efficiency of the system with PVT was less than the system without PVT due to less thermal energy addition to basin in the system with PVT.
Kumar et al. (2025, 2025a, 2025b)	Conical solar still with PVT integrated concentrators	Exergo-enviro-economic, energy metrics and parametric study	A comparison of active conical solar still with/without PVT integrated concentrators was done based on the said parameters.
Bady et al. (2025)	Conical solar still with fins and wick material as energy storage	Environmental analysis	The best value of enviro-economic parameter was reported as 50.22 $.
Attia et al. (2024, 2025, 2025a, 2025b)	Conical solar still	Effect of aluminium ball, surface tension, external reflecting mirrors, and	The experimental investigation concluded that the increase in daily distillate output of conical solar still with aluminium ball was 46.08%

		secondary porous absorber of wire mesh on distillate output	higher than the traditional conical solar still. Further, the distillate output was increased with the reduction in surface tension using floating plastic tubes. Use of reflecting mirrors also improved the distillate output. The use of secondary wire mesh as absorber improved the carbon credit by 43.48 % as compared to conventional conical solar still.
Kabeel et al. (2024), and Omara et al. (2025)	Conical solar still	Distillate output, production cost, environmental and economic analyses, Design aspect	A detailed review on conical solar still including design aspect was reported and it was stated that the conical solar still provided better performance than the traditional solar still based on the said parameters due to low shading effect and increased condensing surface.
Abdel-Aziz and	Conical solar still	Distillate output	The experimental study

Attia (2025)	with broken glass of different colours		indicated that the solar still using broken glass with brown color gave 46.94% improvement in yield over the traditional conical solar still.
Bady et al. (2024, 2024a)	Conical solar still containing copper hollow tube with/without PCM	Distillate output, carbon credit	Experimental investigation was done and it was reported that the daily maximum efficiency of solar still with tube and PCM was 9.10% higher than the solar still with tube only. Further, carbon credit by solar still with tube was 2.5 times higher than the traditional conical solar still.
Alahmadi et al. (2025)	Conical solar still with nano wick, nano PCM and conical reflector	Exergo-enviro-economic analysis	The experimental study concluded that there was an improvement in carbon credit by 188.65 % than the traditional conical solar still.
Alahmadi et al. (2025a)	Conical solar still	Effect of extended	Mult objective optimization improved the distillate output

		magnetic poles on the output	by 108.54 % than the conventional conical solar still.

2.3 Research gap

From the literature study, one can easily deduce that lots of work on passive and active solar stills are reported, However, research work on conical solar still remains quite limited. Based on the literature review, the identified research gaps outlined as follows:

i. The integration of evacuated tube collectors into a thermal model for conical solar stills has not yet been documented. Its energy, exergy, economic, efficiency, exergo-enviro-economic, efficiency and energy metrics analyses have not been touched upon.
ii. The effect of nanofluid/hybrid nanofluid on conical solar still has not been analysed.
iii. The effect of different locations on conical solar still has not been studied.
iv. The analysis of conical solar still by integrated with dish type collectors has not been done.
v. The conical solar still with concentrator assisted evacuated tubular collector has not been investigated.

2.4 Motivation

Passive solar stills typically experience low distillate output, which may be attributed to the shading effects caused by the side walls. This issue can be mitigated in a conical passive solar still, where the geometric design helps reduce shading and improve overall productivity. The output of passive conical solar still can further be improved by providing heat either by conventional source or using some kind of solar collector as suggested by some authors in their reports. The additional heat supplied to the basin raises the water temperature, leading to a relatively higher distillate yield. Therefore, the current research focused on analyzing the performance of a conical solar still integrated with an evacuated tube collector.

2.5 Objectives of research work

The ongoing issue of freshwater scarcity can be mitigated in a sustainable manner by providing freshwater using solar distillation system. It will also diminish the dependance on fossil fuel which is depleting slowly. As a result, solar systems design and performance for providing freshwater to remote locations particularly in developing and under-developed countries is important as it contributes towards sustainable development goals of the United Nations. The current research emphasizes the development of a thermal model based on energy balance principles, followed by comprehensive analyses including energy, exergy, efficiency, and exergo-enviro-economic evaluations. The primary objectives of this study are outlined as follows:

i. To develop thermal model for conical solar still (CSS) by incorporating N number of evacuated tubular collectors (NETC).
ii. To compute annual energy, exergy and efficiency of NETC-CSS using the computational code in MATLAB.
iii. To carry out exergo-enviro-economic analysis for NETC-CSS.
iv. To compare the performance of solar still with earlier published research.

2.6 Organization of present thesis

First chapter provides a general introduction to solar stills. Second chapter presents a comprehensive literature review, outlining the identified research gaps, motivation for the study, and defined objectives. Third chapter focuses on the development of a thermal model for the NETC-CSS, along with its annual evaluations in terms of energy, exergy, and efficiency. Fourth chapter discusses exergo-enviro-economic analysis of NETC-CSS. The fifth and the last chapter deals with results and discussion followed by future scope.

In the next chapter, the thermal model of NETC-CSS has been developed using energy balance equations followed by annual energy, exergy and efficiency analyses. It also includes the validation of developed thermal model using data reported in the literature.

CHAPTER - III

Energy, exergy and efficiency analyses of NETC-CSS

3.1 Introduction

The adoption of solar energy technology for obtaining clean water for use of society in remote locations will be useful for in fulfilling the sustainable and long-term eco-conscious intentions of the world. In addition, fostering solar energy for the use of society will subside dependency on the fossil fuel or conventional energy. This chapter covers the annual energy, exergy and efficiency analyses of N identical ETCs incorporated conical solar still (NETC-CSS). The thermal model developed for the proposed system is based on balancing input and output heat across various elements. The developed fundamental equations are fed to the MATLAB computational code. The four weather situations across all months of the year under New Delhi's climate conditions is considered for the annual analysis. The annual energy, exergy, thermal efficiency as well as exergy efficiency for NETC-CSS are computed to be 1796.61 kWh, 170.19 kWh, 38.79% and 3.94% under optimized values of mass flow rate and number of solar collectors. Finally, results are compared with earlier published research. Concludingly, the boost in annual energy, exergy, thermal efficiency and exergy efficiency for NETC-CSS is 68.03% than modified solar still, 74.14% than conventional conical solar still, 61.12% than modified solar still and 72.59% than solar still integrated with parabolic trough collector.

The significance of collectors in present world cannot be denied and one of most used collectors are evacuated type collectors (ETC). The exceptional reduction in the losses compare to flat plate collector (FPC), ETC has gained popularity in early past decades. Their utility in generating fresh water form solar still has been the area of interest of the various scholars. Therefore, a lot of studies have been done on the application of the ETC based solar stills in which ETCs have been combined with the basin of solar stills with certain additions like the use of nanofluid, use of disinfectant, humidification-dehumidification concept, thermoelectric cooling, calcium stone, phase change material etc. However, the utilization of evacuated collector in conjunction with conical solar still has not been addressed by researchers worldwide, indicating a significant gap in current research. This study has effectively utilized the identified research gap for findings. A thermal model incorporating energy balance equations has been formulated for conical-shaped solar still equipped with evacuated tube collectors followed by annual energy, exergy, thermal efficiency as well as exergy efficiency analyses. The conical-shaped solar still has 360^{o} sunlight exposure. Unlike single-slope solar stills that depend on the sun's direction, a conical design allows sunlight to reach different parts of the basin from all directions. This reduces the formation of large, shadowed areas, enhancing continuous solar absorption and hence it has the potential to provide greater productivity. A conical-shaped solar still with integrated evacuated tube**s** is an advanced water purification system that enhances the efficiency of solar desalination. It combines the traditional conical solar still design with evacuated tube collectors (ETCs) to improve water evaporation rates and overall distillation performance. The conical glass cover promotes better light penetration, minimizing the shading effect. Moreover, output of the ongoing research work has been compared with the earlier research for the validation.

Ensuring reliable access to hygienic drinking water is essential not only for humans but also for animals. Fresh water is a fundamental requirement in both agriculture and industrial sectors. The Earth holds around 1.4 billion cubic kilometers of water, which accounts for about 70% of its surface area. However, 97.5% of this is saline water, leaving only a small fraction, approximately 0.5% of freshwater but on the harsh side it is merely available at fresh form. Over population, and industrialization has made the freshest water sources polluted. Collective factors raise a question to global concern of water scarcity. According to a joint report by UNICEF and WHO titled “Progress on Sanitation and Drinking Water 2015 update and MDG Assessment”, nearly 54% of the global population resided in urban areas at that time. Moreover, the report highlighted that 91% of people had access to improved drinking water sources, around 159 million still relied on untreated surface water, and about 663 million lacked access to safe drinking water. In 2010, the global water demand reached 2,769 km^3 annually for agricultural use, making up 69% of total withdrawals. The industrial and municipal sectors accounted for 768 km^3/year (19%) and 464 km^3/year (12%) respectively. This indicates that agriculture consumes the largest share of water globally (Navi et al., 2018).

Additionally, the war like situation in present days critically seen in gulf countries have exaugurated the dependency on renewable sources. Majorities of the population does not have enough water for daily quota. However, if they have a technique which is quite simple and runs on solar energy, they can purify the brackish water and can be used for drinking. Similar situation was evident in case on Russia-Ukraine war. There Russia is targeting the water treatment plants, similar persistent situation can be observed. Those nations have merely water for drinking and rely on the border nations for supplies which is a dangerous situation for both the nations.

However, in these scenarios, Solar Desalination can a promising solution to address the growing water scarcity challenges as mentioned above. By utilizing abundant and renewable solar energy, this method offers an environmentally friendly and cost-effective way to convert saline or contaminated water into clean, drinkable water. Especially in remote or arid regions where conventional water purification facilities are lacking. In these regions solar stills can be deployed easily and maintained with minimal resources. This technique not only reduces dependence on freshwater sources but also lowers the burden on over exploited groundwater and river systems.

Solar stills can be divided into categories as either passive (PSS) or active (ASS). Both types of solar distillation systems used to purify water, but they differ in their approach to harnessing solar energy. To enhance the distillation process, active solar stills use external energy sources. They rely not only on solar energy but may also use electrical energy or a mechanical system to increase water circulation or improve the evaporation-condensation process. Passive solar stills utilize only solar energy to drive the natural processes of water evaporation and condensation. They do not require any external mechanical energy; all the processes (evaporation, condensation) occur passively, with the sun providing the only energy input. To enhance performance, heat has to be supplied to the basin of a passive solar still using a solar collector. When a passive solar still (PSS) is connected with an external heat supplying element, it becomes an active solar still. Following that, many enhancements in design have been made, which are detailed in following sections.

Utilizing an evacuated collector (ETC) increases the heat provided to the solar still's basin, as it effectively minimizes convective heat loss, leaving only radiative heat loss (Singh, 2022). These are highly efficient solar thermal collectors designed to absorb and retain heat. Their integration into a solar still suggests an attempt to improve water desalination efficiency. In contrast, other collectors experience both kind of heat transfers radiative as well as convective (Raturi et al., 2023). Research incorporating evacuated tubes in a natural circulation mode into a solar still confirmed that using 10 evacuated tubes provided the best performance in terms of freshwater generation and resulted in a freshwater generation rate of 3.8 kg per unit area (Omara et al., 2013; Singh et al., 2013). More or fewer tubes might have reduced efficiency due to factors like thermal losses or insufficient heat absorption. Natural circulation mode implies that the movement of water or working fluid within the system occurs due to buoyancy effects rather than mechanical pumps, making it a passive and energy-efficient approach. Determining the optimal number of tubes suggests that an excessive number could lead to diminishing returns due to thermal inefficiencies. Esen et al. (2005) studied solar water heater with different refrigerants and concluded that the peak performance was attained using R410A because of its higher latent heat value. Esen et al. (2007) investigated heat pump with heat exchanger and reported the efficiency of the system as 56.3%. Further, study on the utilization of solar energy for cooking using solar cooker by incorporating heat pipe with refrigerant was done and they concluded that several foods were cooked in 27-70 min period (Esen, 2004). In another study, solar cooker with collector containing heat pipe was studied and concluded that several foods were cooked in 25-73 min periods using Freon 404A and Freon 410A as refrigerants (Esen, 2005). In their study, Kumar et al. (2014) analysed solar stills with ETC attached to it and revealed that the best possible daily freshwater yield was 3.9 kg, which was higher than that of solar stills operating under natural circulation conditions. Shafii et al. (2016) by their experimental work demonstrated that the integration of TEMs and ETCs can result in substantial improvements in solar still output. By utilizing the heat dissipated during vapor condensation, TEMs can generate electrical energy to power a low wattage propeller fan, thereby inducing forced convection and further increasing the evaporation rate. The experimental findings show that this approach leads to a considerable marked rise in both water yield and system efficiency. Specifically, forced convection generated by a fan has been observed to enhance hourly efficiency, with recorded maximum values reaching 68% and a water generation rate of 1.11 kg/m²/h. Another critical factor influencing the performance of solar stills is the water depth inside the evacuated tubes. Studies indicate that maintaining an optimal water level within the tubes is crucial for maximizing output. Experiments comparing two different water depths in evacuated tubes reveal that a fully filled tube configuration results in a 27% increase in output compared to a half-filled tube. These findings highlight the importance of optimizing water levels to attain greater efficiency in solar stills. Sharshir et al. (2016) explored the integration of an evacuated heater and the humidification-dehumidification concept in a solar still, finding that the gain output ratio was 39 % higher in comparison with a regular solar still. Singh (2017) analysed the influence of incorporating partially covered PVT collectors into double slope solar stills (DSSS) to optimize energy, exergy, and productivity. Their research highlighted the importance of exergy-based cost efficiency, showing an increase of 40.73% to 54.63% when utilizing N number of identical PVT FPC (N-PVT-FPC-DS). However, these modifications lead to higher environmental costs (59.70% to 92.55%), emphasizing the trade-offs between efficiency and sustainability. Productivity-based comparisons reveal 9.25% improvement over PVT compound parabolic concentrator-based DSSS but 25.13% lower performance compared to conventional DSSS. Negi et al. (2022) investigated the impact of inclined wick and FPC. It has been reported that, the tilted wick still showed the best performance, yielding 3.99 kg/m²/day and achieving 22.1% higher cumulative efficiency than HWSS at the same water flow rate and depth.

Singh and Al-Helal (2018) and Singh (2018) examined solar stills with the inclusion of evacuated collectors and analysed their energy matrices. Their findings indicated that the energy payback time for systems with evacuated collectors was lower than other collector types due to the reduction of convective heat loss occurring in the evacuated solar collectors. In another experimental research work Singh et al. (2018, 2019) examined various solar distillers with and without the use of nanofluids. While working on solar distillation system, Sharshir et al. (2019) investigated the impact of ETC and nanofluids on the pyramid solar distillation system. The sloped surfaces of pyramid solar distillation system allow for uniform solar radiation absorption throughout the day. The enclosed structure helps trap heat efficiently, maintaining a high temperature inside the still for prolonged evaporation. They reported that the modified pyramid solar still produced 4.77 % more freshwater when compared with the regular conventional design, attributing the improvement to the combined effects of the evacuated collector and the nanofluid.

Literature (Singh et al., 2022; Kumar et al., 2020) investigated the synergetic effect of the ETC in the performance. To do so, SSSS integrated with N identical ETC was studied using mathematical study in MATLAB. Additionally, the study evaluates numerous parameters including energy output, carbon mitigation, and enviro-economic parameters. Data from IMD, Pune, support the numerical computations for typical days in May and December in New Delhi. The findings suggest that increasing the number of collectors raises the enviro-economic cost at a fixed fluid flow rate. Panchal et al. (2020) performed experiments to enhance the efficiency of a solar still using calcium stones and ETC. Experiments conducted in Patan District, Gujarat, from January to June 2019. The experiments are tested on a CSS, CSS with evacuated tubes (SSET), and a CSS with evacuated tubes and calcium stones (SSETCS). This timeframe allowed researchers to assess performance variations over different weather condition. Their results showed that the setup produced 113.52 % more amount of freshwater than a regular conventional solar still. The increased efficiency was attributed to the combination of evacuated tubes supplying heat to the solar still and calcium stones which act as a heat reservoir for the modified solar still (MSS). The stones absorbed and retained heat, allowing for continued evaporation even after sunset, thus extending the productivity of the system. Sharma et al. (2020) developed mathematical equations for double slope solar still combined with concentrator integrated evacuated collectors. This design improves sunlight distribution, enhances evaporation rates, and increases freshwater production compared to a single slope setup. By integrating a concentrator, more heat is supplied to the still, accelerating the evaporation process. Mathematical model likely accounted for heat transfer, evaporation rates, condensation efficiency, and system energy balance to optimize the design. The equations can be used for design improvements, allowing engineers to develop more efficient large-scale systems. Mevada et al. (2021) reported significant improvement of 73.45 % of freshwater for the MSS compared to traditional. In their study, they integrated fins, ETC and condenser on the solar still. Furthermore, Sadeghi and Nazari et al. (2021) investigated simultaneous impact of ETC with concentrator and nanofluid. The nanoparticles that were used in the study has a special disinfectant property. Therefore, the addition of nanoparticles ensures the quality of the distilled water and make it free from microbial contamination. The improved heat transfer capabilities of the nanofluid help further intensifies evaporation efficiency. The author reported significant improvement in yield of more than 100 % with incorporating aforementioned modifications compared to CSS. These modifications not only improve the yield of the system but also ensure the quality of water which has been identified as the critical aspect of drinking water.

Dawood et al. (2020) experimented with solar distillation system that aimed to enhance the efficiency and economic viability of a solar still by integrating: (i) A Parabolic Concentrator with Evacuated Tubes and (ii) Phase Change Material (PCM) in the Receiver Tube. This setup enhances evaporation rates and increases freshwater production. PCMs store thermal energy when exposed to heat and release it gradually when the heat source is removed (i.e., after sunset). The PCM in the receiver tube acted as a thermal reservoir, allowing the solar still to continue producing freshwater even at night. They found that the suggested system reduced the expense of freshwater generation by 29.87% compared to a regular traditional solar still. The reduction in cost was linked to the PCM, which continued supplying heat to the basin during the night. Several sensitivity analysis (Prasad et al., 2019; Singh, 2021; Raturi et al., 2021, 2021a; Singh et al., 2021, 2022; Bharti et al., 2021) of solar systems was undertook and it was concluded that the output of such analysis gave information to the designer and installer about which parameter affected most to the output of the system. The information would be helpful while installing such systems as per the need of user. Sharshir et al. (2022) conducted an experimental study on a pyramid solar distillation system equipped with condenser, evacuated tubes, nanofluid and ultrasonic defogger. Their analysis revealed that the cost of producing freshwater with this enhanced system was 32.04% reduced compared to a traditional pyramid solar still. This cost savings was due to the increased rate of evaporation facilitated by the advanced components. Moghadam and Samimi (2022) reported a solar distillation system with an evacuated tubular collector basin and found that expanding the effective surface area of condenser was the key factor in improving generation of freshwater from the solar still. In another research work Gangavathi et al. (2022) experimented with solar distillation system equipped with several evacuated tubes and containing condenser that was nano coated. From the results It was concluded that the proposed system produced 28.53% more freshwater compared to the conventional solar still. The reason of this rise is the provision of excess heat by collector to the basin. Gopi et al. (2022) reported the thermal modelling of multi effect solar still and validated with experimental findings. They concluded that there was a reasonable correlation between theoretical values and values obtained by experiments. The recommended number of effects is seven, as no notable enhancement in generation of freshwater was observed beyond this point. Kumar et al. (2022) studied the performance of a solar distillation system that was equipped with evacuated collectors focusing on the impact of water mass. The final findings of the research indicated that the optimal water depth for maximum efficiency was 0.56 meters.

Farghaly et al. (2023)] studied the independent impact of parabolic reflectors and ETC on the efficiency of the solar still. The reported key finding was noteworthy as parabolic reflector increased the freshwater yield by 30.31% compared to ETC. This improvement primarily attributed to the higher concentration of solar radiation to receiver surface. It was observed that the reflector directs more radiation towards the collector, amplifying heat absorption. Improved heat means faster evaporating resulting in improved yield. Dahab et al. (2023) conducted an experimental study on a hemispherical solar still (HSS) integrated with ETC to enhance freshwater production. Their findings revealed that the efficiency of the proposed system was 47.3% than the efficiency of conventional HSS. HSS system has a dome-shaped transparent cover, which offers better light absorption and uniform condensation compared to traditional sloped designs. This design helps reduce thermal losses and ensures efficient water collection. Nagpal and Singh (2023) investigated double slope solar still enhanced with evacuated collectors and analyzed its impact on carbon mitigation. Their study revealed that the carbon footprint reduction was 16.57% more for concentrator integrated evacuated collectors solar still than evacuated collectors integrated solar still. This setup boosts thermal efficiency, leading to higher freshwater output and greater energy savings Further, a review on different solar stills including solar collectors with their design, output, and cost consideration was reported (Shelake et al., 2023; Kumar et al., 2021; Patel et al., 2020; Singh et al., 2020). Their findings indicated that the

ASS exhibited superior performance when compared with a PSS, however cost of active solar still was higher side than the PSS. Solar stills (SS) have been extensively studied for their ability to produce distilled water using solar energy. Various modifications have been introduced to enhance their efficiency, including the use of thermal energy storage materials. Arani et al. (2023) integrated blue metal stones and tar-coated blue metal stones with CSS in order to improve yield of the system. Their findings indicate that integrating tar-coated blue metal stones improves yield by 34.4%. Furthermore, blue metal stones enhance yield by 27% compared to CSS. Diurnal fresh water generation capacity of a CSS with tar-coated stones reaches up to 2.83 kg, significantly surpassing the 2.59 kg from a CSS with blue metal stones and the 2.02 kg from a regular used conventional setup. Nighttime production also improves, with respective increases of 78.6% and 71.7% over the regular used conventional system. the freshwater output from the reported system was 34.4% higher than the conventional solar still. Kumar et al. (2023) performed tests with solar still that was equipped with evacuated tubes and confirmed that the freshwater generated by the reported system was 52.97% higher than the regular solar still. The conical solar distillation system experiences less shading in comparison to basin type solar stills, which enhances its potential for higher output. This reduced shading effect has garnered significant interest from researchers. Gad et al. (2015) found through experimentation that the conical solar still produced 42.90% more freshwater than traditional solar stills. Additionally, Kabeel et al. (2023)] investigated the impact of different glass inclination of the conical solar still. The glass inclination angles were varied 30, 45 and 60 degrees. Based on the experimental study author recommended a 30-degree angle more suitable for achieving hiked yield and efficiency. In another study, Abdallah and Aldarabseh (2024) developed a new design of solar still. The study majorly resembles to a hexagonal PSS shape. Furthermore, conical inner surface varying the mass flow rate was also introduced. The study demonstrated that the innovative design substantially enhances both freshwater output and system efficiency compared to the conventional conical solar still (CSS). Furthermore, experimental results indicate that using lower saline water flow rates contributes to better overall performance. The optimal flowrate suggested by the author was 40 mL/s, particularly while integrated with an array of mirrors. Theoretical modelling using Mathcad software provided results that closely matched experimental data, validating the model's accuracy. These findings emphasize the effectiveness of conical solar stills as a promising solution for enhancing solar desalination performance and increasing freshwater output. Additionally, Singh et al. (2023, 2024) evaluated the conical solar stills from various perspectives including exergo-enviro-economic analysis, energy metrics and sensitivity. It was observed that the cost of freshwater output using the conical solar still was 13.56% lower compared to traditional solar stills. Additionally, the conical design exhibited better performance in terms of energy metrics and overall efficiency. Furthermore, Kumar et al. (2024) developed characteristic equations for conical solar still incorporated with partially/fully covered photovoltaic thermal (PVT) concentrators. Furthermore, the impact of various PVT on the performance of the ASS was later studied by Singh et al. (2024). In their study, computational analysis was performed using MATLAB. The results revealed that copper indium gallium selenide (CIGS) based PVT offers the shortest energy payback time of 1.64 years, while crystalline silicon PVT demonstrates superior life cycle conversion efficiency, along with exceptional CO_2 mitigation capacity with carbon credit value. These findings score a valuable insight into optimizing PVT integration in solar desalination systems for better environmental and economic benefits. In another study, solar still with ETC was investigated from economic and energy metrics viewpoint (Singh et al., 2024, 2024a). Krishna et al. (2023, 2024) studied the effect of input parameters on the output of ASS and suggested that the results would help in deciding number of collectors and mass flow rate. Yan et al. (2024) investigated hybrid microgrid system for its optimization and from the results it can be concluded that the system consisting of wind turbine/hydrogen energy/ solar configuration has the minimum cost among all the studied systems. In another study, Yan et al. (2024a) studied solar energy system and liquified natural gas for its integration in a best and most favorable way and they revealed that there was a significant improvement in the capacity of production. Zheng et al. (2024) investigated a multigeneration system and the results from their work revealed that the exergy efficiency was 33.25% under optimized condition. Gao et al. (2024) investigated a system consisting of solar and geothermal energies and concluded that the exergy efficiency was 9.34 % under optimal condition. Xiao et al. (2023) investigated closed loop geothermal system and suggested that the study would work as guideline for engineers in developing system for extracting heat from geothermal resources.

From the literature, it is clear that the investigation on the conical solar still combined with evacuated collectors has not been carried out by any researcher which form a research gap. This research gap has been addressed in the present analysis. Fundamental equations were formulated, followed by annual analyses of energy, exergy, and efficiency for a conical solar still integrated with an array of evacuated tube collectors (NETC-CSS). The primary objectives of the study are as follows:

i. To develop thermal model for NETC-CSS followed by the numerical evaluation of annual energy and exergy.

ii. To evaluate thermal efficiency as well as exergy efficiency for NETC-CSS

iii. To compare results of the suggested system with prior research publications.

3.2. Methodology for NETC-CSS Analysis

Fig. 1 shows the three dimensions of the proposed system, and its specifications are given in Table 1. It can be clearly evident from the Fig. 1 that a series connection of N evacuated collectors is designed to achieve the higher water temperatures for improved evaporation rate and higher generation of freshwater.

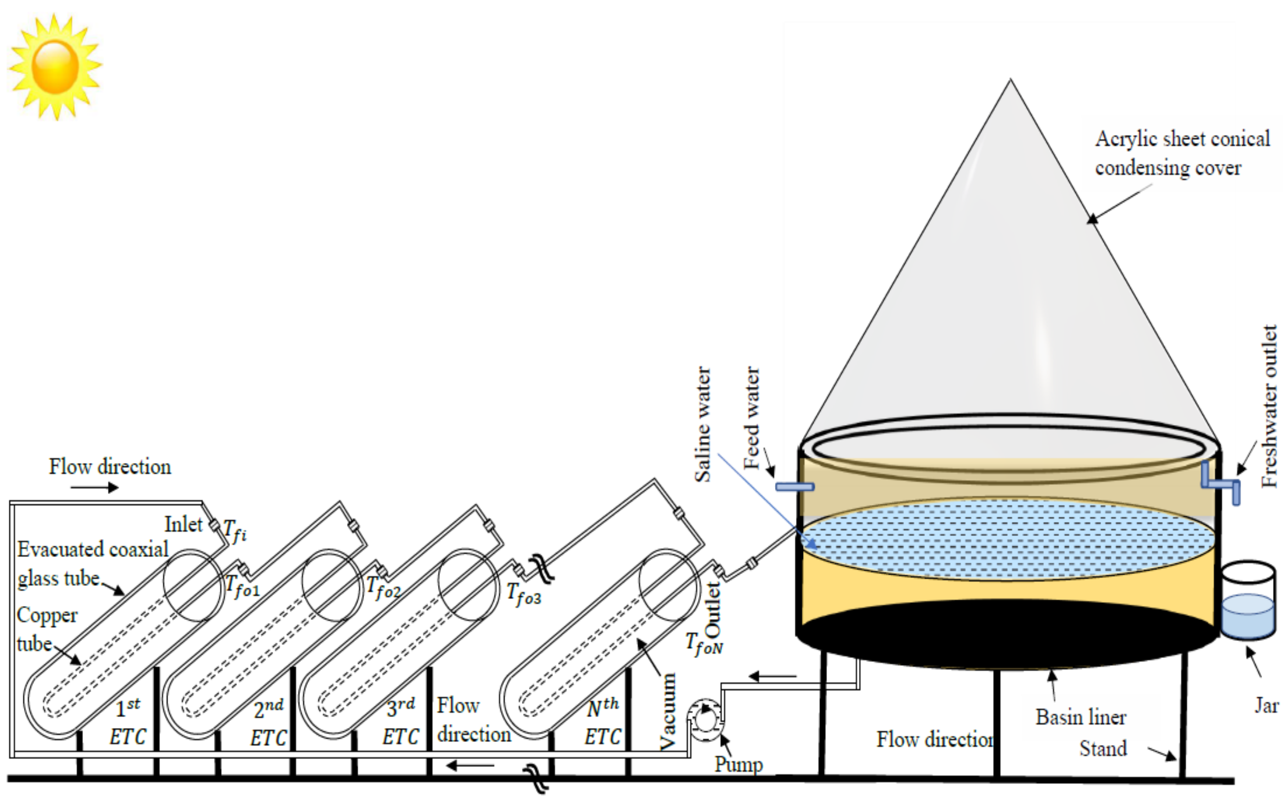

Fig. 3.1: Conical solar still combined with N alike evacuated tubular collectors (NETC-CSS)

Table 3.1: Specifications of NETC-CSS and the mean wind speed for different month

CSS			
System Component	**Specification**	**System Component**	**Specification**
Surface area of conical passive solar still	1 square meter	α_a	0.01
Configuration of basin	Round	α_w	0.02
Condensing surface material	Acrylic	ε_w	0.96
Acrylic condensing surface depth	0.004 meters	α_b	0.82
Insulation material composition	Foam	σ	$5.67\text{x}10^{-8}$ W/m^2-K^4
Insulation layer depth	5 centimetres	ε_g	0.88
Basin material composition	Black-coated GI	Water basin mass	25 kg
Cover incline for condensation	30 degrees	Acrylic reflectivity	0.05
Insulation thermal conductivity	0.166 watts per meter kelvin	Water reflectivity	0.05
Insulation layer depth	0.1 meter		
NETC			
System Component	**Specification**	**System Component**	**Specification**
Type and no. of collectors	ETC, N	α_p	0.8
DC motor rating	12 *V*, 24 *W*	F'	0.968
Radius of inner copper tube	0.0125 meter	τ_g	0.95
Thickness of copper tube	0.0005 meter	$K_g\ (Wm^{-1}K^{-1})$	1.09
Differential thickness between external and internal glass elements of evacuated coaxial glass tube	0.002 meter	Individual length of each copper tube	2 meter
The external radius of the outer glass component in the evacuated coaxial glass tube	0.024 meter	Inclination angle of the ETC with respect to the horizontal plane	30 degree
The internal radius of inner glass element within the evacuated coaxial glass tube	0.0165 meter		

Average air velocity variations across different months of the year

Month	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
Air velocity (m/s)	2.77	3.13	3.46	3.87	4.02	4.11	3.39	2.91	2.85	2.16	1.83	2.40

As the sunlight approaches the condensing surface, a small portion is reflected back due to the property of the glass surface. Maximum portion of the radiation is transferred to the absorber surface, resulting in increase in temperature of the basin surface and consequently leading water temperature. This heat may aid in processes such as water vapor condensation in a solar still. This energy contributes to heating the water, promoting evaporation. This solar radiation is absorbed by the basin liner, causing its temperature to rise. This elevated temperature of the basin liner then transfers heat to the water in the basin. Additionally, the water in the basin receives heat from the collectors. As the basin water temperature rises, it creates a temperature gradient between the inner surface and the condensing surface. This temperature difference causes evaporation leading to the condensation of vapor on the inner side of the condensing cover through film wise condensation. The condensate then drips down due to gravity, and it is accumulated in the beaker. The thermal model was constructed in accordance with the assumptions presented by Singh and Tiwari (2017).

Following Singh et al. (2023), the energy balance equations (EBEs) for condensing surface are written below:

For east facing condensing surface

$$\dot{\alpha}_g I_{SE}(t)\frac{A_g}{4} + h_{1wE}\left(T_w - T_{gE}\right)\frac{A_b}{4} + h_{EW}\left(T_{gW} - T_{gE}\right)\frac{A_g}{4} = h_{1gE}\left(T_{gE} - T_a\right)\frac{A_g}{4} \tag{3.1}$$

For west facing condensing surface

$$\dot{\alpha}_g I_{SW}(t)\frac{A_g}{4} + h_{1wW}\left(T_w - T_{gW}\right)\frac{A_b}{4} - h_{EW}\left(T_{gW} - T_{gE}\right)\frac{A_g}{4} = h_{1gW}\left(T_{gW} - T_a\right)\frac{A_g}{4} \tag{3.2}$$

For south facing condensing surface

$$\dot{\alpha}_g I_{SS}(t)\frac{A_g}{4} + h_{1wS}\left(T_w - T_{gS}\right)\frac{A_b}{4} + h_{NS}\left(T_{gS} - T_{gN}\right)\frac{A_g}{4} = h_{1gS}\left(T_{gS} - T_a\right)\frac{A_g}{4} \tag{3.3}$$

For north facing condensing surface

$$\dot{\alpha}_g I_{SN}(t)\frac{A_g}{4} + h_{1wN}\left(T_w - T_{gN}\right)\frac{A_b}{4} - h_{NS}\left(T_{gS} - T_{gN}\right)\frac{A_g}{4} = h_{1g}\left(T_{gN} - T_a\right)\frac{A_g}{4} \tag{3.4}$$

All unspecified terms in equations (1) to (4) are given in Appendix-A. By ensuring the steps outlined in Singh et al. (2024), solution to equations (1) to (4) are written below:

$$T_{gE} = \frac{A_1 + A_2 T_w}{P_1} \tag{3.5}$$

$$T_{gW} = \frac{B_1 + B_2 T_w}{P_1} \tag{3.6}$$

$$T_{gS} = \frac{C_1 + C_2 T_w}{P_2} \tag{3.7}$$

$$T_{gN} = \frac{D_1 + D_2 T_w}{P_2} \tag{3.8}$$

Again, all unspecified terms in equations (3.5) to (3.8) are provided in Appendix-A. Now, EBEs for basin liner is given below:

$$[\dot{\alpha}_b (I_{SE}(t) + I_{SW}(t) + I_{SN}(t) + I_{SS}(t)) \frac{A_b}{4}] = h_{bw}(T_b - T_w)A_b + h_{ba}(T_b - T_a)\mathrm{A_b} \tag{3.9}$$

Equations (3.9) can further be simplified as: $h_{bw}(T_b - T_w)A_b = \dot{\alpha}_b h_1 \big(I_{SE}(t) + I_{SW}(t) + I_{SN}(t) + I_{SS}(t)\big)A_b - U_b A_b (T_w - T_a)$ (3.10)

where $h_1 = \frac{h_{bw}}{4(h_{bw} + h_{ba})}$ (3.11)

and

$$U_b = \frac{h_{ba} h_{bw}}{(h_{bw} + h_{ba})} \tag{3.12}$$

Furthermore, EBS for water mass can be expressed as:

$$[\dot{\alpha}_w(I_{SE}(t) + I_{SW}(t) + I_{SN}(t) + I_{SS}(t))\frac{A_b}{4}] + [h_{bw}(T_b - T_w)A_b] + \dot{Q}_{u,N} = h_{1wE}\left(T_w - T_{gE}\right)\frac{A_b}{4} + h_{1wW}\left(T_w - T_{gW}\right)\frac{A_b}{4} + h_{1wS}\left(T_w - T_{gS}\right)\frac{A_b}{4} + h_{1wN}\left(T_w - T_{gN}\right)\frac{A_b}{4} + M_w C_w \frac{dT_w}{dt} \quad (3.13)$$

Where, $\dot{Q}_{u,N}$ is the useful heat extracted from a series of N connected evacuated collectors and mathematically it can be expressed as (Mishra et al. 2015):

$$\dot{Q}_{uN} = \frac{(1-K_k{}^N)}{(1-K_k)}(A\,F_R(\alpha\tau))_1 I(t) + \frac{(1-K_k{}^N)}{(1-K_k)}(A\,F_R U_L)_1(\,T_{fi} - T_a) \quad (3.14)$$

In this context, the inlet temperature of the inlet fluid T_{fi} is equal to the water temperature T_w. The heated water exiting the Nth evacuated tube collector (ETC) is released into the basin. Hence, the value of water temperature at outlet T_{wo} is equal to the temperature value at outlet of the NETC (T_{foN}). The temperature at the exit of the Nth ETC (T_{foN}), can be expressed as follows: $$T_{foN} = \frac{(A\,F_R(\alpha\tau))_1}{\dot{m}_f C_f}\frac{(1-K_k{}^N)}{(1-K_k)} I(t) + \frac{(A\,F_R U_L)_1}{\dot{m}_f C_f}\frac{(1-K_k{}^N)}{(1-K_k)} T_a + K_k{}^N T_{fi} \quad (3.15)$$

Appendix – A has all unknown parameters utilized in equations (14) and (15) are prov

Now, one can derive differential equation by utilizing equations (3.5) to (3.8), equation (3.10) and equations (3.13) – (3.14) as expressed below:

$$\frac{dT_w}{dt} + a_1 T_w = f(t) \quad (3.16)$$

Where,

$$f(t)=\frac{1}{M_wC_w}\begin{bmatrix}\left(\frac{\dot{\alpha}_w}{4}+\dot{\alpha}_bh_1\right)A_b(I_{SE}(t)+I_{SW}(t)+I_{SN}(t)+I_{SS}(t))+\frac{(1-K_k^N)}{(1-K_k)}(AF_R(\alpha\tau))_1I(t)-E_1+\\ \{\frac{(1-K_k^N)}{(1-K_k)}(AF_RU_L)_1+U_bA_b+F_1\}T_a\end{bmatrix} \tag{3.17}$$

$$a_1=\left(\frac{\dot{m}_fC_f(1-K_k^N)+F_1+U_bA_b}{M_wC_w}\right) \tag{3.18}$$

By taking certain assumptions such as considering the time interval is taken from 0 to Δt, using the average values of both environment temperature as well as intensity of solar radiation to keep constant the $f(t)$ and thereby using the average $\bar{f}(t)$ in the expression, equation (3.16) can be solved provided, assuming that the value of a_1 will remain constant during the time Δt. Once the procedure was conducted, the solution of equation (3.16) is as follows:

$$T_w=\frac{\bar{f}(t)}{a_1}(1-e^{-a_1t})+T_{wo}e^{-a_1t} \tag{3.19}$$

Where, $$\bar{f}(t)=\frac{1}{M_wC_w}\begin{bmatrix}\left(\frac{\dot{\alpha}_w}{4}+\dot{\alpha}_bh_1\right)A_b(\bar{I}_{SE}(t)+\bar{I}_{SW}(t)+\bar{I}_{SN}(t)+\bar{I}_{SS}(t))-E_1+\\ (U_bA_b+F_1)\bar{T}_a\end{bmatrix} \tag{3.20}$$

To identify the unspecified variables, Appendix- A can be referred.

The heat transfer rate resulting from evaporation is provided in equation (3.21)

$$\dot{q}_{ew}=\left[h_{ewgE}(T_w-T_{gE})+h_{ewgW}(T_w-T_{gW})+h_{ewgS}(T_w-T_{gS})+h_{ewgN}(T_w-T_{gN})\right]\left(\frac{A_b}{4}\right) \tag{3.21}$$

The hourly freshwater yield by NETC-CSS is as follows:

$$Hourly\ freshwater\ yield=\frac{\dot{q}_{ew}\times 3600}{(Latent\ heat)} \tag{3.22}$$

3.2.1 Experimental Validation

Kumar et al. (2024) did experimentation with passive conical solar still for the climatic condition of Greater Noida, India. The conical passive solar still was fabricated and collection of data was done on 13th March 2024. The experimental data was compared with analytical predictions, showing a reasonable degree of agreement between the two. This indicates that the theoretical model used for analysis effectively represents the real-world performance of the solar still. Concludingly, statistical performance analysis showed the correlation coefficient values were reported as for water temperature 0.996, for condensing surface temperature 0.992 and for freshwater yield reported as 0.993. These values suggest a strong relationship between experimental and predicted outcomes, confirming the reliability of the model used. The suggested analysis makes use of the same code that was used for the conical solar still portion. Furthermore, Mishra et al. (2017) experimented with evacuated tubular solar collectors arranged in series (N=6) for the climatic condition of Ghaziabad, India. The setup was fabricated, and collection of data was done on 16th March 2016. A strong correlation was observed between analytical and experimental values. Concludingly, at the outlet of 6th collector, the value of correlation coefficient for temperature was reported as 0.981, indicating high agreement and reliability of the model. The same code for the NETC part has been used in the suggested analysis. Hence, the previously validated thermal model for NETC-CSS has been utilized in the present analysis.

3.3. Analysis

The environmental conditions considered for different months to identify the efficiency of the NETC based CSS are presented in Table 3.2. These conditions are aligned with previously used study by Singh and Tiwari (2004). Therefore, present relation shows S as the duration of sunlight while γ presents the diffuse radiation of the relative fraction compared to the total global radiation incident throughout the day.

Table 3.2: Description of climatic conditions in a year for New Delhi

Type of climatic situation	Description	Remarks
a_1	Clear day (blue sky)	$\gamma \leq 0.25$ and $S \geq 9\,h$
b_1	Hazy day (fully)	$0.25 \leq \gamma \leq 0.50$ and $7\,h \leq S \leq 9\,h$
c_1	Hazy and cloudy (partially)	$0.50 \leq \gamma \leq 0.75$ and $5\,h \leq S \leq 7\,h$
d_1	Cloudy day (fully)	$\gamma \geq 0.75$ and $S \leq 5\,h$

3.3.1 Exergy analysis

The exergy study is important to evaluate the maximum useful energy of NETC-CSS. The exergy is based on the second law of thermodynamics. Exergy gain on an hourly basis from the NETC-CSS is determined as described below (Nag 2004):

$$\dot{E}x_{hourly} = h_{ewgE} \times \frac{A_b}{4} \times \left[\left(T_w - T_{gE}\right) - (T_a + 273) \times ln\frac{(T_w+273)}{(T_{gE}+273)}\right] + h_{ewgW} \times \frac{A_b}{4} \times \left[\left(T_w - T_{gW}\right) - (T_a + 273) \times ln\frac{(T_w+273)}{(T_{gW}+273)}\right] + h_{ewgS} \times \frac{A_b}{4} \times \left[\left(T_w - T_{gS}\right) - (T_a + 273) \times ln\frac{(T_w+273)}{(T_{gS}+273)}\right] + h_{ewgN} \times \frac{A_b}{4} \times \left[\left(T_w - T_{gN}\right) - (T_a + 273) \times ln\frac{(T_w+273)}{(T_{gN}+273)}\right] \quad (3.23)$$

Daily exergy output for weather type 'a1' is evaluated by summing up the hourly values over a 24-hour period. Following the same approach, was utilized to study the gain in exergy per day for weather condition for type c_1, b_1, and d_1. In the next step, to find out the exergy gain for weather type 'a1' for a complete month, the daily gain in exergy for type 'a_1' will be summed up for a whole month. In the same manner the per month gain in exergy for remaining weather conditions type c_1, d_1, and b_1 can be find out. To compute the monthly gain in exergy in total, the gain in exergy per month for type all four weather conditions a_1, b_1, c_1, and d_1 will be added. For a complete year, the gain in exergy for NETC-CSS will be found by the addition of per month gain in exergy for a total of 12 months.

3.3.2 Energy analysis

It will be possible to examine energy in NETC-CSS by applying the first thermodynamic law. To determine the per hour energy, equation (3.24) will be applied.

$$Hourly\ energy = \frac{(Hourly\ freshwater\ output)\times(Latent\ heat)}{3600} \tag{3.24}$$

A similar approach to that used for annual exergy calculation will be adopted to evaluate the annual energy.

3.3.3 Efficiency analysis for NETC-CSS

A very important aspect of solar still is the time, material, energy consumed during the operation and before it (during the time of installation) which is also to be reduced. Meanwhile, the yield of fresh water is to be increased. Efficiency also represents how effectively the resources are utilized without leaving any waste that harms the atmosphere. The analysis of thermal efficiency was performed in accordance with the first thermodynamics law while the second thermodynamics law was implemented to examine the exergy efficiency. The various types of efficiencies evaluated for the considered case of NETC-CSS is as follows:

3.3.3.1 Thermal efficiency (η_{therm}) for NETC-CSS

The value of η_{therm} on hourly, daily and yearly basis for NETC-CSS can be estimated as follows:

$$\eta_{thermal,hourly,NETC-CSS} = \frac{\frac{((Hourly\ freshwater\ output)\times(Latent\ heat))}{3600}}{((Basin\ area)\times(Hourly\ solar\ intensity))+Hourly\ pump\ work} \times 100 \quad (3.25)$$

$$\eta_{thermal,daily,NETC-CSS} = \frac{\frac{((Daily\ freshwater\ output)\times(Latent\ heat))}{3600}}{((Basin\ area)\times(Daily\ solar\ intensity))+Daily\ pump\ work} \times 100 \quad (3.26)$$

$$\eta_{thermal,yearly,NETC-CSS} = \frac{\frac{((Annual\ freshwater\ output)\times(Latent\ heat))}{3600}}{((Basin\ area)\times(Annual\ solar\ intensity))+Annual\ pump\ work} \times 100 \quad (3.27)$$

3.3.3.2 Exergy (η_{exer}) efficiency

The value of η_{exer} on hourly, daily and yearly basis for NETC-CSS can be computed as follows:

$$\eta_{\text{exergy},hourly,NETC-CSS} = \frac{(Hourly\ \text{exergy}\ output)}{[(Basin\ area\times 0.93\times Hourly\ solar\ intensity)+Horly\ pump\ work]} \times 100 \quad (3.28)$$

$$\eta_{\text{exergy},daily,NETC-CSS} = \frac{(Daily\ \text{exergy}\ output)}{[(Basin\ area\times 0.93\times Daily\ solar\ intensity)+Daily\ pump\ work]} \times 100 \quad (3.29)$$

$$\eta_{\text{exergy},yearly,NETC-CSS} = \frac{(yearly\ \text{exergy}\ output)}{[(Basin\ area\times 0.93\times Yearly\ solar\ intensity)+Yearly\ pump\ work]} \times 100 \quad (3.30)$$

The factor 0.933 alters solar energy into the consistent exergy, which can be expressed as [68].

$$Exergy\ input = (Area \times Solar\ intensity)\left[1 - \frac{4}{3}\left(\frac{(Atmospheric\ temperature)}{(Sun\ temperature)}\right) + \frac{1}{3}\left(\frac{(Atmospheric\ temperature)}{(Sun\ temperature)}\right)^4\right] \quad (3.31)$$

3.4. Methodology

The complete steps for identifying the important parameters of NETC-CSS are discussed below:

Step I: The complete data was obtained from the Indian metrological Department situated in Pune (https://imdpune.gov.in/), all the required equations were implemented to estimate the radiation intensity on an inclined surface was given by Liu and Jordan (1960). A mathematical code was developed in the MATLAB software for this purpose.

STEP II: At this stage, multiple temperatures of condensing surface are calculated by using appropriate equations. By applying the equation (3.5), T_{gE} is evaluated. Following the same approach, T_{gW}, T_{gS}, and T_{gN} are calculated using equations (3.6), (3.7), and (3.8) respectively. After that, using equation (3.19), T_w is computed.

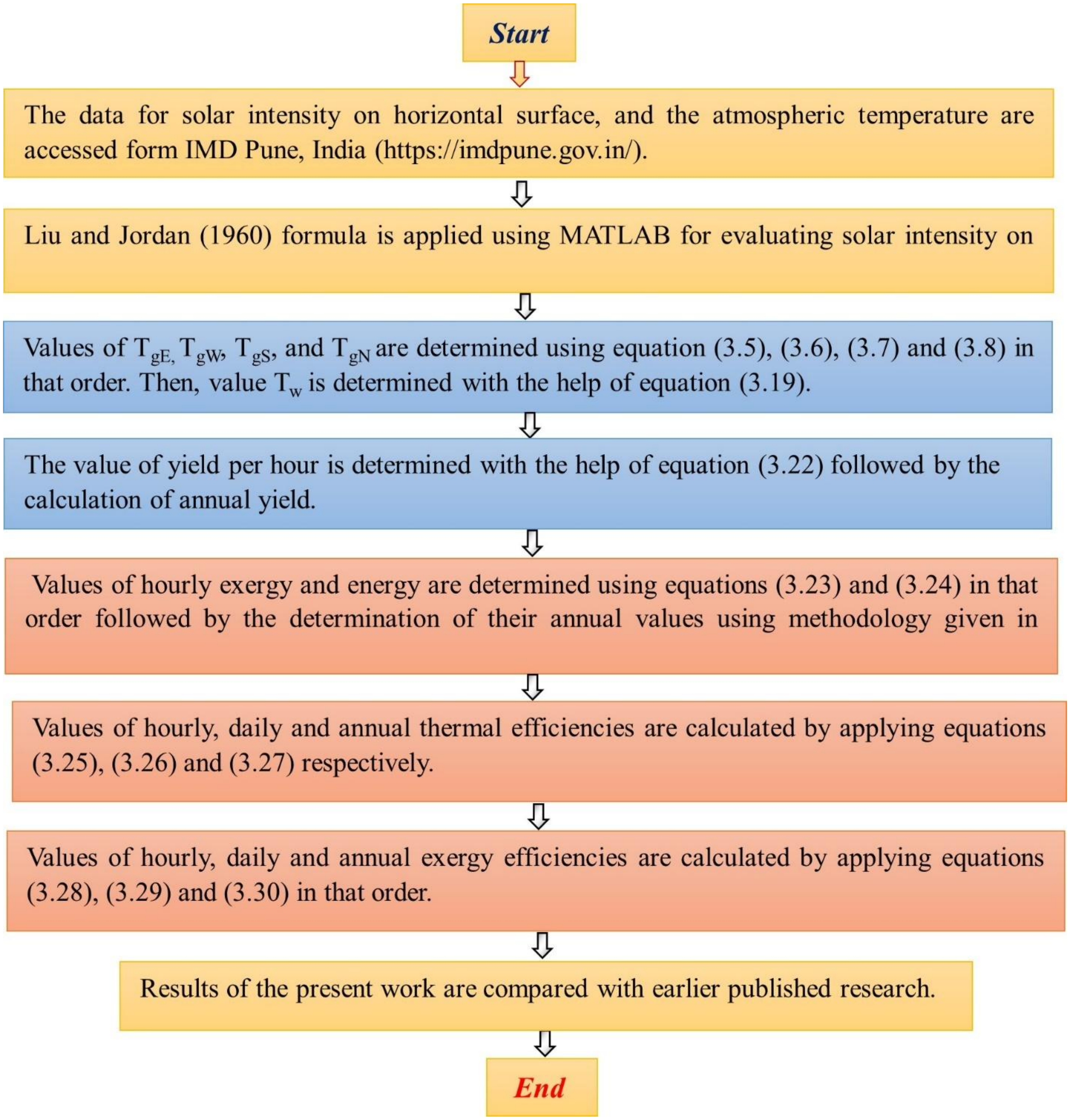

Fig. 3.2: The flow chart representing the methodology followed for the present analysis

Step III: At this point, equations (3.22), (3.23), and (3.24) are employed to determine the production of fresh water, the associated net exergy, and net energy output respectively. This process follows the computation of daily, monthly, and yearly freshwater production, along with the corresponding exergy and energy output.

Step IV: In this step, equations (3.25) to (3.27) are implemented to get various thermal efficiencies. Further, equations (3.28) to (3.30) are implemented for getting various exergy efficiencies.

Step V: Results of NETC-CSS are compared with results of previously documented research considering overall energy, overall exergy and efficiency.

The flow chart representing the computation of performance parameters of NETC-CSS is shown in Fig. 3.2 for better understanding the methodology followed in the present analysis.

3.5 Results and discussion

The representation illustrated in Figs. 3.3 – 3.6 and data represented in Table 3.2 to Table 3.5 are the results of the computations carried out in MATLAB with the required input data, equations, and concept. The analysis was conducted for four different types of weather conditions in a given Calander year. Courtesy to IMD Pune, India, for providing necessary information such as intensity of solar radiation falling on a horizontal plane and temperature of environment. With the valuable information provided by IMD Pune (https://imdpune.gov.in/), India, the data for incident solar radiation on surface which is horizontal was converted to solar radiation falling on the surface which is inclined by implementing formula given by Liu and Jordan (1960).

Fig. 3.3 and 3.4 depict how the highest temperature reached by the fluid at Nth ETC ($T_{foN,max}$) changes in relation to N and mfr for NETC-CSS for an average day in the month of May and

December in that order. By analysing the Fig. 3.3, it can be seen that the boost in mfr above 0.008 kg/s does not have a major impact and the reason of it is the overlapping of curves. The boost in mfr value is noticed and the reason of it is that mfr is directly proportional to the useful heat gain by ETC. Furthermore, it can be seen that the value of $T_{foN,max}$ becomes exceeding 100ºC for $N > 15$. As a result, values of N and mfr are taken as 15 and 0.008 kg/s. It is noticed that these values of N and mfr are significantly valid for the month of December illustrated in Fig. 3.4.

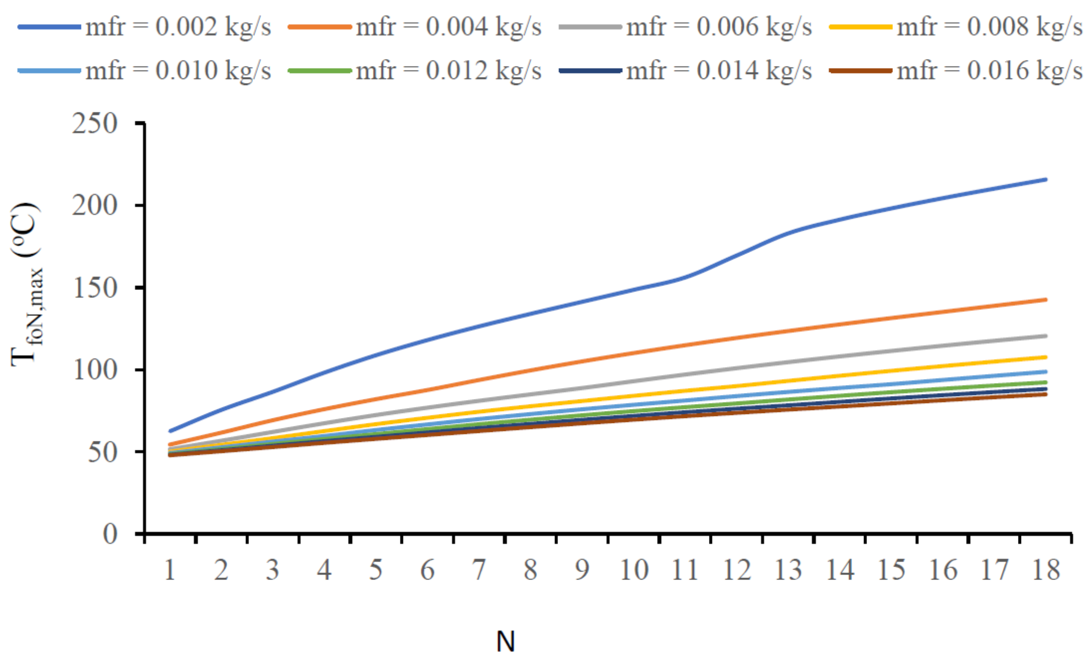

Fig. 3.3: Variation of $T_{foN,max}$ with N and mfr for NETC-CSS for a typical day in May

The hourly alteration in yield of freshwater and the temperatures like temperature of fluid at the exit of Nth ETC, temperature of water, temperature of condensing surfaces and environment temperature are shown in Fig. 3.5. Upon giving a clear observation to Fig. 3.5, As anticipated, the temperature of the water has been found to be higher than that of the condensing surface. This is the difference required to get the freshwater produced from NETC-CSS. Through this analysis, key parameters were assessed by using mean value of intensity of solar radiation and temperature of atmosphere. Also, the change in temperature of water and change in condensing surface temperature with respect to the change in intensity of solar radiation were also evaluated using useful parameters. While the temperature of the basin peaked at around 2:00 pm, the intensity of solar radiation was observed to be at its highest at 12:00 pm. Since water first absorbs solar radiation before beginning to heat up, this phenomenon is evident. The water takes a while to reach its maximum temperature.

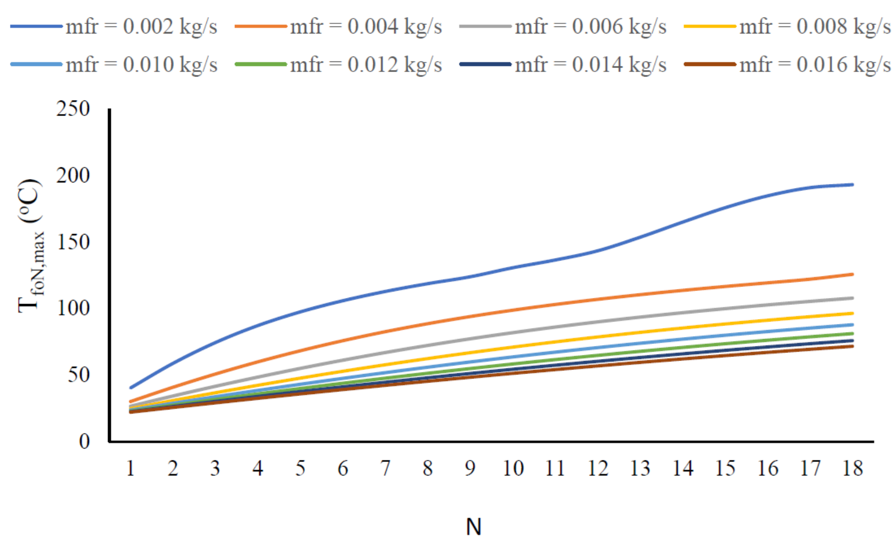

Fig. 3.4: Variation of $T_{foN,max}$ with N and mfr for NETC-CSS for a typical day in December

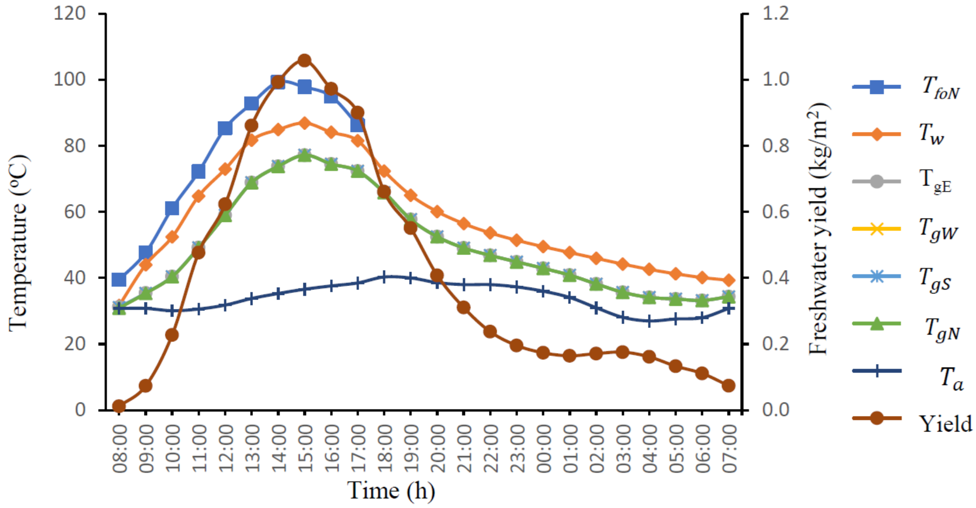

Fig. 3.5: Hourly variation of temperatures and freshwater output for an archetypal day in May for NETC-CSS

From the data tabulated in Table 3.3, the evaluation of freshwater output for the NETC-CSS has been performed. The technique implemented for the analysis has already been represented in the analysis section. It should be mentioned that the output of freshwater is usually at its highest in May, while it is at its lowest in November. In May, the weather tends to be warm and humid, with sunlight lingering for longer durations than in other months of the year. The NETC-CSS receives less heat from the sun due to the winter season in November, which results in a significantly reduced amount of daylight. This lowers the freshwater yield.

Table 3.3: Evaluation of yearly distillate output for NETC-CSS

Month	Type a_1			Type b_1			Type c_1			Type d_1			Monthly yield (kg)
	Daily yield	N	Monthly yield	Daily yield	n	Monthly yield	Daily yield	n	Monthly yield	Daily yield	n	Monthly yield	
Jan	9.61	3	28.83	9.36	8	74.86	5.89	11	64.74	2.89	9	26.02	194.46
Feb	9.90	3	29.70	10.12	4	40.47	6.00	12	71.97	2.77	9	24.97	167.12
Mar	10.33	5	51.67	11.07	6	66.44	8.16	12	97.91	6.88	8	55.01	271.03
Apr	10.39	4	41.58	10.72	7	75.04	8.26	14	115.60	8.39	5	41.94	274.16
May	9.73	4	38.90	9.72	9	87.44	9.10	12	109.14	8.04	6	48.26	283.75
Jun	10.20	3	30.59	10.34	4	41.37	9.33	14	130.56	7.30	9	65.72	268.24
Jul	9.14	2	18.27	9.22	3	27.67	8.19	10	81.90	6.99	17	118.90	246.73
Aug	8.86	2	17.72	9.05	3	27.16	7.78	7	54.49	6.54	19	124.22	223.59
Sep	8.82	7	61.77	8.84	3	26.53	7.75	10	77.53	6.18	10	61.78	227.61
Oct	7.48	5	37.40	7.07	10	70.74	5.92	13	77.00	4.47	3	13.40	198.54
Nov	7.15	6	42.88	6.40	10	64.03	3.78	12	45.30	3.73	2	7.45	159.67
Dec	8.69	3	26.06	8.11	7	56.78	5.78	13	75.19	2.75	8	21.96	180.00
Yearly yield (kg)													**2694.91**

From the data tabulated in Table 3.4, the evaluation of energy output for the NETC-CSS has been performed. The technique implemented for the analysis has already been represented in the analysis section. A significant observation is that the energy output in May is the highest compared to all other months. On the other hand, November is noted to be the month with the lowest levels. This occurs because of the similar variation in value of freshwater yielding. Although the NETC-CSS system produced more freshwater and showed higher exergy efficiency, its overall thermal efficiency (38.79%) was slightly lower than that of conventional passive conical stills. This is because, in the NETC-CSS, some of the solar energy is used to run the evacuated tube collector system instead of directly heating the basin water. So, more energy is used overall but not all of it goes into evaporation. To address this trade-off, the system design can be optimized by increasing heat transfer between collector and basin by using high conductive materials, nanofluids and ensuring proper sealing around joints to prevent air leakage and unnecessary heat escapes.

Table 3.4: Evaluation of yearly energy output from NETC-CSS

Month	Type a_1			Type b_1			Type c_1			Type d_1			Energy per month
	Daily energy	N	Monthly energy	Daily energy	n	Monthly energy	Daily energy	N	Monthly energy	Daily energy	n	Monthly energy	(kWh)
Jan	6.41	3	19.22	6.24	8	49.91	3.92	11	43.16	1.93	9	17.35	129.64
Feb	6.60	3	19.80	6.75	4	26.98	4.00	12	47.98	1.85	9	16.65	111.41
Mar	6.89	5	34.44	7.38	6	44.29	5.44	12	65.27	4.58	8	36.68	180.69
Apr	6.93	4	27.72	7.15	7	50.03	5.50	14	77.07	5.59	5	27.96	182.78
May	6.48	4	25.93	6.48	9	58.29	6.06	12	72.76	5.36	6	32.18	189.17
Jun	6.80	3	20.39	6.89	4	27.58	6.22	14	87.04	4.87	9	43.82	178.83
Jul	6.09	2	12.18	6.15	3	18.45	5.46	10	54.60	4.66	17	79.26	164.49
Aug	5.91	2	11.81	6.04	3	18.11	5.19	7	36.33	4.36	19	82.82	149.06
Sep	5.88	7	41.18	5.89	3	17.68	5.17	10	51.69	4.12	10	41.19	151.74
Oct	4.99	5	24.94	4.72	10	47.16	3.95	13	51.33	2.98	3	8.93	132.36
Nov	4.76	6	28.58	4.27	10	42.69	2.52	12	30.20	2.48	2	4.97	106.45
Dec	5.79	3	17.37	5.41	7	37.86	3.86	13	50.13	1.83	8	14.64	120.00
Yearly energy (kWh)													**1796.61**

Table 3.5: Evaluation of yearly exergy output from NETC-CSS

Month	Type a_1			Type b_1			Type c_1			Type d_1			Exergy per month
	Daily exergy	N	Monthly exergy	Daily exergy	N	Monthly exergy	Daily exergy	N	Monthly exergy	Daily exergy	n	Monthly exergy	(kWh)
Jan	0.79	3	2.37	0.73	8	5.86	0.28	11	3.05	0.08	9	0.76	12.04
Feb	0.86	3	2.57	0.89	4	3.55	0.31	12	3.73	0.09	9	0.81	10.67
Mar	0.86	5	4.29	0.97	6	5.80	0.46	12	5.50	0.35	8	2.76	18.35
Apr	0.81	4	3.24	0.86	7	6.02	0.48	14	6.76	0.50	5	2.50	18.51
May	0.69	4	2.74	0.68	9	6.13	0.60	12	7.22	0.45	6	2.68	18.77
Jun	0.74	3	2.21	0.78	4	3.13	0.62	14	8.75	0.37	9	3.29	17.38
Jul	0.67	2	1.34	0.69	3	2.06	0.53	10	5.31	0.33	17	5.55	14.25
Aug	0.67	2	1.35	0.73	3	2.18	0.51	7	3.59	0.33	19	6.23	13.34
Sep	0.67	7	4.68	0.65	3	1.95	0.51	10	5.11	0.28	10	2.84	14.58
Oct	0.55	5	2.74	0.48	10	4.78	0.32	13	4.11	0.18	3	0.53	12.16
Nov	0.53	6	3.15	0.37	10	3.72	0.15	12	1.81	0.15	2	0.29	8.97
Dec	0.71	3	2.12	0.59	7	4.13	0.32	13	4.15	0.10	8	0.77	11.16
Yearly exergy (kWh)													**170.19**

From the data tabulated in Table 3.5, the evaluation of exergy output for the NETC-CSS has been performed. The technique implemented for the analysis has already been represented in the analysis section. Significantly, throughout May, the exergy output reaches its peak in comparison to other months, and it is noted to be minimum in the month of November. May is generally marked by high temperatures and humidity, making it one of the warmest months of the year. The prolonged presence of sunlight during this period ensures a continuous and substantial influx of solar energy, which enhances heat absorption and energy generation in solar-based systems like the NETC-CSS. This extended solar availability contributes to increased thermal efficiency and higher exergy output. Conversely, November experiences colder temperatures due to the winter season, leading to shorter daylight hours and a diminished intensity of solar radiation. This reduction in solar exposure directly impacts the heat supply to solar thermal systems, including the NETC-CSS. As a result, the system receives less thermal energy, leading to a lower exergy output. The seasonal variation in solar radiation highlights the importance of optimizing system performance by incorporating thermal storage solutions or alternative energy sources to compensate for reduced efficiency during winter months.

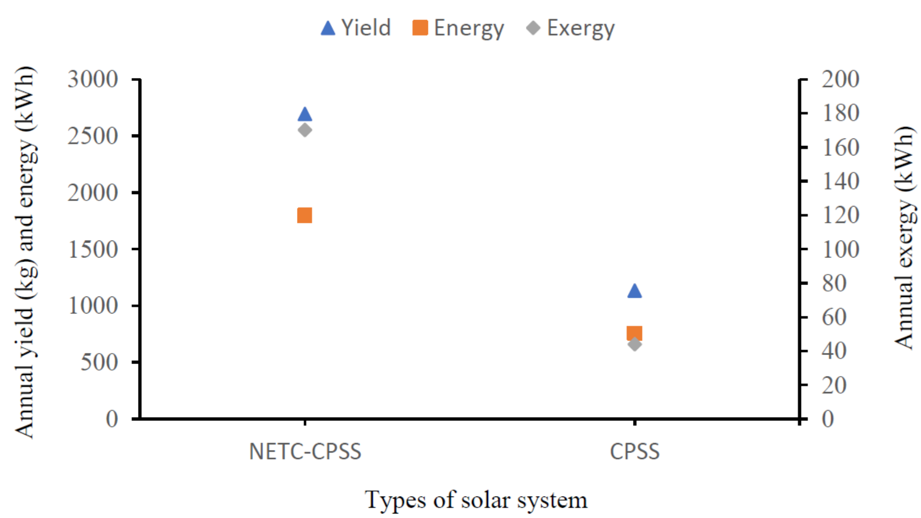

Fig. 3.6: Comparison of NETC-CSS with CPSS by incorporating yield, energy and exergy

The comparative analysis of results of NETC-CSS with previously documented results of CPSS by incorporating freshwater yield, annual energy and annual exergy are rendered as Fig. 3.6. It is seen that the value of freshwater yield, annual energy and annual exergy for NETC-CSS are higher by 57.94%, 57.94% and 74.14% in that order. The freshwater yield, annual energy and annual exergy are higher for NETC-CSS than CPSS because NETCs present in NETC-CSS provides heat to the basin. Further, the percentage increase in exergy is higher because heat is accessible at elevated temperatures in situations where the case of NETC-CSS is more than the temperature of heat in CPSS because collectors provide heat which raises the temperature.

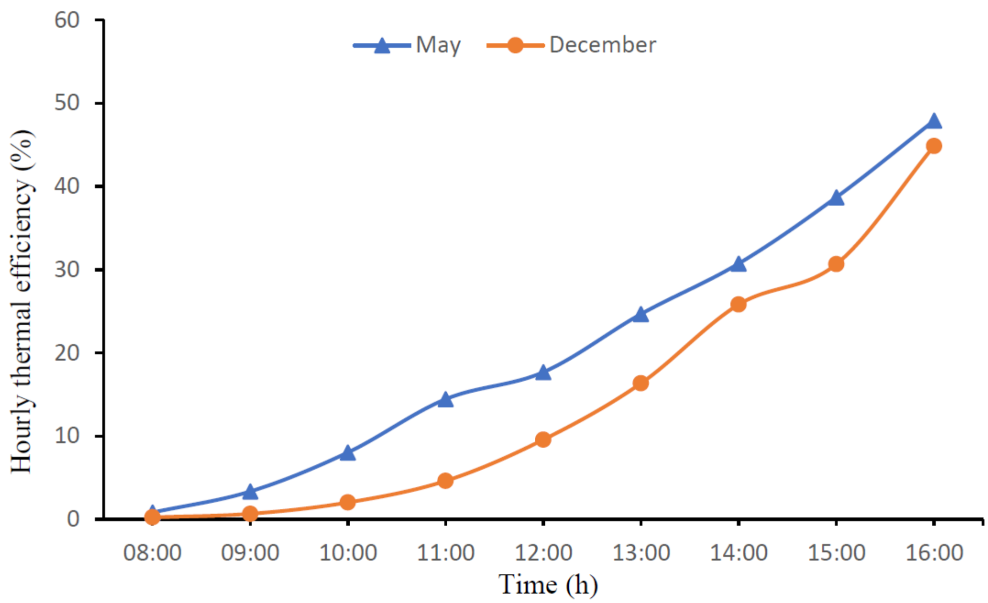

Fig. 3.7: Variation of hourly thermal efficiency for NETC-CSS considering a typical day of May

The variation of hourly thermal and exergy efficiencies of NETC-CSS is shown in Figs. 3.7 and 3.8 in that order. The values of both thermal and exergy efficiencies are higher for May than their corresponding values in December. It occurs because heat is available at higher temperature in May. Further, exergy efficiency is much lower than thermal efficacies. Due to exergy's representation of energy's quality, its value is often substantially lower than that of energy. Value of daily thermal efficiency is computed using equation (3.26). Its value is obtained as 38.48% for an archetypal day in May and 37.69% for an archetypal day in December. Further, Value of daily exergy efficiency is computed using equation (3.29). Its value is obtained as

4.09% for an archetypal day in May and 3.76% for an archetypal day in December. Values of thermal and exergy efficiencies are higher for May than their corresponding values in December most likely because of fact that heat is available at elevated temperature in May.

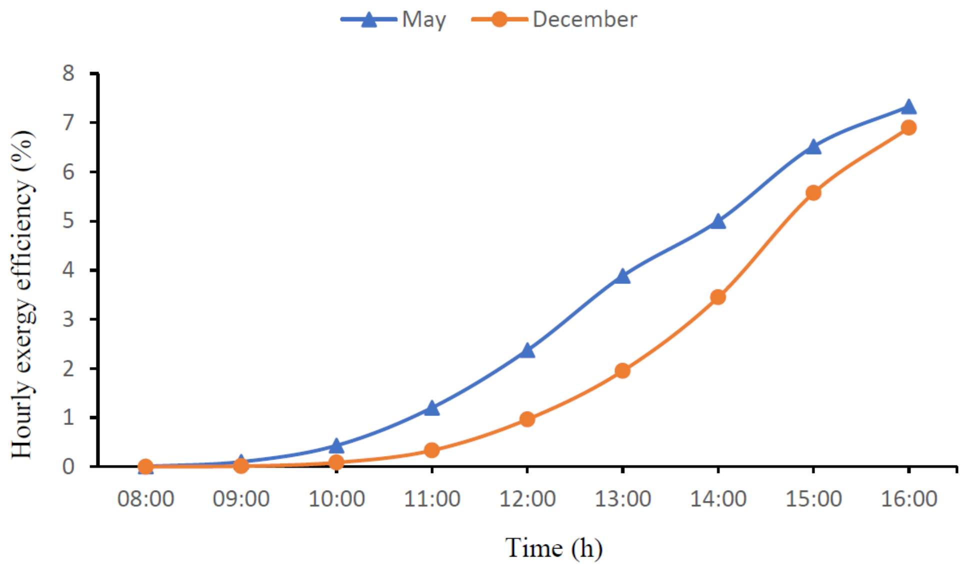

Fig. 3.8: Variation of hourly exergy efficiency for NETC-CSS considering a typical day of May

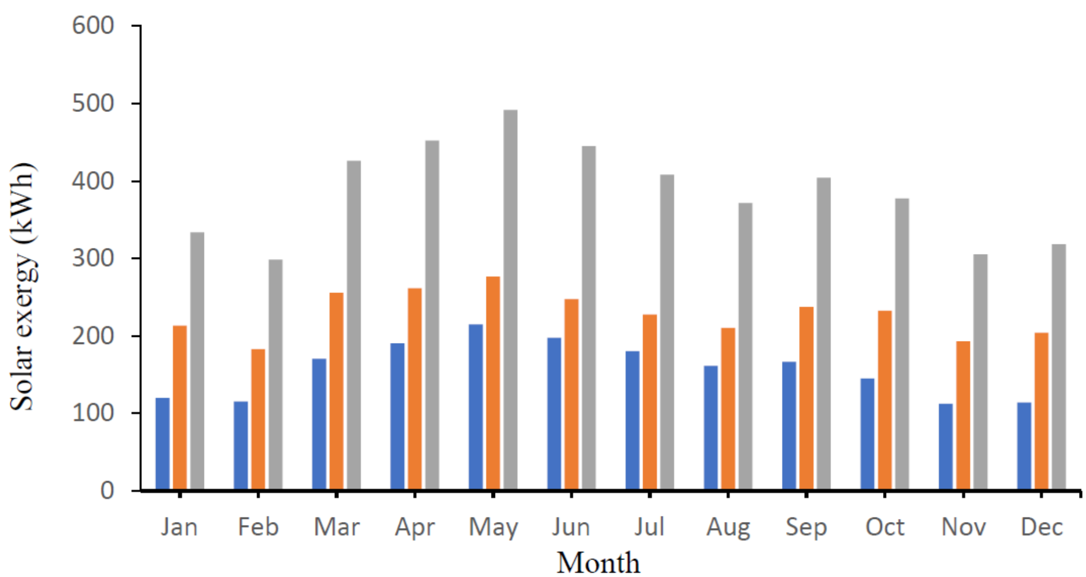

Fig. 3.9: Monthly distribution of solar energy falling on the system

The distribution of monthly solar energy falling on the system is shown in Fig. 3.9. The value of corresponding exergy coming to the system can be evaluated by multiplying the solar energy falling on the system with 0.933 (Petela 2003). Further, annual thermal and the value of exergy efficiencies are computed with the help of equations (3.27) and (3.30) respectively. Table 3.6 presents the computation of exergy efficiencies and annual thermal for NETC-CSS. Annual thermal efficiency and exergy efficiency values for NETC-CSS are obtained as 38.79% and 3.94% respectively.

Table 3.6: Computation of yearly thermal and exergy efficiencies for NETC-CSS

Parameter	Value
Annual energy output (kWh)	1796.61
Annual solar energy falling on the system (kWh)	4631.42
Annual thermal efficiency (%)	38.79
Annual energy output (kWh)	170.19
Annual solar energy falling on the system (kWh)	4321.12
Annual exergy efficiency (%)	3.94

The comparison of results of present system with earlier published research is shown in Table 3.7 considering yearly energy, exergy, thermal efficiency and exergy efficiency. It is observed form Table 3.7 that values of overall energy, exergy and exergy efficiency are higher for NETC-CSS than corresponding values for CPSS because heat is provided to the basin by NETCs. Further, thermal efficiency is lower because thermal efficiency of NETC-CSS depends on thermal efficiencies of both CSS and NETCs. That can be further observed that values of annual energy, thermal efficiency and exergy efficiency are higher for NETC-CSS than other solar stills under consideration probably because the shading effect is less as for NETC-CSS when compared with other solar stills. However, annual exergy output of NETC-CSS is higher in contrast to alternative solar stills under consideration except PTC-SS, PTC-SS with wire mesh in the basin and PTC-SS with sand in the basin. The highest rise in annual energy, annual exergy, thermal efficiency and exergy efficiency for NETC-CSS is 68.03% than the modified single slope SS, 74.14% than CPSS, 61.12% than the modified single slope SS, and 72.59% than PTC-SS respectively.

Table 3.7: Comparison of results with earlier published research considering yearly energy exergy and efficiency

System	Energy (kWh)	Exergy (kWh)	Thermal efficiency (%)	Exergy efficiency (%)
ETC-CSS (Present system)	1796.61	170.19	38.79	3.94
CSS (Singh et al. 2023, 2024)	755.71	44.01	40.02	2.5
Solar still coupled with parabolic trough collector (PTC-SS) (Hassan et al. (2020)	1527.04	233.94	21.53	1.08
Solar still with wire mess in the basin (Hassan et al. (2020)	1602.30	102.00	34.76	1.42
PTC-SS with wire mesh in the basin (Hassan et al. (2020)	861.00	264.57	22.31	1.19
SS with sand in the basin (Hassan et al. (2020)	931.00	111.11	38.27	1.58
PTC-SS with sand in the basin (Hassan et al. (2020)	1728.79	295.47	24.13	1.33
Modified single slope SS (Pal et al. 2021)	574.37	72.96	15.08	1.76
Modified double slope SS (Pal et al. 2021)	1034.32	66.32	17.48	1.16
Modified single slope multiwick SS (Pal et al. 2021)	781.35	100.70	23.93%	2.58
Modified double slope multiwick SS (Pal et al. 2021)	1722.66	97.36	28.78%	2.23

3.6 Conclusions

Fundamental equations are derived for NETC-CSS followed by the computation of performance parameters using MATLAB code. Outcomes of NETC-CSS are compared with results of past documented research considering annual energy, exergy, thermal efficiency as well as exergy efficiency. Based on the analysis, conclusions are drawn which can be summarized in the following manner:

i. Annual freshwater generation, energy, exergy, thermal efficiency and exergy efficiency for NETC-CSS are computed to be 2694.91 kg, 1796.61kWh and 170.19 kWh, 38.79% and 3.94% respectively.

ii. Annual freshwater yield, energy, exergy and exergy efficiency are higher respectively by 57.94%, 57.94%, 74.14% and 36.55% for NETC-CSS than CPSS. However, the thermal efficiency for NETC-CSS is lower by 3.12% than CPSS.

iii. May and November have the highest and lowest monthly yield values, respectively. The hourly thermal and exergy efficiencies of the suggested system are greater in May among all the months. The hourly exergy efficiency is significantly reduced compared to the hourly thermal efficiency.

iv. A comparative analysis of results of present system with previously documented research represents that the increase in annual exergy, energy, thermal efficiency and exergy efficiency is 68.03% than modified solar still, 74.14% than conventional conical solar still, 61.12% than modified solar still and 72.59% than solar still with parabolic trough collector.

Some limitations are there as revealed in assumptions. These limitations may cause small variation in results, but they do not affect the overall conclusions.

CHAPTER - IV

Exergo-enviro-economic analysis of NETC-CSS

4.1 Introduction

Harnessing solar energy for freshwater generation presents a sustainable approach to addressing the global water scarcity issue, aligning with the United Nations' sustainable development objectives. While recent studies have investigated conical solar stills, the potential of active conical solar distillers remains largely unexplored. Additionally, conical solar distillation units exhibit a reduced shading effect compared to other designs, serving as the primary motivation for this study. This chapter emphasizes exergo-economic and enviro-economic assessment, productivity evaluation, fresh distilled water cost estimation, and analysis of payback period for a conical shape solar distillation unit that is integrated with N identical evacuated tubular solar collectors (NETC-CSS) under optimized conditions. Core thermodynamic equations are formulated and implemented in MATLAB, utilizing relevant supporting data. The NETC-CSS outcomes are cross-validated for N = 0, with existing experimental findings. The study performed for time spans of full year, experiencing all four seasonal variations across each month for the latitude of New Delhi. In this regard, the exergy output per unit currency, annual efficiency, payback period and fresh distilled water cost are determined as 0.841 kWh/₹, 630.80%, 4.03 years and ₹ 0.79 per kg, respectively. The rate of interest is assumed flat 2% over the operational period of 30-year. Additionally, a significant improvement in the enviro-economic factor of 84.30 % is observed for NETC-CSS. Moreover, the fresh water yield is reduced by 81.10 % compared to modified water-cooled solar stills and dish-integrated solar stills, respectively.

The shortage of water can be seen in many places of the both developed and developing countries. From Japan to U.S.A. and Antarctica to Arctic, this problem is felt by everyone. Whether talk about urban or rural, hilly area or planes, shortage or water is prime concern that revolve around like a minute hand of a clock. It is the greatest concern of the life of the mankind that has been tried many times by many ways to resolve but did not get complete success. This shortage of water is not new but existed since the initial phase of development of mankind. The issue of shortage of drinking water has been gradually becoming a cacogenic for the population as it directly connects with the health of human. This issue is further exacerbated by rapid population growth and improper water management in the recent past decades. Although, Earth surface covers approximately ¾ of water bodies in their entire area. However, the fresh water is limited only less than 1 % of total water content. Contrary to this, saline water is plenty but due to high salinity it cannot be drinkable until found purified. Population of many arid areas are forcefully drinking saline water as they are left with no choice. Systems of Purification of saline water was installed in such areas but it failed after sometime due to unavailability of funds. Thus, a need was arisen to develop a feasible and low-cost saline water purification technique. So many such techniques are introduced to treat the saline or impure water. Negi et al. (2025) discusses several techniques in their study, they highlighted solar distillation, as it has attracted particular interest due to its sustainable nature. It utilizes solar radiation, a freely available energy source which contributes to lowering the overall carbon footprint (Negi et al. 2024). Literature (Negi et al. 2022, 2025a) has suggested utilization of organic PCM and collectors are the cost-effective modifications to increase the overall yield of the system while significantly mitigating the carbon footprint.

Additionally, geometry and additional modification of CSS should be simple and have low maintenance compared to other designs. However, the distillate yield obtained by using SSSS is low. So various researchers have made various efforts to overcome this limitation by providing technical modification to the existing solar still. For instance, other designs were developed such as pyramid solar distiller (PSD), double slope solar still (DSSS), stepped solar still (SSS), conical-shaped solar still (CSSS), inclined solar still (ISS) and so on which results in higher distillate yield compared to SSSS. Various literatures have integrated various thermal collectors including flat plate collectors (FPC), evacuated tube collectors (ETC), parabolic trough collectors (PTC) and solar ponds to enhance the yield efficacy of the solar still (Singh 2013).

Examining solar distillation system is essential for tackling the issue of freshwater shortage in isolated regions that receive ample sunlight but lack clean water sources. The studies dealt with various research relevant to water distillation confirms a sustainable and renewable solution because the energy source is Sun. Moreover, no trace of harmful substance is present during the working of solar distillation and hence the development of ecological system can be achieved. The solar stills are broadly classified as - Passive Solar Still (PSS) and Active Solar Still (ASS). One can convert passive into active. A passive solar distillation unit becomes an active variant when supplemented with an external source of heat. To bridge the gap between water scarcity challenges and practical solutions, exploring advanced solar distillation methods becomes necessary. The following discussion delves into the types and enhancements of solar distillation systems, with a focus on the role of ETC in improving efficiency and output.

Alwan et al. [6] improved the performance of a CSS through a rotating hollow cylinder and ETC placed inside the still to increase the evaporation surface area. Three rotation speeds were identified and tested 0.5, 1, and 3 rpm and the best results were found at the slowest speed of 0.5

rpm. In the second stage, an external solar collector was added to raise the water temperature in the basin. This combination significantly improved the system's efficiency, with the modified solar still (MSS) producing 5.5 L/m² of freshwater compared to just 1.4 L/m² from the traditional design. Overall, the productivity increased by 292%, and the cost of producing 1 liter of water slightly decreased to $0.048 for the MSS versus $0.049 for the TSS, showing both higher output and better cost-effectiveness. Furthermore, it has been investigated that the integration of ETC enhances heat transfer to the solar still basin by eliminating convective heat loss, allowing only radiative heat dissipation. In contrast, other collector types experience both radiative as well as convective heat losses. In this regard, Shafii et al. (2016), experimentally investigated the operational functionality and performance of a newly developed solar still. The still was additionally modified with ETC as well as thermoelectric modules. In their study, latent heat of vapor is converted into electric energy by using thermoelectric modules. Thermoelectric modules were used to produce electricity by using temperature difference between two reservoirs. Electrical energy generated by module was used to run a low wattage propeller fan. This propeller fan was used to induced the forced convection. It has been reported that forced convection increases the hourly efficiency of system and water yield. Moreover, the effect of water inside the ETC was also investigated and results showed that maintaining fully filled ETC enhances the system's efficiency, making a substantial enhancement in output performance. Sharshir et al. (2016) examined continuous solar distillation units equipped with evacuated heaters along with a humidification-dehumidification mechanism. Their study reported a gain output ratio 39% greater than that of regular solar distillation units.

Singh (2017) introduced an improved double slope solar still (DSSS) aimed at enhancing both economic and environmental performance. The system integrates multiple photovoltaic thermal

(PVT) collectors, which are partially covered and designed to be identical. Upon comparing the design of solar still that is used conventionally, the set up develop in that study found to work in enhanced manner as far as exergy of the system is concerned and also the hazardous effect to the environment. Similar to the previous one as discussed lately, both single and double type of solar stills were examined by Singh and Tiwari (2017) having incorporation with ETCs. Similar types of many ETCs were installed in the system design in order to increase the efficiency. The reported results indicated that output of energy per year experience a jump of 6.85 % while the exergy per year of the system shoot up by 12.30 %. The most influential finding reported in the study was the cost for the production of pure water which was reduced by a significant amount of 15.19 %. The findings suggested that design of solar still working on given parameters can be promoted for commercial application provided the environmental condition must with inclined with the condition of New Delhi. Singh and Al-Helal (2018) carried out a theoretical analysis of a dual slope solar distillation unit.

The condition selected to carry out the analysis was similar to the condition of New Delhi. To project the analysis for a complete year, 4 types of conditions of weather were taken into consideration. For the analysis part, the designed unit for the distillation of water was incorporated with ETC having N in numbers. It was mentioned in the study that the incorporated ETCs were all similar in dimensions and physical properties. A comparative study of dual slope unit equipped with N identical ETC had done with dual slope unit with FPC and traditional unit. Comparative study revealed that N-ETC-DS performed better than other two units. Singh (2018) investigated for the selected type of solar distillation units coupled with identical ETC. The primary focus of the study was on evaluating energy performance indicators, particularly the energy payback time (EPBT). The findings reported in the study were noteworthy when compared with the previously reported findings. The system which was incorporated with ETC exhibit very short EPBT when compare to the EPBT of the system that contained collector arranged alternatively. When a cross examination was conducted for the shorter EPBT for ETC case it was come to know that ETCs are exposed with very less dissipation of heat by the means of convection that consequently resulted in the overall enhancement of the thermal efficiency. Since, the heat which is to be dissipated to the environment can be controlled and utilized to provide addition heat to the system leading to ultimate increase in the output of the system. Systems of solar desalination containing different nano fluids and the systems which does not contain any of the nano fluids were examined by Singh et al. (2018, 2019). Extending the previous work that has been done separately on ETC and nanofluids, a solar desalination system having shape of pyramid containing ETC as well nano fluids were analysed by Sharshir et al. (2019). The effect of utilization of both ETC and nano fluids together to the systems was reported to be excellent as the amount of fresh water produced by the proposed system was 4.77 % higher when compared to the production of fresh water by the conventional system design.

Increasing the number of collectors in any type of SS is not always beneficial with respect to the economy and also environment. In this regard various research has been reported to optimize the installed number of collectors and the cost related to it. To follow it, an examination was carried out Kumar et al. (2020) to check the effect of increasing N on the energy output, economic analysis, and environmental effect of the designed system. The study consisted of the development of a MATLAB code under the real and physical condition. The reported findings not only help in optimizing the N and incurred cost but also pave the way for maintaining a balance between the energy input-output and environmental energy trade off. The incorporation of stones made of calcium in the system of solar desalination along with installation of ET in order to assess the yield of fresh water, a study was carried out by Panchal et al. (2020). The results as obtained in the analysis has been highly influential for the bench marking of the potential use of stone particle for yield enhancement. The analysis also found out that an increase in the yield of fresh water upto 113.52 % can be achieved for the proposed design when compared to the yield of CSS. Overall increase in the yield of the system is mainly because of the utilization of ET. The reason behind this obtained improvement in the yield is solely credited to the incorporation of ET which absorb and later transfer heat to the stone of calcium and that heat is then stored in the form of energy storage material.

Several analytical studies have been carried out for the case of Solar desalination of double type incorporated with concentrator having shape of parabola installed with ETC. In this prospect, a model for the said design was developed by Sharma et al. (2020) and named it NPCETCDS. The model was designed to assess the effect of dynamics of energy and the same model was designed in such as way that it can be performed in NETCDS and PDS also. Upon carrying out modelling for all the said design, it was come to knowledge that NPCETCDS has been proven to be advantageous with respect to NETCDS and PDS by a noteworthy margin of 46.18 % and 56.99 % respectively. Also, the enhancement in the exergy on daily basis was also found to be higher for the case of NPCETCDS as compared to the exergy on daily basis of NETCDS and PDS by an amount of 81.17 % and 92.25 % respectively. The findings in the form of yield enhancement and exergy analysis suggested the importance of NPCETCDS for making solar distillation more effective as a water desalination system. The utilization of fins, ETC, and a condenser in a unit of desalination of water by solar energy was performed by Mevada et al. (2021). The novelty of the study lies in the fact that the outcomes were fascinating and highly influential for the upcoming studies related to the modified solar still. Also, the production of fresh water was noteworthy higher by a margin of 73.45 % when compared to the CSS. The ability of fins to store high amount of heat can be assumed as one of the major factors behind the improvement of distillate yield thus enabling the system to effectively clean the impure water at a reasonable cost. Researchers are also implementing novel approaches to treat impure water in an effective manner. One of the novel approaches was adapted by Sadeghi and Nazari (2021) in which utilization of hybrid nano fluid that can have magnetic properties was performed. The outcomes conclude that installation of thermoelectric cooler to make the solar still modified and also having ETC incorporated with them will be highly beneficial in increasing the distillate yield of solar still. By adding $Ag@Fe_3O_4$ nanoparticles at a 0.08% concentration, freshwater production increased by 218%, and 117 % improvement in the energy efficiency. Additionally, the cost analysis suggested that the proposed system is economic and having a freshwater production cost of 0.019$/L/m^2$ and a PBP of 369 days. This innovation not only boosts efficiency but also helps prevent bacterial contamination, making it a promising solution for clean water production.

Dawood et al. (2020) analyzed a solar distillation unit that was equipped with a parabolic concentrator, identical ETC. The receiver tube also attached and phase change material (PCM) within it. Their study demonstrated that the cost of fresh distilled water generation from this unit was 29.87% lower than that of a regular used traditional solar distillation unit. This reduction was associated to the PCM's ability to retain and release heat, ensuring continuous thermal energy supply to the basin even at night. Furthermore, a sensitivity analysis of the active solar distiller was conducted, revealing insights beneficial for designers and installers by providing information on how various parameters influence system performance (Prasad et al. 2019, Singh 2021, Raturi et al. 2021, 2021a, Singh et al. 2022).

Singh et al. (2021) study evaluates the performance of a CSS integrated with ETC, focusing on energy and environmental metrics. The system demonstrates strong potential with an embodied energy of 1138.52 kWh, daily freshwater output of 3.8 L/m², and an estimated 77.2 tons of carbon mitigation over a 30-year lifespan. It also achieves a carbon credit of $771.23, an energy payback time of just 0.68 years, and a life cycle conversion efficiency of 0.34, indicating both environmental and economic viability.

Sharshir et al. (2022) experimentally investigated a pyramid shaped solar distillation unit and demonstrated significant improvements in the performance of a pyramid shaped solar distillation unit by incorporating various other attachments like evacuated tubes, an external condenser, ultrasonic foggers and nanoparticles. The pyramid shape increases the surface area open to sunlight, due to this there is improvement in the evaporation. The enclosed structure reduces heat loss, maintaining higher temperatures for longer. The modified system (MPSS) produced much higher freshwater output, energy efficiency, and exergy efficiency compared to the regularly used traditional pyramid shaped solar still (CPSS). The addition of carbon black nanoparticles and ultrasonic foggers further boosted these enhancements, with freshwater output increasing by up to 162.15%. After performing an analysis economically, it can be noted that the CPL of fresh distilled water could be reduced by 32.04%, making the system more cost-effective. Although the highest CO_2 emissions recorded were 1.379 tons per year, the proposed modifications remain environmentally and economically viable, making them a promising approach for sustainable water desalination. Moghadam and Samimi (2022) studied a basin type solar distillation unit utilizing an evacuated tubular collector and concluded that the most critical factor influencing freshwater production was the enhancement of the condenser's specific surface area.

Gangavathi et al. (2022) highlighted the complementary benefits of using condensing glass that was nano-coated hydrophobic and ETC to enhance the performance of a single sloped solar still unit (SSS). The experimental results demonstrated that integrating both modifications led to a 28.53% increase in fresh distilled water production when it was compared with a CSS, while the still with only nano-coated glass showed a 15.49% improvement. Hence, by analyzing the obtained results, it is obvious that combination of ETCs and nano coating is highly recommended for the upsurge of efficiency of SS marking a revolution in the field of desalination to seek improved performance in the upcoming research. The concept of multi effect has been gaining attention from all corners of research fraternity. In this regard a multi effect solar still MESS was developed and examine by Gopi et al. (2022) to calculate the yield of fresh water, ratio of output gained (GOR) and obtained efficiency and made a comparison of with The CSS on the basis of said parameters. The process of conserving heat at every stage of all the stages have brought significant save in overall loss of energy. By providing or producing an overall yield of 28.625 kg/m^3 and GOR of 2.84, this modification has the ability to enhance the efficiency of already existed system. This MESS has ability to deliver an efficiency of 87.35 % and suitable to arid area where access to pure water is very limited. One of the important findings that come to the knowledge is that exceeding the number of collector after a certain limit does not help in the enhancement of efficiency but participate in deceasing the same. If the level of water level is at lower side, then it can be suggested that large evaporation area will be required. While on the other hand if the basin area is small then higher rate of evaporation is expected because of the effective utilization of exergy. Yield, GOR, and efficiency were reported by the author as 8.6 kg/m^2, 3.36, and 109.01% respectively. The condition at basin were as follows: area of basin was taken as 0.56 m^2 and the mass was water was taken as 2 kg. This is to be precisely noted that exergy efficiency at highest was found to be 10.09 % but in this case the basin area was kept at 0.16 m^2 but having same amount of mass of water. From the results analysis it can be clearly conclude that this technique is highly beneficial for the optimizing the input parameter to obtain high yield.

To examine novel type of solar desalination system having equipped with ETC to assess the impact of mass of water on the yield output of Solar still, an analysis was carried out by Kumar et al. (2022). In the result output influential findings were reported in which depth of water is focused primarily. Optimization was carried out and found that 0.56 m is the optimum depth at which the efficiency becomes maximum. This happened due to the balance that maintain between the rate of evaporation and the absorption that occurs thermally.

In order to achieve very high efficiency from the solar still along with obtaining high productivity from the system, a solar desalination system was modified with a single slope to examine the said parameters by Farghaly at al. (2023). The coupling of ETC was also performed on the solar still in hope of increasing the temperature of water present in the basin. In order to expose the reflectors in much greater way so that ETC can receive high amount of radiation, some tough reflectors were installed to it which are having shape of parabola. As obtained in the analysis, the results suggested that productivity was enhanced by 82.26 % due to the integration of ETC. On the other hand, when combining these two modifications then the efficiency was further enhanced by 112.57 %. Upon carrying out cost analysis it was come to the knowledge that both production cost and performance have been improved that signifies the efficacy of the modification in solar still.

An improved version of solar distillation having shape of hemisphere and also coupled with ETC was studied by Dahab et al. (2023). The basis fundamental of hemispherical SS is doomed to be covered with a glass of dome shape that receive energy falling into it from the Sun and utilize it for purifying the impure water. The effect of green house was applied on HSS that results in evaporation of water that converts it into desalinated water or without any contamination. Upon examining the HSS it was found that HSS had produced efficient productivity with a margin of 47.3 % when compared with the output of CSS. Since the HSS was coupled with ETC which provides additional energy to the system required for the evaporation and thus results in higher productivity. The formation of vacuum and installation of insulation were also the reason behind the higher productivity for the case of HSS. Insulation leads to attainment of high temperature and thus more evaporation takes place. The retention of high temperature can also be observed during the oncourse of the complete cycle. In the area of carbon foot print, Nagpal and Singh (2023) investigated system of solar desalination having double slope and containing ETC. It was reported that the footprint of carbon got shoot up by 16.57 % the system was equipped with concentrator ETC rather than equipping it with single ETC. Having said that many times earlier in this discussion, this analysis also gets benefited by the effective combination of concentrator ETC and evacuated tubes having very high thermal efficiency. The results said itself as the yield of the system increased significantly per unit area of the system. The study concludes that upon utilising solar collectors and evacuated tubes together, a prolific system for purifying impure water can be developed that not only participate for sustainable system but also contributes in maintain environmental balance.

A comparison of cost analysis was performed by Shelake et al. (2023) and Kumar et al. (2021) between active and passive solar still by examining various design of solar still. Factors consider in the studies were productivity of pure water, yield, and cost incurred. Studies have shown that while active solar stills offer higher efficiency and productivity compared to passive ones, the cost of producing the same quantity of purified water is significantly greater in active systems.

The utilization of blue metal stone that was coated with tar in the solar desalination system for the examination of yield and efficiency and also exergy was carried out by Arani et al. (2023). Several modifications were performed on the system which was aiming to increase the absorption of solar radiation and retention of heat. The advantage of utilizing the tar coating was to reduce the heat loss and enhance the absorption of radiation. While the stones of blue metal had the important role to play in which it acts as heat storage component that store the heat and later supply to basin water during the midnight time thus maintain the evaporation rate during daytime as well nighttime. On the basis of obtained results, it was presented that yield of the modified solar still was 34.4 % greater that yield of CSS. The modifications performed on the solar still on the basis of material was noted to be beneficial and can be implemented in various other active and passive solar still.

Several experimental studies were carried in the domain of solar still and one of them was carried out by Kumar et al. (2023) where an integration of ETC was done with solar still. The aim was to capture as much solar energy as possible and lowering of heat loss and for that various insulation were provided in the modified solar still. After performing the experiment, it was found that the modification done to the solar still were doomed to be beneficial as the production of fresh water was jumped to an increase of 52.97 % when it is compared to the production of fresh water via CSS. The prime reason of enhancement of productivity is due to the higher rate of absorption, lowering of loss of heat by means of convection, and last but not the least the high thermal energy that was provided the evacuated tubes. The findings can be implemented to the passive solar still for an economical system and the technology can be used very astutely by any common man. Thus, it is very much beneficial in all manner leading to ease of utilization for a commoner for the high rate of pure water production.

The process of exploring the solar still was not stop but spread widely across the globe. This technique was not only attractive but easy to utilize and implemented with a very low investment. Taking benefit of all advantage Singh et al. (2024) brought some technical modification into the existing solar still. These modifications are incorporation of tube collector of evacuated type concentrator having shape of parabola in compounding form and named it NCPCETC-SU. As we have been constantly focusing on capturing of solar energy and improved efficiency, this very modified system also produced efficiency as expected. The modified system that is NCPCETC-SU showed better exergy per annum than NETC-SU by a margin of 36.51 % and when we talk about the efficiency of exergy on daily basis the margin was noted as 30.81 % higher. But the most important thing that is to be noted here is the cost which was found to be higher by a margin of 9.85 % for the case of NCPCETC-SU when compared with the cost incurred with NETC-SU. The study suggested that if cost is not the barrier for any solar system, then the NCPCETC-SU model is best suited for desalination system.

In a separate study, Singh et al. (2024) examined the impact of photovoltaic (PV) technologies on the efficacy of a SSSS unit integrated with multiple identical photovoltaic thermal (PVT) FPC. Under New Delhi's climate conditions, they evaluated various energy and environmental-economic factors to determine the most effective PV technology. The results indicated that copper indium gallium selenide (CIGS) had the shortest energy payback time of 1.64 years, suggesting quick recovery of the initial energy investment. On the other hand, crystalline silicon PV technology stood out in terms of long-term performance, offering the highest life cycle conversion efficiency (0.171), the greatest CO_2 reduction (199.10 tons), and the most carbon credit value (US$15,269.25), making it the most sustainable and economically beneficial choice in the long run. Saxena et al (2022) in their study, solar stills are analyzed from a thermodynamic perspective, marking a novel approach in existing research. The review aims to identify gaps in current knowledge and highlight opportunities for future investigation.

Sahu and Tiwari (2024) explored the impact of nanofluids in solar distillation units while considering water mass variations. They found that a solar still using hybrid nanofluid exhibited 46.47% higher efficiency than one using only a base fluid (water), attributed to better thermos-physical properties of hybrid nanofluids.

The conical shaped solar distillation unit has gained significant attention due to its reduced shading effects compared to basin-type solar distillation units, making it a promising candidate for improved output. Gad et al. (2016) experimentally studied conical shaped solar distillation units and observed that their freshwater production was higher than that of regular solar distillation units by 42.90%. In another study Kabeel et al. (2023) investigated conical shaped solar distillation units with inclination angles of 30°, 45°, and 60°, recommending a 30° inclination for optimal efficiency and yield.

Abdallah and Aldarabseh (2024) worked on and performed experiments with a hexagonal pyramid shaped solar distillation unit incorporating a conical inner surface and varying mass flow rates. The findings demonstrated that freshwater production from this system was higher than that of regular solar distillation units by 221.5%, owing to minimized effects of shading as well as design enhancements.

Furthermore, Singh et al. (2023. 2024) analyzed conical shaped solar distillation units from exergoeconomic, enviro-economic, energy metric, efficiency, and sensitivity standpoints. The results revealed that the cost of fresh distilled water production from a conical shaped solar distillation unit was 13.56% lower than that of a regularly used common solar still due to its geometric configuration which minimized shading effects and maximized solar energy absorption throughout the day. The conical design enabled a more uniform and prolonged exposure to solar radiation, thereby enhancing thermal performance and reducing the dependency on external energy inputs. Another significant finding was that conical-shaped solar distillation units performed better than traditionally used previous designs not only in terms of energy efficiency but also in terms of overall operational efficacy. These units demonstrated higher evaporation and condensation rates, translating to improved freshwater yield. From an exergo-economic perspective, the conical design offered better cost-effectiveness by delivering higher exergy output for each unit of investment. Moreover, the enviro-economic analysis indicated that the reduction in fossil fuel-based energy demand, due to the improved efficiency of the conical unit, contributed to lower environmental impact and greenhouse gas emissions. Sensitivity analysis further reinforced the robustness of the design under varying climatic and operational conditions, making conical solar distillers a viable and sustainable alternative for decentralized water purification in resource-scarce regions.

As per the reviewed literature, it is evident that prior research has primarily focused on conical shaped solar distillation units operating in passive mode. Nevertheless, there is a clear research gap, as no study has explored the performance of conical shaped solar distillation units in active mode. To bridge this gap, the authors have analyzed a conical shaped solar distillation unit that was equipped with N number of evacuated collectors. The primary goals of this study are outlined as:

i. To express undetermined parameters in terms of known variables such as intensity of solar radiation, ambient temperature, and various constants using thermodynamic principles.

ii. To examine the exergo-enviro-economic parameters of the suggested system through MATLAB-based simulations to assess its efficiency, environmental impact, and economic viability.

iii. To determine the annual productivity of the NETC-CSS system and assess its feasibility.

iv. To investigate the NETC-CSS system with prior documented studies on active solar stills, focusing on enviro-economic aspects.

The findings from this research are expected to play a pivotal role in enhancing the goals of sustainable development of the United Nation. By facilitating fresh distilled water production, this system has the potential to benefit both developed as well as developing nations. As per the need distilled water generated by the NETC-CSS can be utilized in various applications, including batteries, cosmetics, automotive coolant systems, and the pharmaceutical industry. Additionally, after mineral supplementation, it can be made suitable for human consumption. Furthermore, the production of distilled water can open opportunities for small businesses, and the system can be employed for household purposes such as purifying harvested rainwater, this contributes to management of water sustainably, especially in the areas those are facing problem of water scarcity.

4.2. Materials and Methods for the analysis of NETC-CSS

Fig. 3.1 presents a 3D model of the proposed solar distillation, and its design details are listed in Table 3.2. The system includes ETC (shown with N in the Fig. 3.1) are connected in series to heat the water in the basin more effectively. This higher water temperature improves the evaporation rate, leading to more freshwater production. When sunlight hits the transparent cover, part of it is reflected, some is absorbed, and the rest passes through to the water. A similar process happens at the water surface some energy is absorbed, and the rest reaches the basin's black liner. This liner absorbs the remaining solar energy and gets heated, then transfers the heat back to the water through conduction and convection. At the same time, the collectors also help in raising the water temperature. As a result, a temperature difference is created between the warm water surface and the cooler inner surface of the glass cover. This difference drives the evaporation process. When the vapor touches the cooler cover, it condenses into a thin film of water droplets. These droplets combine and grow larger, eventually sliding down due to gravity and are collected in a beaker using a siphon system.

The thermodynamic model has been formulated based on the assumptions established by Singh and Tiwari (2017). In accordance with Singh et al. (2023), the set of the equations for the condensing surface to define the energy balance are presented as given below:

For east facing condensing surface

$$\dot{\alpha}_g I_{SE}(t)\frac{A_g}{4} + h_{1wE}\left(T_w - T_{gE}\right)\frac{A_b}{4} + h_{EW}\left(T_{gW} - T_{gE}\right)\frac{A_g}{4} = h_{1gE}\left(T_{gE} - T_a\right)\frac{A_g}{4} \tag{4.1}$$

In equation (1), the first term on the left-hand side (LHS) signifies the energy taken in by the eastward-facing condensing surface. The second term denotes the thermal energy transferred from the surface of water to the same eastward surface, and the third term captures the energy exchange occurring between the east- and west-facing condensing surfaces. In this context it can be observed that on the right-hand side (RHS), the term depicts the heat dissipated from the east-facing condensing surface into the environment through both convective and radiative processes.

For west facing condensing surface

$$\dot{\alpha}_g I_{SW}(t)\frac{A_g}{4} + h_{1wW}\left(T_w - T_{gW}\right)\frac{A_b}{4} - h_{EW}\left(T_{gW} - T_{gE}\right)\frac{A_g}{4} = h_{1gW}\left(T_{gW} - T_a\right)\frac{A_g}{4}$$

(4.2)

In equation (2), the first term on the LHS corresponds to the energy absorbed by the west-facing condensing surface. The second term signifies the heat transfer from the water surface to the west-facing condensing surface, while the third term accounts for the energy exchange between the east- and west-facing condensing surfaces. In this context, it is important to note that on the RHS, the term depicts the heat dissipation from the west-facing condensing surface to the surrounding environment via convection as well as radiation.

For south facing condensing surface

$$\dot{\alpha}_g I_{SS}(t)\frac{A_g}{4} + h_{1wS}\left(T_w - T_{gS}\right)\frac{A_b}{4} + h_{NS}\left(T_{gS} - T_{gN}\right)\frac{A_g}{4} = h_{1gS}\left(T_{gS} - T_a\right)\frac{A_g}{4}$$

(4.3)

In equation (3), the initial term on the LHS denotes the energy that is absorbed by the south-facing condensing surface. In this context the second term signifies the heat transfer from the water surface to the south-facing condensing surface, while the third term accounts for the energy exchange between the south- and north-facing condensing surfaces. It has to be noted that on the RHS, the term depicts the heat dissipation from the south-facing condensing surface to the surrounding environment through radiation as well as convection.

For north facing condensing surface

$$\dot{\alpha}_g I_{SN}(t)\frac{A_g}{4} + h_{1wN}\left(T_w - T_{gN}\right)\frac{A_b}{4} - h_{NS}\left(T_{gS} - T_{gN}\right)\frac{A_g}{4} = h_{1g}\left(T_{gN} - T_a\right)\frac{A_g}{4}$$

(4.4)

In equation (4), the first term on the LHS signifies the energy that is absorbed by the north-facing condensing surface. In this context the second term represents the heat transfer from the water surface to the north-facing condensing surface, while the third term accounts for the energy exchange between the north- and south-facing condensing surfaces. In this context on the RHS, the term denotes the heat dissipation from the north-facing condensing surface to the surrounding environment via convection as well as radiation.

All undefined terms appearing in equations (1) to (4) are elaborated in Appendix-A. By following the methodology outlined in Singh et al. [49], the solutions to equations (1) through (4) are expressed as given below:

$$T_{gE} = \frac{A_1 + A_2 T_w}{P_1} \tag{4.5}$$

$$T_{gW} = \frac{B_1 + B_2 T_w}{P_1} \tag{4.6}$$

$$T_{gS} = \frac{C_1 + C_2 T_w}{P_2} \tag{4.7}$$

$$T_{gN} = \frac{D_1 + D_2 T_w}{P_2} \tag{4.8}$$

All undefined terms in equations (4.5) to (4.8) are provided in Appendix-A. The energy balance equations (EBEs) for the basin liner are presented as given below:

$$[\acute{\alpha}_b (I_{SE}(t) + I_{SW}(t) + I_{SN}(t) + I_{SS}(t)) \frac{A_b}{4}] = h_{bw}(T_b - T_w)A_b + h_{ba}(T_b - T_a)\mathrm{A_b} \tag{4.9}$$

The LHS of equation (9) denotes the energy that is absorbed by the basin liner. In this context on the RHS, the first term signifies the heat transferred from the basin liner to the water mass, while the second term accounts for the heat dissipated from the basin liner to the surroundings.

More simplified form of Equation (9) can be given by:

$$h_{bw}(T_b - T_w)A_b = \dot{\alpha}_b h_1\left(I_{SE}(t) + I_{SW}(t) + I_{SN}(t) + I_{SS}(t)\right)A_b - U_b A_b (T_w - T_a) \quad (4.10)$$

where $h_1 = \dfrac{h_{bw}}{4(h_{bw} + h_{ba})}$ (4.11)

and $U_b = \dfrac{h_{ba} h_{bw}}{(h_{bw} + h_{ba})}$ (4.12)

Further, the energy balance equation (EBE) for the water mass is given by:

$$[\dot{\alpha}_w (I_{SE}(t) + I_{SW}(t) + I_{SN}(t) + I_{SS}(t))\frac{A_b}{4}] + [h_{bw}(T_b - T_w)A_b] + \dot{Q}_{u,N} = h_{1wE}\left(T_w - T_{gE}\right)\frac{A_b}{4} + h_{1wW}\left(T_w - T_{gW}\right)\frac{A_b}{4} + h_{1wS}\left(T_w - T_{gS}\right)\frac{A_b}{4} + h_{1wN}\left(T_w - T_{gN}\right)\frac{A_b}{4} + M_w C_w \frac{dT_w}{dt}$$

(4.13)

Where, $\dot{Q}_{u,N}$ represents the useful heat gained from the N evacuated collectors connected in series and is given by: [56]:

$$\dot{Q}_{uN} = \frac{(1 - K_k{}^N)}{(1 - K_k)}(A\,F_R(\alpha\tau))_1 I(t) + \frac{(1 - K_k{}^N)}{(1 - K_k)}(A\,F_R U_L)_1 (T_{fi} - T_a) \quad (4.14)$$

In this scenario the temperature T_{fi} and T_w are equivalent. The heated water exiting at the outlet of the Nth Evacuated Tube Collector (ETC) is channeled into the basin. Hence, the value of T_{wo}

matches that of T_{foN}. T_{foN} (outlet temperature of the N^th ETC) can be given by the following equation:

$$T_{foN} = \frac{(A\,F_R(\alpha\tau))_1}{\dot{m}_f C_f}\frac{(1-K_k{}^N)}{(1-K_k)} I(t) + \frac{(A\,F_R U_L)_1}{\dot{m}_f C_f}\frac{(1-K_k{}^N)}{(1-K_k)} T_a + K_k{}^N T_{fi} \tag{4.15}$$

All unidentified parameters in equation (14) are listed in Appendix-A. Now, by utilizing equations (5) to (8), equation (10), and equations (13) and (14), the differential equation can be formulated as follows:

$$\frac{dT_w}{dt} + a_1 T_w = f(t) \tag{4.16}$$

Where,

$$f(t) = \frac{1}{M_w C_w}\left[\begin{array}{l}\left(\frac{\dot{\alpha}_w}{4} + \dot{\alpha}_b h_1\right) A_b (I_{SE}(t) + I_{SW}(t) + I_{SN}(t) + I_{SS}(t)) + \frac{(1-K_k^N)}{(1-K_k)}(AF_R(\alpha\tau))_1 I(t) - E_1 + \\ \{\frac{(1-K_k^N)}{(1-K_k)}(AF_R U_L)_1 + U_b A_b + F_1\} T_a\end{array}\right] \tag{4.17}$$

$$a_1 = \left(\frac{\dot{m}_f C_f (1-K_k^N) + F_1 + U_b A_b}{M_w C_w}\right) \tag{4.18}$$

By assuming a time interval from 0 to Δt and considering the average values of both ambient temperature and solar radiation intensity as constant to maintain f(t), the average function $\bar{f}(t)$ is used in the expression. Consequently, equation (16) can be solved, provided that the value of a1a_1a1 remains constant during the interval Δt. Following this procedure, the solution to equation (16) is presented in equation (19).

$$T_w = \frac{\bar{f}(t)}{a_1}(1 - e^{-a_1 t}) + T_{wo} e^{-a_1 t} \tag{4.19}$$

Where,

$$\bar{f}(t) = \frac{1}{M_w C_w}\left[\begin{array}{l}\left(\frac{\dot{\alpha}_w}{4} + \dot{\alpha}_b h_1\right) A_b (\bar{I}_{SE}(t) + \bar{I}_{SW}(t) + \bar{I}_{SN}(t) + \bar{I}_{SS}(t)) - E_1 + \\ (U_b A_b + F_1)\bar{T}_a\end{array}\right] \tag{4.20}$$

To clarify the unknown variables, refer to Appendix-A. In equation (21), the heat transfer rate associated with the evaporation process is provided.

$$\dot{q}_{ew} = \left[h_{ewgE}(T_w - T_{gE}) + h_{ewgW}(T_w - T_{gW}) + h_{ewgS}(T_w - T_{gS}) + h_{ewgN}(T_w - T_{gN})\right]\left(\frac{A_b}{4}\right) \tag{4.21}$$

The hourly fresh distilled water output of NETC-CSS is represented by the equation (22).

$$Hourly\ freshwater\ yield = \frac{\dot{q}_{ew} \times 3600}{(Latent\ heat)} \tag{4.22}$$

4.3. Experimental Validation

The experimental validation is shown in heading 3.2.1.

4.4. Analysis

Table 3.3 provides a detailed outline of the environmental parameters selected for various months to assess the performance of NETC-CSS following the conditions specified in Singh and

Tiwari (2004). "S" (Sunshine Hours): Represents the total duration of sunlight available each day for a given month. This factor influences the solar energy absorption and the overall thermal efficiency of the system. "γ" (Diffuse Radiation to Global Radiation Ratio): Indicates the proportion of diffuse solar radiation relative to total global radiation. A higher $\boldsymbol{\gamma}$ value suggests greater atmospheric scattering, which may affect the efficiency of solar energy utilization.

4.4.1. Energy and exergy analyses of NETC-CSS

The hourly freshwater yield is determined using equation (4.22). The annual yield is then computed through a step-by-step approach:

Step I: Daily Yield Calculation:

The hourly yield values for a 24-hour period are summed to obtain the daily yield for a specific weather condition (type ‘a1’). The same procedure is repeated for other weather types (b1, c1, and d1).

Step II: Monthly Yield Calculation:

i. The daily yield for each weather type is summed over the entire month.
ii. This gives the monthly yield for a1, b1, c1, and d1 weather conditions.
iii. The total monthly yield is obtained by adding up the values for all four weather types.

Step III: Annual Yield Calculation:

The monthly yields are summed across 12 months to obtain the annual freshwater yield for NETC-CSS.

This systematic approach ensures an accurate estimation of the system's performance throughout the year.

By applying the First Law of Thermodynamics, the energy analysis of NETC-CSS will be conducted. The hourly energy output is determined using Equation (4.23).

$$Hourly\ energy = \frac{(Hourly\ freshwater\ output)\times(Latent\ heat)}{3600} \tag{4.23}$$

To measure total energy output annually, the same process used for the calculation of freshwater generation will be followed.

The Second Law of Thermodynamics is applied to analyze the exergy of NETC-CSS. Exergy refers to the usable energy in a system, indicating the quality and potential of energy to do work. In this context the hourly exergy output from NETC-CSS is calculated following the methodology outlined by Nag (2004), as described below:

$$\dot{E}x_{hourly} = h_{ewgE} \times \frac{A_b}{4} \times [(T_w - T_{gE}) - (T_a + 273) \times ln\frac{(T_w+273)}{(T_{gE}+273)}] + h_{ewgW} \times \frac{A_b}{4} \times [(T_w - T_{gW}) - (T_a + 273) \times ln\frac{(T_w+273)}{(T_{gW}+273)}] + h_{ewgS} \times \frac{A_b}{4} \times [(T_w - T_{gS}) - (T_a + 273) \times ln\frac{(T_w+273)}{(T_{gS}+273)}] + h_{ewgN} \times \frac{A_b}{4} \times [(T_w - T_{gN}) - (T_a + 273) \times ln\frac{(T_w+273)}{(T_{gN}+273)}] \tag{4.24}$$

For the annual exergy assessment by using Equation (24), the same step-by-step process used for the calculation of yield is followed:

4.4.2. Exergo-economic analysis of NETC-CSS

The exergo-economic parameter is a crucial metric that establishes the relationship between cost and exergy/energy. This is determined by dividing the annual exergy gain by the uniform end-of-year annual cost (UEC). If exergy loss is considered, the objective is to minimize it, whereas, for exergy gain, the goal is to maximize it. As per the methodology outlined by Singh and Tiwari (2017), the exergo-economic parameter is calculated using equations (4.25) and (4.26).

$$(Exergo - economic\ parameter)_{energy} = \frac{Annual\ energy\ output}{UEC} \tag{4.25}$$

$$(Exergo - economic\ parameter)_{exergy} = \frac{Annual\ exergy\ gain}{UEC} \tag{4.26}$$

In this analysis, exergy gain is prioritized since solar radiation from the sun is freely available, incurring no cost. Given that this energy source is abundant and cost-free, the primary objective is to maximize exergy gain rather than focusing on identifying and minimizing exergy losses. By enhancing exergy gain, the system's overall efficiency and cost-effectiveness can be improved without concerns about energy input costs.

The calculation of Uniform End-of-Year Annual Cost (UEC) is carried out using the Present Value Method. This approach ensures an accurate estimation of costs over the system's lifespan. The UEC is determined by applying Equation (27) as outlined in reference (Tiwari 2013).

$$UEC = (\text{Present value} + \text{maintenance cost}) \times F_{CR,i,n} - (\text{Salvage value}) \times F_{SR,i,n} \tag{4.27}$$

To estimate the maintenance cost of the system, 10% of the present evaluation is taken into account. This implies that a fixed percentage-based approach is used rather than a detailed breakdown of individual maintenance components. Two key financial parameters $F_{CR_{i,n}}$ and $F_{SR_{i,n}}$ are introduced. These parameters represent the $F_{CR_{i,n}}$ capital recovery factor (CRF) and the $F_{SR_{i,n}}$ sinking fund factor (SFF), which are essential in financial modeling for engineering systems. These factors are mathematically defined using Equations (4.28) and (4.29).

$$F_{CR_{i,n}} = \frac{r(1+r)^l}{(1+r)^l - 1} \quad (4.28)$$

$$F_{SR_{i,n}} = \frac{r}{(1+r)^l - 1} \quad (4.29)$$

Here, $r = interest\ rate$r and $l = system's\ span\ of\ life.$

4.4.3. Analysis for payback period

When designing a solar distillation unit, a crucial consideration for the designer is the timeframe within which the system will begin to generate returns. The duration required to reach the break-even point is commonly referred to as the payback period. Mathematically, it is formulated in accordance with Kumar and Tiwari (2009) and is shown in equation (4.30).

$$Payback\ period = \frac{ln\left[\frac{(Annual\ cash\ flow)}{(Annual\ cash\ flow)-(Net\ present\ cost \times r)}\right]}{\ln(1+r)} \quad (4.30)$$

The annual cash flow is determined using the following relation:

$$Annual\ cash\ flow = UEA$$

This holds true when the selling price of the produced freshwater is equal to its production cost.

When the selling price of the fresh distilled water produced is higher than its production cost:

$Annual\ cash\ flow = (Annual\ freshwater\ production) \times (Selling\ price)$,

4.4.4. Enviro-economic analysis of NETC-CSS

This parameter represents the cost associated with reducing CO_2 emissions over the entire operational lifespan of the analyzed system. Based on the methodology outlined by Caliskan et al. (2012), it is computed using the following equation:

$$Enviro - economic\ parameter = (CO_2 emission\ reduction\ price) \times (\xi_{CO_2}) \qquad (4.\ 31)$$

Here, ξ_{CO2} represents the total reduction in CO_2 emissions over the entire lifespan of the NETC-CSS system.

When an individual consumes a single unit of electricity, approximately 40% of the energy is lost in transmission and distribution, while an additional 20% is lost due to inefficiencies in household appliances. As a result, the total power required at the source to deliver 1 unit of usable electricity is 2.08 units, which can be expressed mathematically as:

$$Power\ required\ to\ be\ generated\ in\ power\ plant = \frac{1}{(1-0.2)(1-0.4)} = 2.08\ units. \qquad (4.32)$$

The average CO_2 emission associated with generating one unit of electrical energy is 0.96 kg, as reported in (Sovacool 2008). Given that the total power required at the source to deliver one unit of usable electricity is 2.08 units, the corresponding CO_2 emission is calculated as:

$2.08 \times 0.96 = 2$ kg.

The total reduction in CO_2 emissions over the entire lifespan of the NETC-CSS system can be computed in metric tons of CO_2 using equations (33) and (34).

$$\left(\xi_{CO_2}\right)_{energy} = [(Annual\ energy\ output)(life\ of\ system) - embodied\ energy] \times (0.002) \qquad (4.33)$$

$$\left(\xi_{CO_2}\right)_{exergy} = [(Annual\ exergy\ output)(life\ of\ system) - embodied\ energy] \times (0.002) \qquad (4.34)$$

4.4.5. Productivity and cost of freshwater analyses of NETC-CSS

4.4.5.1. Analysis for Productivity

The key parameter that determines the efficiency in engineering and industrial appliations is its productivity, which is expressed as the ratio of output to input. Higher output for a given input results in greater productivity. The annual productivity (ηp,annual)(\eta_{p,annual})(ηp,annual) is determined using the following equation (ILO 1979):

$$\eta_{p,annual} = \frac{(Annual\ freshwater\ output) \times (Selling\ price\ of\ freshwater)}{UEC} \times 100 \quad (4.35)$$

4.4.5.2. Cost of freshwater production from NETC-CSS

The cost associated with freshwater generation is calculated using equation (36), which defines it as the ratio of UEC to the annual freshwater yield.

$$Cost\ of\ freshwater = \frac{UEC}{annual\ freshwater\ production} \times 100 \quad (4.36)$$

4.5. Methodology

The procedure for determining all the essential parameters involved in NETC-CSS is outlined in the following steps:

Step 1:

Upon obtaining the data from IMD situated in Pune, India, the required equations are implemented to determine the intensity of solar radiation on a surface that is horizontal. This is achieved using Liu and Jordan's theory, for which a computational algorithm is developed and executed in the MATLAB.

Step II:

At this stage, various condensing surface temperatures are computed. Using equation (5), Tg_E is evaluated. Similarly, equations (6), (7), and (8) are employed to determine Tg_W, Tg_S, and Tg_N, respectively. Following this, equation (19) is used to calculate Tw.

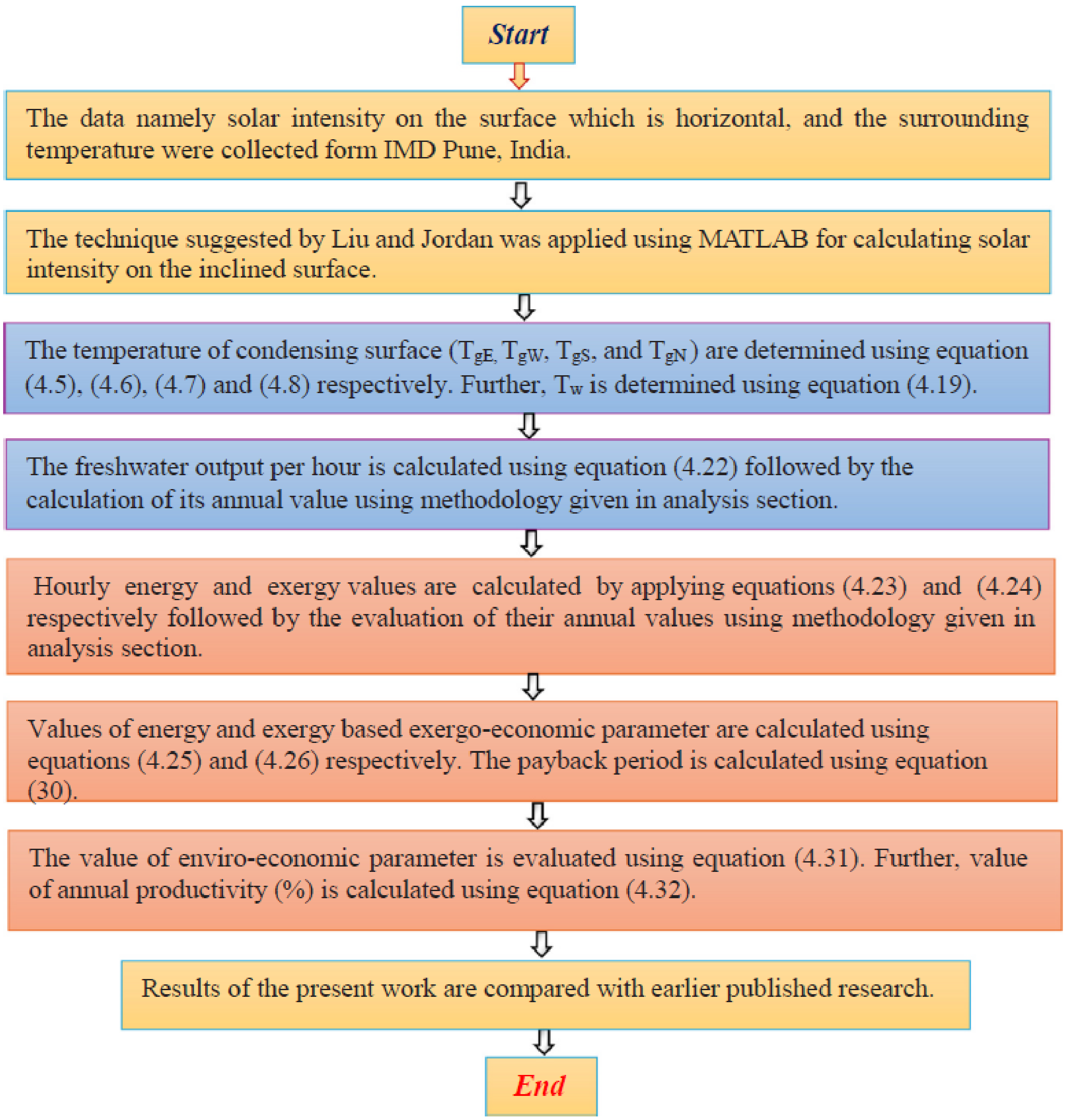

Fig. 4.1: Flow chart representing the methodology followed for the present analysis

Step III:

At this stage, equations (22), (23), and (24) are applied to determine the freshwater yield, corresponding energy, and exergy, respectively. Subsequently, the daily, monthly, and annual freshwater production, along with the associated energy and exergy output, are computed.

Step IV:

At this stage, equations (25) and (26) are employed to determine the exergo-economic parameters corresponding to energy and exergy, respectively. Additionally, the payback period is computed using equation (30).

Step V:

At this step, equation (31) is utilized to determine the environmental and economic parameters. Furthermore, productivity-associated parameters and the cost of freshwater production are calculated using equations (35) and (36), respectively.

The flowchart depicting the systematic method adopted for the performance evaluation of NETC-CSS is presented in Fig. 4.2. This diagram offers a systematic representation of the approach, enhancing the reader's comprehension of the methodology.

For better understanding of the methodology followed for the present analysis, a flow chart is shown in Fig. 4.1.

6. Results and discussion

The methodology section provides a detailed explanation of the solution procedure. The computational results from MATLAB simulations are well depicted in Figs. 4.2–4.6 and Tables

4.1–4.6. Figs. 4.2 and 4.3 depict the variations in the maximum value of fluid temperature at the Nth ETC ($T_{foN,max}$) as a function of N and mfr for NETC-CSS, considering a representative day in the month of May and in the month of December, respectively.

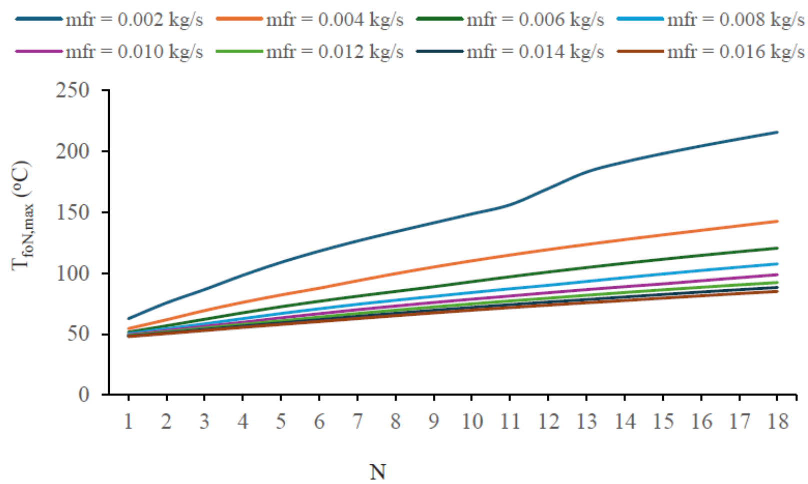

Fig. 4.2: Variation of temperature with N and mfr for a typical day in May

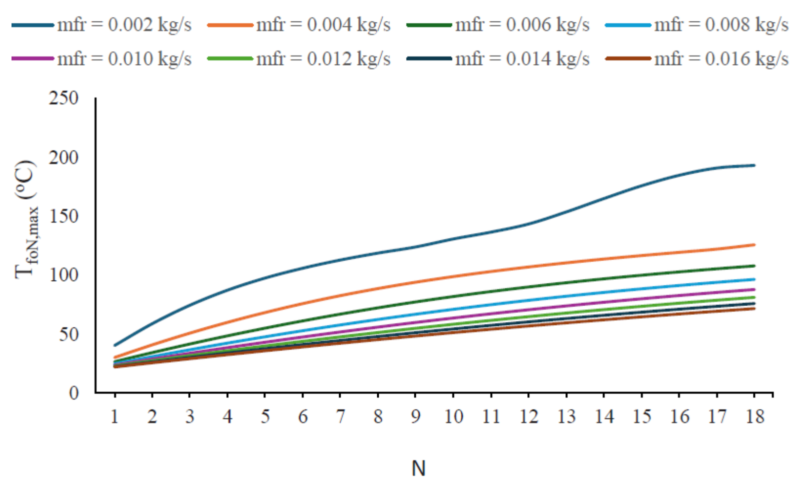

Fig. 4.3: Variation of temperature with N and mfr for a typical day in December

From Fig. 4.2, it is evident that increasing mfr beyond 0.008 kg/s has a negligible effect, as indicated by the overlapping curves. The variation in mfr is considered because heat gain is directly influenced by mfr. Additionally, it is observed that ($T_{foN,max}$)exceeds 100°C when

N>15. Consequently, the optimal values of N and mfr are determined to be 15 and 0.008 kg/s, respectively. In this context these values are also found to be valid for December, as demonstrated in Fig. 4.3.

Fig. 4.4 depicts the per-hour variations in fresh distilled water generation, fluid temperature at the outlet of the Nth ETC, temperature of water, condensing surface temperature, and surrounding temperature for chosen values of mfr , N, and water depth. As observed, the water temperature remains higher than the condensing surface temperature, which, as expect, facilitates the evaporation and condensation process necessary for freshwater production. In this analysis, key parameters were determined using the average values of solar intensity and ambient temperature. The intensity of solar radiation peaked at 12:00 noon, whereas the highest basin temperature was recorded around 2:00 PM. This is a natural occurrence, as water first absorbs solar radiation before gradually heating up, requiring a certain amount of time to reach its maximum temperature.

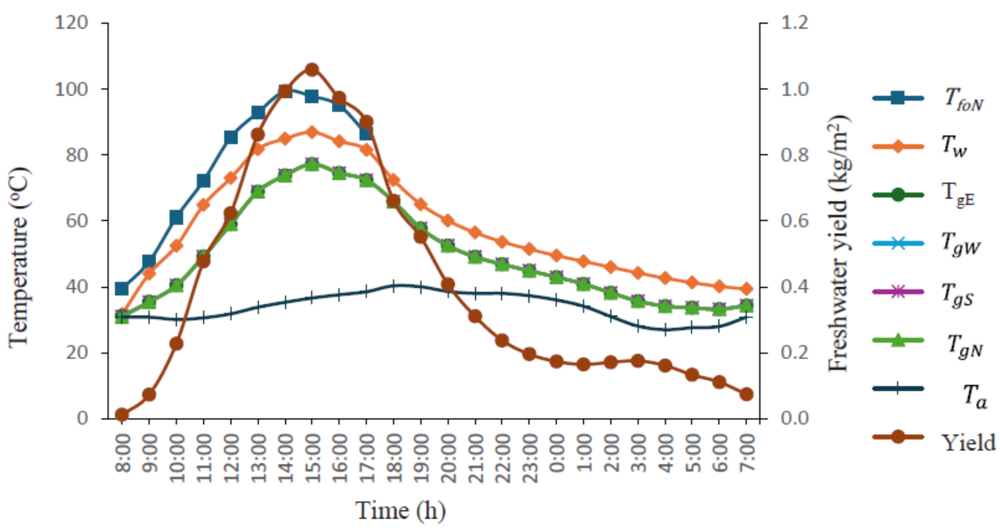

Fig. 4.4: Variation of temperature and distillate output for a typical day in May for NETC-CSS

Table 4.1 presents the computed annual generation of freshwater based on the system's performance under specific input conditions. The method implemented for these calculations has been detailed in the analysis section. It is observed that the highest freshwater output occurs in May, while the lowest is recorded in November. This trend is attributed to seasonal climatic variations—May experiences hot and humid conditions with extended sunlight exposure, enhancing system performance. Conversely, during November, the onset of winter significantly reduces daylight hours, limiting the heat supply from the sun to the system and consequently leading to a lower freshwater yield.

Table 4.1: Evaluation of yearly freshwater output from NETC-CSS

Month	Type a_1			Type b_1			Type c_1			Type d_1			Monthly yield
	Daily yield	N	Monthly yield	Daily yield	n	Monthly yield	Daily yield	n	Monthly yield	Daily yield	N	Monthly yield	(kg)
Jan	9.61	3	28.83	9.36	8	74.86	5.89	11	64.74	2.89	9	26.02	194.46
Feb	9.90	3	29.70	10.12	4	40.47	6.00	12	71.97	2.77	9	24.97	167.12
Mar	10.33	5	51.67	11.07	6	66.44	8.16	12	97.91	6.88	8	55.01	271.03
Apr	10.39	4	41.58	10.72	7	75.04	8.26	14	115.60	8.39	5	41.94	274.16
May	9.73	4	38.90	9.72	9	87.44	9.10	12	109.14	8.04	6	48.26	283.75
Jun	10.20	3	30.59	10.34	4	41.37	9.33	14	130.56	7.30	9	65.72	268.24
Jul	9.14	2	18.27	9.22	3	27.67	8.19	10	81.90	6.99	17	118.90	246.73
Aug	8.86	2	17.72	9.05	3	27.16	7.78	7	54.49	6.54	19	124.22	223.59
Sep	8.82	7	61.77	8.84	3	26.53	7.75	10	77.53	6.18	10	61.78	227.61
Oct	7.48	5	37.40	7.07	10	70.74	5.92	13	77.00	4.47	3	13.40	198.54
Nov	7.15	6	42.88	6.40	10	64.03	3.78	12	45.30	3.73	2	7.45	159.67
Dec	8.69	3	26.06	8.11	7	56.78	5.78	13	75.19	2.75	8	21.96	180.00
						Yearly yield (kg)							**2694.91**

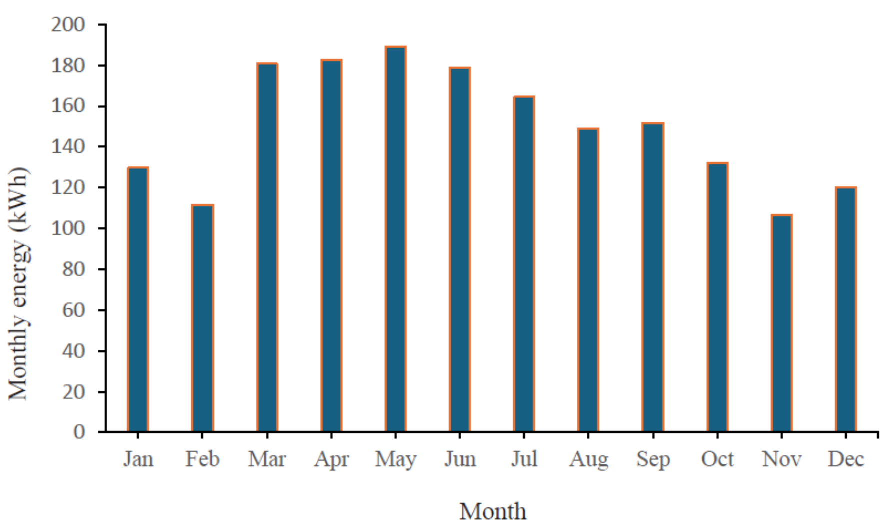

Fig. 4.5: Variation of monthly energy for NETC-CSS

Fig. 4.5 illustrates the monthly variation in energy output from the system under selected values of mass flow rate (mfr), number of evacuated collectors (N), and water mass in the basin. Notably, the highest and lowest energy production amount are recorded in the month of May and in the month of November, respectively, which align with similar trends observed in fresh distilled water generation.

Fig. 4.6 depicts the month-to-month variations in exergy for types a1, b1, c1, d1, as well as overall exergy for the month throughout the year. The exergy output reaches its peak in May and drops to its lowest in November. This can be attributed to seasonal climatic conditions—May experiences hot and humid weather with prolonged sunlight exposure, enhancing system performance. In contrast, November marks the winter season, during which shorter daylight hours significantly reduce solar heat supply to the NETC-CSS, leading to a comparatively lower exergy output.

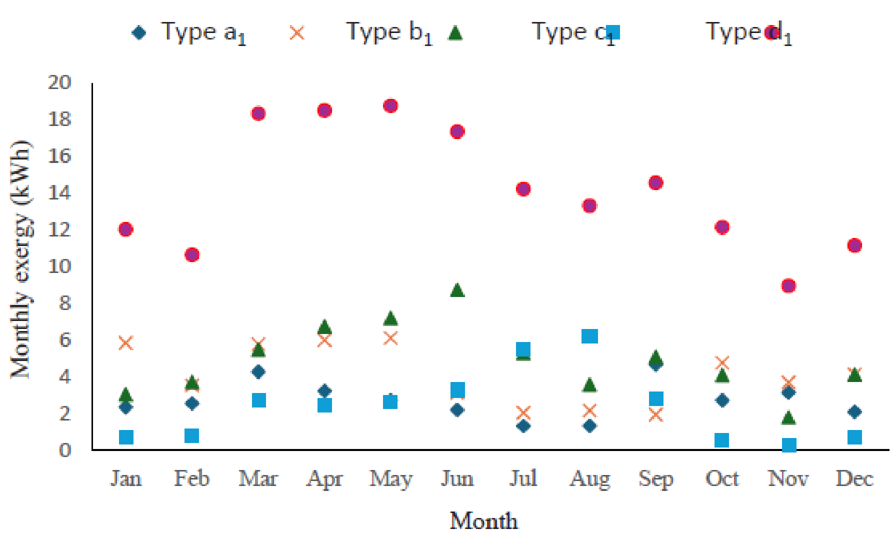

Fig. 4.6: Variation of monthly exergy for NETC-CSS

Table 4.2 presents a detailed cost breakdown of several components in the conceptualized system, calculated using regional market rates. Additionally, the depreciated value is considered, accounting for potential revenue from selling the system for resale as scrap in domestic markets".

The cost breakdown provided in Table 4.2 offers a comprehensive financial assessment of the proposed system, ensuring transparency in budgeting and investment planning. By incorporating local market prices, the analysis reflects realistic cost estimations, making it more applicable for practical implementation. Additionally, the inclusion of salvage value acknowledges the residual worth of the system at the end of its operational life. Table 4.3 provides an assessment of the unit energy cost (UEC) for the proposed setup, calculated using the present value method. In this context the analysis assumes a system lifespan of 30 years. It has been noted that applying an interest rate of 2 percent results in the UEC being at its lowest. However, because of the impact of interest rate fluctuations, it peaks at a 10 percent interest rate.

Table 4.2: Cost of components of NETC-CSS

S.N.	Component	Cost
1	Cost of CSS (₹)	15,000
2	Cost of ETC (N = 15)	24,720
3	Cost of Stand (₹)	4000
4	Maintenance cost (₹)	4372
5	Cost of motor and pump (₹)	2000
6	Fabrication cost (₹)	5000
7	Salvage value accounting for a 4 % inflation rate (₹)	14,837.41
8	System life span (Years)	30

Table 4.3: Computation of UEC for NETC-CSS

Life of system (Year)	Rate of interest (%)	Present Value (₹)	Maintenance cost (₹)	Salvage value (₹)	Capital recovery factor (Fraction)	Sinking fund factor (Fraction)	UEC (₹)
30	2	51,706.64	4372	14,837.41	0.0446	0.0246	2136.11
30	5	50,701.61	4372	14,837.41	0.0651	0.0151	3361.25
30	10	49,788.37	4372	14,837.41	0.1061	0.0061	5655.91

The Unit Energy Cost (UEC) is directly influenced by interest rate variations, which play a significant role in financial planning and investment decisions. A lower interest rate (2%) minimizes the financing cost, leading to a reduced UEC, making the system more economically viable. In contrast, at a higher interest rate (10%), borrowing and capital recovery expenses increase, resulting in a higher UEC.

Table 4.4: Evaluation of exergoeconomic parameter and productivity

Rate of interest (%)	UEC (₹)	Annual energy (kWh)	Annual exergy (kWh)	Exergo-economic parameter based on energy (Fraction)	Exergo-economic parameter based on exergy (Fraction)	Annual freshwater output (%)	Selling price of freshwater	Annual productivity (%)
2	2136.11	1796.61	170.19	0.841	0.080	2694.91	5	630.80
5	3361.25	1796.61	170.19	0.534	0.051	2694.91	5	400.86
10	5655.91	1796.61	170.19	0.317	0.030	2694.91	5	238.24

Table 4.4 comprehensively shows an analysis of exergo-economic parameters and annual productivity based on varying mass flow rates (mfr), the number of evacuated collectors (N), and the amount of water mass in the basin. The results indicate that exergy output per unit cost (₹) is at its maximum when the interest rate is 2% and at its minimum when the interest rate rises to 10%. This trend aligns with the behavior of Unit Energy Cost (UEC), where a lower interest rate results in reduced financial burden, making the system more cost-effective. Conversely, a higher interest rate inflates financing costs, leading to an increased UEC and lower exergy output per monetary unit. Additionally, an annual productivity exceeding 100% suggests that the system is not only technically efficient but also economically viable, reinforcing its feasibility for long-term implementation. This insight underscores the importance of optimizing financial and operational parameters to enhance both economic returns and energy efficiency in sustainable energy systems.

Table 4.5: Cost of distillate output, annual cash flow and payback period

Rate of interest (%)	Present value (Rs.)	Annual freshwater output (Kg)	Selling price of freshwater (Rs.)	Annual cash flow (Rs.)	Cost of freshwater (Rs./kg)	Payback period (Year)
2	51706.64	2694.91	5	13474.55	0.79	4.03
5	50701.61	2694.91	5	13474.55	1.25	4.27
10	49788.37	2694.91	5	13474.55	2.10	4.84

Table 4.5 details the calculation of freshwater production cost, payback period and yearly net cash flow based on specified values of mass flow rate ($\dot{m}_{fr}$), number of evacuated collectors (N), and water mass. From ₹0.79/kg to ₹2.10/kg is the expense of producing freshwater using the conceptualized solar distillation unit. The lowest cost is observed at a 2% interest rate, as the unit energy cost (UEC) is at its minimum. On the other hand, the highest cost is recorded at a 10% interest rate, where UEC reaches its maximum. This pattern suggests that cost of distilled freshwater output rises as the interest rate increases. Notably, the price of selling of fresh distilled water remains higher than its cost of production, ensuring economic viability. Additionally, the cost recoupment period for the NETC-CSS system varies from 4.03 to 4.84 years, influenced by the interplay of yearly net flow of cash, present value, and rate of interest.

Table 4.6: Evaluation of enviro-economic parameter for NETC-CSS

Element	Density (kg/m3)	Mass (kg)	Specific energy (kWh/kg)	Embodied energy (kWh)
GRP body	1700	10.17	25.64	260.76
Glass condensing cover	2500	11.54	8.72	100.63
Others				73.40
Evacuated tubular collectors for N = 15				1650.55
Total embodied energy for CSS (kWh)				2085.34
Yearly freshwater yield (kg)				2694.91
Annual energy production (kWh)				1796.61
System lifespan (year)				30.00
Total available net energy over the system's lifespan (kWh)				53,898.30
Yearly exergy generation (kWh)				170.19
Total available net exergy over the lifespan of system (kWh)				5105.70
CO_2 emissions offset based on energy (t)				103.62
CO_2 emissions offset based on exergy (t)				6.04
Enviro-economic variable based on energy ($)				5181
Enviro-economic variable based on exergy ($)				302

Table 4.6 provides an evaluation of embedded energy, total carbon credits (in tonnes of CO_2), and the environmental-economic parameter. In this context the energy required for manufacturing the system, also referred to as embodied energy, is estimated at 2085.34 kWh—a value significantly lesser than the total energy output generated by the system over its

operational lifetime. This suggests that the system plays a role in carbon credit accumulation, contributing to environmental sustainability. The carbon credits calculated based on energy output amount to 103.62 tonnes of CO_2, whereas the credits derived from exergy calculations are notably lower, at 6.04 tonnes of CO_2. This variation stems from the fact that exergy output is considerably lower than energy output, highlighting the difference between usable energy potential and total energy availability. Additionally, the enviro-economic parameter, which quantifies the economic benefit of carbon reduction at an international market rate of $50 per tonne of CO_2, is estimated at $5181 when based on energy and $302 when based on exergy. These findings emphasize the system's environmental and economic advantages, reinforcing its potential for sustainable energy applications and carbon footprint reduction.

Table 4.7 provides a comparative analysis between the proposed system and prior documented active type solar distillation units, emphasizing environmental-economic parameters. The data highlights that the carbon credit and environmental-economic parameter exhibit an 84.3% increase compared to the advanced water-cooled solar desalination system. This improvement is primarily due to the greater amount of green energy generated by the proposed system, surpassing the renewable energy output of the advanced water-cooled solar desalination system.

Table 4.7: Comparison of NETC-CSS with earlier published research based on carbon credit and enviroeconomic parameter

System	CO_2 credited based on energy (t)	Energy based enviro-economic parameter ($)	Percentage Increase (%)
NETC-CSS (Current system)	103.62	5181.00	-
Trapezoidal solar still with additives (Sharshir et al. 2023)	18.41	920.50	82.23
Modified water cooled solar still (Shoeibi et al. 2021)	16.27	813.50	84.30
Active solar still operational in Tehran (Parsa et al. 2020)	30.83	1541.50	70.25
Double slope active solar still incorporated CuO nanofluid (Sahota and Tiwari 2017)	24.61	1230.50	76.25
Solar dish-integrated solar still with Al_2O_3 nanofluid (Kant et al. 2024)	75.87	3793.50	26.78
Solar still with steel fibers (Yousef et al. 2019)	15.63	781.50	84.92

Table 4.8: Comparison of NETC-CSS with earlier published research based distillate output cost

System	Cost of freshwater (₹/kg)	Percentage Decrease (%)
NETC-CSS (Current system)	0.79	-
Trapezoidal solar still with additives (Sharshir et al. 2023)	1.19	33.61
Solar dish-integrated solar still with Al_2O_3 nanofluid (Kant et al. 2024)	4.18	81.10
Solar still with steel fibers (Yousef et al. 2019)	2.86	72.38
Modified solar still (Pal et al. 2021)	0.98	19.39
Novel small-decentralized solar still (Fang et al. 2021)	3.55	77.80

A comparison of NETC-CSS's freshwater costs with those of other published studies is shown in Table 4.8. The analysis reveals that NETC-CSS offers a lower freshwater production cost compared to other solar still configurations. The most significant reduction in cost is observed in comparison with the dish-integrated solar still incorporating Al_2O_3 nanofluid [64]. This cost reduction is primarily attributed to the minimal shading effect in conical solar stills compared to other designs. Additionally, heat loss in ETC is lower than in alternative solar energy collectors, as heat losses through convection are effectively eliminated in the ETC setup.

4.7. Conclusions

In this study, an analytical investigation of NETC-CSS is carried out, taking into account exergo-enviro-economic parameters, annual fresh distilled water yield, payback period and production cost. The system lifespan and water depth are set at 30 years and 0.14 m and, respectively. Additionally, the performance of NETC-CSS is evaluated in relation to prior documented studies on active solar distillation units. Based on the findings, the key conclusions are as follows:

i. The optimized values for mass flow rate (mfr) is determined to be 0.008 Kg/s and optimized value for the number of evacuated collectors (N) is determined to be 15.

ii. While the exergy output per unit cost is found to be 0.841 kWh/₹ based on energy and 0.080 kWh/₹ based on exergy, the calculated annual productivity comes to 630.80 % under optimal conditions with a 2% rate of interest.

iii. The production cost of fresh distilled water for NETC-CSS is ₹0.79 per kg, with a payback period of 4.03 years under a 2% rate of interest.

iv. The enviro-economic parameter of NETC-CSS is valued at $5181, considering a CO_2 emission reduction price of $50 per tonne in the international market. This amount significantly surpasses that of a modified water-cooled solar distiller by 84.30%. The comparison highlights the superior environmental and economic benefits of NETC-CSS.

v. For NETC-CSS the fresh distilled water production cost is 81.10% lesser compared to a dish-integrated solar distillation unit utilizing Al_2O_3 nanofluid.

The next chapter discusses the conclusions and recommendations.

CHAPTER – V

Conclusions and Recommendations

5.1 Introduction

This chapter deals with the conclusions and recommendation of the research work presented in chapters III and IV. It also presents the industrial relevance of the work carried out in this thesis including its significance.

5.2 Conclusions

Fundamental equations are derived for NETC-CSS followed by the computation of performance parameters using MATLAB code. Outcomes of NETC-CSS are compared with results of past documented research considering annual energy, exergy, thermal efficiency as well as exergy efficiency, exergo-enviro-economic parameters, annual fresh distilled water yield, payback period and production cost. The system lifespan and water depth are set at 30 years and 0.14 m, respectively. Based on the analysis, conclusions are drawn which can be summarized in the following manner:

i. The optimized value for mass flow rate is determined to be 0.008 kg/s and optimized value for the number of evacuated collectors (N) is determined to be 15.

ii. Annual freshwater generation, energy, exergy, thermal efficiency and exergy efficiency for NETC-CSS are computed to be 2694.91 kg, 1796.61kWh and 170.19 kWh, 38.79% and 3.94% respectively.

iii. Annual freshwater yield, energy, exergy and exergy efficiency are higher respectively by 57.94%, 57.94%, 74.14% and 36.55% for NETC-CSS than CPSS. However, the thermal efficiency for NETC-CSS is lower by 3.12% than CPSS.

iv. May and November have the highest and lowest monthly yield values, respectively. The hourly thermal and exergy efficiencies of the suggested system are greater in May compared to the respective values in December. The hourly exergy efficiency is significantly reduced compared to the hourly thermal efficiency.

v. A comparative analysis of results of present system with previously documented research represents that the increase in annual exergy, energy, thermal efficiency and exergy efficiency is 68.03% than modified solar still, 74.14% than conventional conical solar still, 61.12% than modified solar still and 72.59% than solar still with parabolic trough collector.

vi. While the exergy output per unit cost is found to be 0.841 kWh/₹ based on energy and 0.080 kWh/₹ based on exergy, the calculated annual productivity comes to 630.80 % under optimal conditions with a 2% rate of interest.

vii. The production cost of fresh distilled water for NETC-CSS is ₹0.79 per kg, with a payback period of 4.03 years under a 2% rate of interest.

viii. The enviro-economic parameter of NETC-CSS is valued at $5181, considering a CO_2 emission reduction price of $50 per ton in the international market. This amount significantly surpasses that of a modified water-cooled solar distiller by 84.30%. The comparison highlights the superior environmental and economic benefits of NETC-CSS.

ix. For NETC-CSS the fresh distilled water production cost is 81.10% lesser compared to a dish-integrated solar distillation unit utilizing Al_2O_3 nanofluid.

Some limitations are there as revealed in assumptions. These limitations may cause small variation in results, but they do not affect the overall conclusions.

5.3 Recommendations

The current evaluation of NETC-CSS does not account for nanofluid/hybrid nanofluid, which could significantly enhance performance due to improved thermophysical properties. Here are some potential extensions for future studies:

1. Effect of Nanofluid/Hybrid Nanofluid:
   (i) Investigating how different nanofluids (e.g., Al_2O_3, CuO, TiO_2) or hybrid nanofluids affect thermal conductivity, heat transfer coefficient, and evaporation rate.
   (ii) Assessing the optimal nanoparticle concentration for maximizing exergy efficiency without causing excessive viscosity.
2. Effect of Location on Performance:
   (i) Evaluating how geographical variations (latitude, altitude, solar irradiance, and climate conditions) impact NETC-CSS efficiency.
   (ii) Comparing performance in tropical, arid, and temperate regions to optimize system design for different locations.
3. Integration of Parabolic Surface:
   (i) Studying the effect of adding a parabolic concentrator to ETC to enhance solar radiation absorption.

(ii) Analyzing how a parabolic surface influences heat transfer rate, water evaporation, and freshwater yield.

By incorporating these aspects, the performance optimization of NETC-CSS can be further enhanced for practical applications.

5.4 Statement of industrial relevance

Distilled water generated by use of the active conical solar still will be beneficial for use in batteries, various cosmetic products, as a coolant in automobiles, and in the pharmaceutical industry. In the battery sector, it will be used to maintain the proper chemical composition of battery cells, ensuring efficient performance and longevity. In the cosmetics industry, it will act as a key ingredient in the formulation of skincare products, where purity and pH balance are essential. It can be made suitable for human consumption by reintroducing essential minerals that are removed during distillation process. Small business of distilled water can be set up. It also finds utility in domestic settings, where it serves to purify harvested rainwater for household use.

5.5 Novelty or Significance

The significance of collectors in present world cannot be denied and one of most used collectors are evacuated type collectors (ETC). The exceptional reduction in the losses compare to flat plate collector (FPC), ETC has gained popularity in early past decades. Their utility in generating fresh water form solar still has been the area of interest of the various scholars. Therefore, a lot of studies have been done on the application of the ETC based solar stills in which ETCs have been combined with the basin of solar stills with certain additions like the use of nanofluid, use of disinfectant, humidification-dehumidification concept, thermoelectric cooling, calcium stone, phase change material etc. However, the utilization of evacuated collector in conjunction with conical solar still has not been addressed by researchers worldwide, indicating a significant gap in current research.

This study has effectively utilized the identified research gap for findings. A thermal model incorporating energy balance equations has been formulated for conical-shaped solar still equipped with evacuated tube collectors followed by annual energy, exergy, thermal efficiency as well as exergy efficiency analyses. The conical-shaped solar still has 360^{o} sunlight exposure. Unlike single-slope solar stills that depend on the sun’s direction, a conical design allows sunlight to reach different parts of the basin from all directions. This reduces the formation of large shadowed areas, enhancing continuous solar absorption and hence it has the potential to provide greater productivity. A conical-shaped solar still with integrated evacuated tubes is an advanced water purification system that enhances the efficiency of solar desalination. It combines the traditional conical solar still design with evacuated tube collectors (ETCs) to improve water evaporation rates and overall distillation performance.

The conical glass cover promotes better light penetration, minimizing the shading effect. Moreover, output of the ongoing research work has been compared with the earlier research for the validation.

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APPENDIX - A

$(AF_R(\alpha\tau))_1 = PF_1\alpha\tau^2 A_R F_R$; $(A\,F_R U_L)_1 = (1-K_k)\dot{m}_f c_f$; $PF_1 = \frac{h_{pf}}{F' h_{pf} + U_{tpa}}$;

$U_L = \frac{U_{t,pa}.h_{pf}}{F' h_{pf} + U_{t,pa}}$; $F_R = \frac{\dot{m}_f C_f}{U_L A_R}\left[1 - \exp\left(-\frac{2\pi r' L' U_L}{\dot{m}_f c_f}\right)\right]$; $K_K = \left(1 - \frac{A_R F_R U_L}{\dot{m}_f c_f}\right)$

$h_{pf} = 100\,Wm^2K^{-1}$ and $U_{t,pa} = \left[\frac{Ro_2}{R_{o1}h_i} + \frac{R_{o2}\ln\left(\frac{Ri_2}{Ri_1}\right)}{K_g} + \frac{1}{C_{ev}} + \frac{R_{o2}\ln\left(\frac{Ro_2}{Ro_1}\right)}{K_g} + \frac{1}{h_o}\right]^{-1}$

$$A_1 = A_g^2 h_{1g}^2 T_a + A_b A_g h_{1g} h_{1wW} T_a + 2A_g^2 h_{1g} h_{EW} T_a + A_g^2 h_{1g} I_{SE}\dot{\alpha}_g + A_b A_g h_{1wW} I_{SE}\dot{\alpha}_g + A_g^2 h_{EW} I_{SE}\dot{\alpha}_g + A_g^2 h_{EW} I_{SW}\dot{\alpha}_g$$

$$A_2 = A_b A_g h_{1wE} h_{1g} + A_b^2 h_{1wE} h_{1wW} + A_b A_g h_{1wE} h_{EW} + A_b A_g h_{1wW} h_{EW}$$

$$B_1 = A_g^2 h_{1g}^2 T_a + A_b A_g h_{1g} h_{1wE} T_a + 2A_g{}^2 h_{1g} h_{EW} T_a + A_g^2 h_{1g} I_{SE}\dot{\alpha}_g + A_b A_g h_{1wE} I_{SW}\dot{\alpha}_g + A_g^2 h_{EW} I_{SW}\dot{\alpha}_g + A_g^2 h_{EW} I_{SW}\dot{\alpha}_g$$

$$B_2 = A_b A_g h_{1wW} h_{1g} + A_b^2 h_{1wE} h_{1wW} + A_b A_g h_{1wE} h_{EW} + A_b A_g h_{1wW} h_{EW}$$

$$C_1 = A_g^2 h_{1g}^2 T_a + A_b A_g h_{1g} h_{1wN} T_a - 2A_g{}^2 h_{1g} h_{NS} T_a + A_g^2 h_{1g} I_{SS}\dot{\alpha}_g + A_b A_g h_{1wN} I_{SS}\dot{\alpha}_g - A_g^2 h_{NS} I_{SN}\dot{\alpha}_g - A_g^2 h_{NS} I_{SS}\dot{\alpha}_g$$

$$C_2 = A_b A_g h_{1wS} h_{1g} + A_b^2 h_{1wN} h_{1wS} - A_b A_g h_{1wN} h_{NS} - A_b A_g h_{1wS} h_{NS}$$

$$D_1 = A_g^2 h_{1g}^2 T_a + A_b A_g h_{1g} h_{1wS} T_a - 2A_g{}^2 h_{1g} h_{NS} T_a + A_g^2 h_{1g} I_{SN}\dot{\alpha}_g + A_b A_g h_{1wS} I_{SN}\dot{\alpha}_g - A_g^2 h_{NS} I_{SN}\dot{\alpha}_g - A_g^2 h_{NS} I_{SS}\dot{\alpha}_g$$

$$D_2 = A_b A_g h_{1wN} h_{1g} + A_b^2 h_{1wN} h_{1wS} - A_b A_g h_{1wN} h_{NS} - A_b A_g h_{1wS} h_{NS}$$

$$P_1 = A_b A_g h_{1wE} h_{1g} + A_g^2 h_{1g}^2 + A_b^2 h_{1wE} h_{1wW} + A_b A_g h_{1wW} h_{1g} + A_b A_g h_{1wE} h_{EW} + 2A_g^2 h_{1g} h_{EW} + A_b A_g h_{1wW} h_{EW}$$

$$P_2 = A_b A_g h_{1wN} h_{1g} + A_g^2 h_{1g}^2 + A_b^2 h_{1wN} h_{1wS} + A_b A_g h_{1wS} h_{1g} - A_b A_g h_{1wS} h_{NS} - 2A_g^2 h_{1g} h_{NS} - A_b A_g h_{1wN} h_{NS}$$

$$I_e = -(A_g^2 h_{1g} I_{SE}\dot{\alpha}_g + A_b A_g h_{1wW} I_{SE}\dot{\alpha}_g + A_g^2 h_{EW} I_{SE}\dot{\alpha}_g + A_g^2 h_{EW} I_{SW}\dot{\alpha}_g)$$

$$I_w = -(A_g^2 h_{1g} I_{SW}\dot{\alpha}_g + A_b A_g h_{1wE} I_{SW}\dot{\alpha}_g + A_g^2 h_{EW} I_{SE}\dot{\alpha}_g + A_g^2 h_{EW} I_{SW}\dot{\alpha}_g)$$

$$I_s = -(A_g^2 h_{1g} I_{SS} \dot{\alpha}_g + A_b A_g h_{1wN} I_{SS} \dot{\alpha}_g - A_g^2 h_{NS} I_{SS} \dot{\alpha}_g - A_g^2 h_{NS} I_{SN} \dot{\alpha}_g)$$

$$I_n = -(A_g^2 h_{1g} I_{SN} \dot{\alpha}_g + A_b A_g h_{1wS} I_{SN} \dot{\alpha}_g - A_g^2 h_{NS} I_{SN} \dot{\alpha}_g - A_g^2 h_{NS} I_{SS} \dot{\alpha}_g)$$

$$U_e = (A_g^2 h_{1g}^2 + A_b A_g h_{1g} h_{1wW} + 2 A_g^2 h_{1g} h_{EW})$$

$$U_w = (A_g^2 h_{1g}^2 + A_b A_g h_{1g} h_{1wE} + 2 A_g^2 h_{1g} h_{EW})$$

$$U_s = (A_g^2 h_{1g}^2 + A_b A_g h_{1g} h_{1wN} - 2 A_g^2 h_{1g} h_{NS})$$

$$U_n = (A_g^2 h_{1g}^2 + A_b A_g h_{1g} h_{1wS} - 2 A_g^2 h_{1g} h_{NS})$$

$$E = \left(\frac{h_{ewgE} I_e + h_{ewgW} I_w}{P_1} + \frac{h_{ewgS} I_s + h_{ewgN} I_n}{P_2} \right) \left(\frac{A_b}{4} \right)$$

$$F_1 = \left(\frac{h_{1wE} U_e + h_{1wW} U_w}{P_1} + \frac{h_{1wS} U_s + h_{1wN} U_n}{P_2} \right) \left(\frac{A_b}{4} \right);$$

$$h_{ewE} = 0.016273\ h_{cwgE} \left[\frac{P_w - P_{gE}}{T_w - T_{gE}} \right]$$ (Cooper 1969)

$$h_{ewgW} = 0.016273\ h_{cwgW} \left[\frac{P_w - P_{gW}}{T_w - T_{gW}} \right]$$ (Cooper 1969)

$$h_{ewS} = 0.016273\ h_{cwgS} \left[\frac{P_w - P_{gS}}{T_w - T_{gS}} \right]$$ (Cooper 1969)

$$h_{ewgN} = 0.016273\ h_{cwgN} \left[\frac{P_w - P_{gN}}{T_w - T_{gN}} \right]$$ (Cooper 1969)

$$h_{cwgE} = 0.884 \left[(T_w - T_{gE}) + \frac{(P_w - P_{gE})(T_w + 273)}{268.9 \times 10^3 - P_w} \right]^{\left(\frac{1}{3}\right)}$$ (Dunkle 1961)

$$h_{cwgW} = 0.884 \left[(T_w - T_{gW}) + \frac{(P_w - P_{gW})(T_w + 273)}{268.9 \times 10^3 - P_w} \right]^{\left(\frac{1}{3}\right)}$$ (Dunkle 1961)

$$h_{cwgS} = 0.884 \left[(T_w - T_{gS}) + \frac{(P_w - P_{gS})(T_w + 273)}{268.9 \times 10^3 - P_w} \right]^{\left(\frac{1}{3}\right)}$$ (Dunkle 1961)

$$h_{cwgN} = 0.884 \left[(T_w - T_{gN}) + \frac{(P_w - P_{gN})(T_w + 273)}{268.9 \times 10^3 - P_w} \right]^{\left(\frac{1}{3}\right)}$$ (Dunkle 1961)

$$P_w = exp\left[25.317 - \frac{5144}{(T_w+273)}\right]; \quad P_{gE} = exp\left[25.317 - \frac{5144}{(T_{gE}+273)}\right];$$

$$P_{gW} = exp\left[25.317 - \frac{5144}{(T_{gW}+273)}\right]; P_{gS} = exp\left[25.317 - \frac{5144}{(T_{gS}+273)}\right];$$

$$P_{gN} = exp\left[25.317 - \frac{5144}{(T_{gN}+273)}\right]$$

$$h_{EW} = 0.034 \times 5.67 \times 10^{-8}\left[\left(T_{gE}+273\right)^2 + \left(T_{gW}+273\right)^2\right]\left[T_{gE}+T_{gW}+546\right]$$

$$h_{NS} = 0.034 \times 5.67 \times 10^{-8}\left[\left(T_{gN}+273\right)^2 + \left(T_{gS}+273\right)^2\right]\left[T_{gN}+T_{gS}+546\right]$$

APPENDIX - B

Table B1: Average hourly radiations (W/m^2) for type 'a' weather situation for New Delhi

Solar Radiation	Month► Time▼	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
Global	8am	132.99	180.29	266.77	368.14	406.31	436.67	367.36	333.59	277.96	168.75	121.46	93.12
	9am	355.56	403.58	488.94	588.48	608.84	637.22	587.04	528.54	501.30	364.58	316.04	275.27
	10am	554.69	594.44	671.21	767.81	776.26	802.22	737.27	674.49	682.04	565.28	485.35	443.25
	11am	680.73	729.39	804.33	888.32	897.98	915.00	831.71	820.20	809.07	694.45	609.97	565.87
	12pm	726.74	786.02	866.93	941.01	956.82	951.67	881.48	868.18	869.07	761.80	664.01	621.83
	1pm	733.85	792.03	869.28	944.12	950.51	946.11	896.53	807.83	855.19	756.25	657.45	618.39
	2pm	656.08	728.58	803.15	878.68	886.62	882.78	820.60	766.67	779.81	686.11	587.37	553.31
	3pm	500.00	584.23	665.33	746.90	761.37	765.56	753.24	658.08	656.48	543.75	454.17	426.19
	4pm	311.46	391.22	483.01	568.30	580.81	611.67	569.68	477.78	483.89	362.50	274.62	253.97
	5pm	106.42	178.23	264.10	348.61	372.48	420.00	373.15	305.81	270.19	152.08	84.09	68.78
Diffuse	8am	52.60	73.30	94.23	122.47	117.68	123.89	109.03	86.62	100.00	44.44	42.80	36.37
	9am	86.28	105.82	123.02	139.54	137.12	149.44	141.44	100.00	124.81	68.75	61.36	53.31
	10am	107.29	126.08	142.20	159.40	153.28	157.22	171.07	155.30	140.93	119.45	77.15	60.19
	11am	121.53	137.36	154.11	174.84	166.67	158.89	205.09	176.26	151.67	137.50	109.60	81.61
	12pm	126.39	141.31	153.21	180.39	174.24	167.78	218.75	189.65	152.41	147.92	141.67	142.46
	1pm	136.63	145.07	153.21	181.78	177.02	185.00	219.68	201.26	160.00	154.17	136.36	141.27
	2pm	128.30	138.35	151.12	177.45	175.76	180.56	204.86	197.48	164.26	142.36	131.82	119.18
	3pm	110.94	123.84	136.54	163.24	165.66	176.11	179.63	172.72	150.74	121.53	114.77	105.03
	4pm	90.28	101.52	116.35	146.08	154.29	142.78	149.54	128.28	123.15	93.06	88.01	78.84
	5pm	41.84	63.98	85.74	115.36	133.08	116.11	110.42	93.69	91.30	59.72	43.05	37.43
Beam	8am	80.38	106.99	172.54	245.67	288.64	312.78	258.33	246.97	177.96	124.31	78.66	56.75
	9am	269.27	297.76	365.92	448.94	471.72	487.78	445.60	428.54	376.48	295.83	254.67	221.96
	10am	447.40	468.37	529.01	608.41	622.98	645.00	566.20	519.19	541.11	445.83	408.21	383.07
	11am	559.20	592.03	650.21	713.48	731.31	756.11	626.62	643.94	657.41	556.95	500.38	484.26
	12pm	600.35	644.71	713.73	760.62	782.58	783.89	662.73	678.53	716.67	613.89	522.35	479.37
	1pm	597.22	646.95	716.08	762.34	773.48	761.11	676.85	606.57	695.19	602.08	521.09	477.12
	2pm	527.78	590.23	652.03	701.23	710.86	702.22	615.74	569.19	615.56	543.75	455.56	434.13
	3pm	389.06	460.39	528.79	583.66	595.71	589.45	573.61	485.36	505.74	422.23	339.39	321.16
	4pm	221.18	289.69	366.67	422.22	426.51	468.89	420.14	349.50	360.74	269.44	186.62	175.13
	5pm	64.58	114.25	178.37	233.25	239.40	303.89	262.73	212.12	178.89	92.36	41.04	31.35

Table B_2: Average hourly radiations (W/m^2) for type 'b' weather situation for New Delhi

Solar Radiation	Month▶ Time▼	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
Global	8am	119.58	186.67	300.45	413.11	439.11	433.34	398.66	366.89	277.34	260.00	153.11	86.66
	9am	332.50	425.84	540.22	635.55	641.34	641.34	592.22	551.78	499.78	442.00	332.22	280.22
	10am	516.25	609.59	733.78	808.89	794.45	794.45	751.11	713.55	687.55	598.00	470.89	456.45
	11am	650.41	752.50	872.45	936.00	898.45	912.89	840.66	832.00	788.66	693.34	574.89	580.66
	12pm	708.75	813.75	933.11	999.55	947.55	999.55	936.00	881.11	837.78	728.00	606.66	629.78
	1pm	723.33	822.50	938.89	982.22	936.00	996.66	907.11	881.11	860.89	702.00	563.34	635.55
	2pm	650.41	758.33	869.55	901.34	852.22	912.89	837.78	808.89	800.22	615.34	491.11	566.22
	3pm	498.75	603.75	713.55	751.11	722.22	808.89	707.78	687.55	667.34	465.11	352.45	424.66
	4pm	315.00	408.33	522.89	557.55	540.22	635.55	554.66	505.55	462.22	283.11	193.55	228.22
	5pm	110.84	183.75	288.89	332.22	340.89	416.00	352.45	317.78	265.78	98.22	86.66	63.55
Diffuse	8am	52.75	84.99	119.58	134.17	204.16	198.33	192.67	170.00	104.84	133.17	107.67	28.34
	9am	102.57	143.60	160.42	166.25	247.92	250.83	229.50	218.17	144.50	187.00	158.67	99.16
	10am	123.09	167.04	180.83	186.67	274.17	277.08	283.34	252.16	204.00	212.50	192.67	133.17
	11am	149.46	181.69	201.25	201.25	297.50	297.50	320.17	260.67	226.66	232.34	212.50	155.84
	12pm	155.32	190.49	204.16	215.84	300.42	300.42	340.00	277.66	240.83	238.00	218.17	170.00
	1pm	161.18	190.49	207.08	215.84	300.42	335.41	328.66	280.50	232.34	232.34	206.84	172.83
	2pm	155.32	181.69	198.33	210.00	297.50	315.00	311.67	252.16	223.83	218.17	201.16	161.50
	3pm	128.94	158.25	177.91	201.25	271.25	291.67	291.83	232.34	204.00	184.17	170.00	136.00
	4pm	96.71	123.09	154.58	175.00	239.17	274.17	243.67	218.17	170.00	141.67	121.83	99.16
	5pm	46.88	70.34	110.84	125.41	189.59	207.08	198.33	178.50	133.17	70.83	48.16	51.00
Beam	8am	66.83	101.68	180.86	278.94	234.95	235.00	206.00	196.89	172.5	126.83	45.44	58.33
	9am	229.94	282.24	379.80	469.31	393.42	390.50	362.72	333.61	355.28	255.00	173.55	181.05
	10am	393.17	442.55	552.95	622.22	520.28	517.36	467.77	461.39	483.55	385.50	278.22	323.27
	11am	500.95	570.81	671.19	734.75	600.95	615.39	520.50	571.33	562.00	461.00	362.39	424.83
	12pm	553.43	623.26	728.95	783.72	647.14	699.14	596.00	603.44	596.95	490.00	388.50	459.78
	1pm	562.15	632.01	731.81	766.38	635.58	661.25	578.44	600.61	628.56	469.66	356.50	462.73
	2pm	495.09	576.64	671.22	691.34	554.72	597.89	526.11	556.73	576.39	397.17	289.94	404.72
	3pm	369.81	445.50	535.64	549.86	450.97	517.22	415.95	455.22	463.34	280.94	182.44	288.67
	4pm	218.29	285.25	368.31	382.55	301.05	361.39	311.00	287.39	292.21	141.44	71.73	129.05
	5pm	63.95	113.41	178.05	206.81	151.30	208.92	154.12	139.28	132.61	27.39	38.50	12.55

Table B3: Average hourly radiations (W/m^2) for type 'c' weather situation for New Delhi

Solar Radiation	Month► Time▼	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
Global	8am	71.11	117.78	197.78	288.89	361.11	358.33	333.33	297.50	261.25	195.83	66.66	66.66
	9am	235.55	284.45	366.66	453.34	566.67	555.56	530.67	490.00	456.53	365.56	206.66	216.00
	10am	360.00	420.00	513.34	582.22	708.33	727.78	642.66	597.50	617.50	496.11	333.34	365.34
	11am	457.78	522.22	613.34	677.78	841.67	816.67	744.00	700.00	691.39	587.50	415.55	482.67
	12pm	515.55	562.22	664.45	724.45	894.44	833.33	778.67	702.50	730.97	624.06	444.45	544.00
	1pm	515.55	562.22	662.22	720.00	872.22	861.11	762.66	702.50	752.09	608.39	453.34	522.66
	2pm	462.22	506.66	602.22	664.45	805.56	763.89	722.67	630.00	712.50	514.39	406.66	448.00
	3pm	353.34	384.45	497.78	564.45	666.67	688.89	602.67	540.00	575.28	383.83	313.34	341.34
	4pm	217.78	266.66	353.34	420.00	513.89	538.89	469.33	430.00	414.30	229.77	177.78	200.00
	5pm	71.11	111.11	188.89	233.34	322.22	333.33	280.00	282.50	255.97	73.11	62.22	58.67
Diffuse	8am	64.16	91.66	134.44	187.50	215.28	277.77	205.84	239.58	169.30	130.56	63.89	45.84
	9am	146.66	161.94	192.50	236.11	291.66	350.70	263.89	290.70	239.58	172.22	137.36	122.22
	10am	195.56	201.66	229.16	277.77	336.80	378.47	295.55	348.20	300.28	205.56	185.28	171.12
	11am	220.00	232.22	241.38	305.55	392.36	416.66	345.70	370.55	313.05	230.56	223.61	226.12
	12pm	226.12	244.44	253.62	319.45	440.97	434.03	387.91	376.95	367.36	241.67	245.97	250.56
	1pm	226.12	241.38	268.88	326.39	440.97	423.61	366.80	367.36	364.17	236.11	258.75	247.50
	2pm	210.84	247.50	259.72	322.91	378.47	402.78	340.41	351.39	345.00	213.89	230.00	235.28
	3pm	180.28	213.88	232.22	284.73	333.34	385.41	321.95	316.25	303.47	188.89	191.67	189.44
	4pm	122.22	168.06	189.44	246.53	319.45	347.22	263.89	277.92	255.55	141.67	140.55	125.28
	5pm	51.94	85.56	128.34	177.09	253.47	246.53	184.72	207.64	198.05	63.89	61.89	61.16
Beam	8am	6.95	26.11	63.33	101.39	145.84	80.56	127.49	57.92	91.95	65.27	2.77	23.60
	9am	88.89	122.51	174.16	217.22	275.01	204.86	266.78	199.30	216.95	193.34	69.31	102.78
	10am	164.44	218.34	284.17	304.45	371.53	349.31	347.11	249.30	317.22	290.55	148.06	209.44
	11am	237.78	290.00	371.95	372.23	449.31	400.01	398.30	329.45	378.34	356.94	191.95	276.66
	12pm	289.44	317.78	410.83	405.00	453.47	399.31	390.75	325.56	363.61	382.39	198.47	316.11
	1pm	289.44	320.84	393.34	393.61	431.25	437.50	395.86	335.15	387.92	372.28	194.59	296.94
	2pm	251.39	259.16	342.50	341.54	427.08	361.11	382.26	278.61	367.50	300.50	176.66	231.39
	3pm	173.06	170.56	265.56	279.72	333.33	303.48	280.72	223.75	271.81	194.94	121.67	166.12
	4pm	95.56	98.61	163.89	173.47	194.44	191.67	205.44	152.08	158.75	88.10	37.22	83.05
	5pm	19.17	25.55	60.55	56.25	68.75	86.80	95.29	74.86	57.91	9.22	1.67	3.05

Table B4: Average hourly radiations (W/m^2) for type ‘d’ weather situation for New Delhi

Solar Radiati	Month► Time▼	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
	8am	51.20	94.30	169.75	266.75	304.12	235.12	262.50	208.47	155.00	110.84	63.88	54.45
	9am	140.11	188.61	331.42	441.89	503.44	350.12	397.50	358.89	287.50	237.66	184.00	176.95
	10am	237.11	247.89	479.61	600.86	623.56	454.88	515.00	440.70	425.00	375.66	273.44	272.22
	11am	301.78	291.00	552.36	716.72	702.78	595.44	587.50	530.41	557.50	488.12	375.66	356.61
Global	12pm	379.92	369.14	590.08	773.30	761.56	672.12	605.00	572.64	585.00	503.44	444.66	397.45
	1pm	379.92	412.25	627.80	757.14	764.12	682.34	615.00	588.47	585.00	511.12	477.88	405.61
	2pm	328.72	374.53	568.53	689.78	621.00	631.22	517.50	562.09	530.00	454.88	424.22	359.34
	3pm	261.36	299.08	463.45	541.58	529.00	536.66	445.00	496.11	442.50	339.88	337.34	239.55
	4pm	161.67	204.78	307.17	425.72	426.78	426.78	347.50	348.34	350.00	237.66	198.33	141.55
	5pm	45.80	88.92	161.67	239.80	255.56	281.12	232.50	195.28	187.50	113.75	66.44	52.72
	8am	48.16	90.67	147.33	207.85	236.17	169.56	215.96	177.50	127.20	107.34	49.58	52.50
	9am	107.67	150.16	229.50	261.95	342.14	251.31	298.08	257.38	224.83	195.42	116.67	140.00
	10am	175.66	204.00	297.50	321.74	372.42	360.31	377.16	340.20	310.63	280.00	145.83	186.67
	11am	221.00	229.50	351.33	387.22	429.94	405.72	438.00	375.71	405.30	335.41	207.08	227.50
Diffuse	12pm	246.50	269.17	357.00	404.30	466.28	454.17	441.04	396.41	414.17	364.58	256.66	262.50
	1pm	255.00	289.00	374.00	432.78	466.28	481.42	431.91	428.96	402.34	332.50	306.25	303.33
	2pm	240.83	272.00	328.66	387.22	399.67	448.11	386.29	402.34	360.92	282.91	277.08	291.67
	3pm	187.00	204.00	303.16	333.12	372.42	393.61	358.92	346.13	295.84	259.58	239.17	207.08
	4pm	138.83	150.16	212.50	298.96	314.89	330.03	276.79	266.25	266.25	224.58	196.78	122.50
	5pm	42.50	82.17	144.50	205.00	230.11	260.39	197.71	162.71	174.54	104.78	64.17	51.50
	8am	3.03	3.64	22.42	58.90	67.94	65.55	46.55	30.96	27.79	3.50	14.30	1.95
	9am	32.44	38.44	101.92	179.94	161.30	98.80	99.42	101.51	62.66	42.25	67.33	36.95

	10am	61.44	43.89	182.10	279.12	251.14	94.57	137.84	100.49	114.37	95.66	127.61	85.56
	11am	80.77	61.50	201.03	329.50	272.84	189.72	149.50	154.70	152.20	152.70	168.58	129.11
	12pm	133.42	99.98	233.08	369.00	295.28	217.94	163.95	176.23	170.83	138.86	188.00	134.95
Beam	1pm	124.92	123.25	253.80	324.37	297.83	200.92	183.09	159.51	182.66	178.61	171.63	102.28
	2pm	87.89	102.52	239.86	302.55	221.33	183.11	131.21	159.75	169.08	171.97	147.14	67.67
	3pm	74.36	95.08	160.28	208.46	156.58	143.05	86.08	149.98	146.67	80.30	98.17	32.47
	4pm	22.84	54.61	94.67	126.76	111.89	96.75	70.70	82.09	83.75	13.08	1.56	19.05
	5pm	3.30	6.75	17.17	34.80	25.45	20.73	34.78	32.57	12.95	8.97	2.28	0.78

Table B_5: Surrounding temperature for an archetypal day in each month of year for New Delhi climate

Month► Time▼	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
12 am	7.80	10.00	15.10	28.40	36.00	32.10	30.20	27.00	28.00	24.90	19.00	13.00
1 am	7.30	9.80	14.20	27.60	34.10	27.10	28.00	25.50	27.10	23.00	19.10	10.00
2 am	6.60	9.60	14.00	26.00	31.00	25.20	26.20	25.30	26.00	21.10	17.00	9.20
3 am	5.00	8.30	13.30	24.20	28.10	24.10	24.00	25.00	26.90	21.00	16.00	8.50
4 am	4.00	8.00	13.10	24.00	27.00	24.00	25.00	24.60	25.00	19.00	15.00	7.00
5 am	5.30	8.10	14.10	24.00	27.60	25.00	26.50	24.60	26.00	20.00	15.40	9.00
6 am	6.40	9.00	15.50	25.50	28.00	26.90	26.20	24.00	26.10	19.50	16.30	9.30
7 am	6.80	9.20	15.70	25.10	30.80	26.60	26.10	24.10	27.50	20.10	16.20	9.50
8am	7.90	9.20	15.80	25.00	30.80	26.50	26.10	24.30	27.90	21.00	17.00	9.60
9am	7.90	9.10	15.90	25.00	30.80	26.30	26.10	24.30	27.90	21.00	16.70	9.10
10am	7.90	8.90	15.90	25.00	30.10	26.30	26.20	24.30	27.90	20.50	16.50	8.90
11am	6.60	8.80	15.80	25.10	30.60	26.50	26.30	24.30	28.30	20.50	16.00	8.70
12pm	6.40	8.90	16.60	25.90	31.80	27.30	26.60	24.40	28.90	22.70	16.20	9.40
1pm	7.70	11.40	19.90	27.60	33.80	29.90	28.00	25.50	30.60	25.00	20.50	13.10
2pm	10.60	15.10	22.80	30.30	35.30	31.40	28.40	25.60	32.30	28.30	25.00	16.80
3pm	13.00	18.30	26.20	31.70	36.60	32.20	29.30	26.00	33.50	30.50	27.60	19.30
4pm	15.00	20.10	27.00	33.20	37.60	33.60	30.40	26.40	33.90	31.60	28.50	20.90
5pm	16.50	21.60	28.90	34.40	38.50	34.30	32.20	27.10	35.50	32.70	29.60	21.70
6 pm	17.00	22.20	25.30	35.30	40.30	34.20	33.80	28.30	36.00	34.00	30.20	20.00
7 pm	15.80	20.70	24.20	34.20	40.00	34.20	33.00	28.00	35.00	32.30	27.00	18.00
8 pm	14.10	19.60	21.10	32.30	38.60	34.10	32.60	27.30	32.00	30.00	25.10	17.00
9 pm	12.90	18.30	20.30	30.00	38.00	34.00	32.40	27.00	29.20	28.10	23.00	15.00
10 pm	10.20	15.20	18.20	29.30	38.00	35.00	31.50	27.50	28.10	27.20	21.00	14.50
11 pm	8.20	13.50	15.00	29.00	37.30	35.00	31.20	27.20	28.00	26.00	19.10	14.20

Table B_6: Number of various types of days in each month of year for New Delhi climate

Type of days	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
a	3	3	5	4	4	3	2	2	7	5	6	3
b	8	4	6	7	9	4	3	3	3	10	10	7
c	11	12	12	14	12	14	10	7	10	13	12	13
d	9	9	8	5	6	9	17	19	10	3	2	8

LIST OF PUBLICATIONS

1. **Abhishek Kumar**, Rajesh Kumar. Annual energy, exergy, and efficiency analyses for conical solar still combined with N number of evacuated collectors. Environ Prog Sustainable Energy. 2025;44(1):e14527. doi:10.1002/ep.14527 **(Published) (SCIE indexed)**
2. **Abhishek Kumar**, Rajesh Kumar. Exergo–enviro–economic analyses and productivity evaluation of conical solar still integrated with evacuated collectors for sustainable solar distillation. Desalin Water Treat 2024; 320:100651. https://doi.org/10.1016/j.dwt.2024.100651 **(Published) (SCIE indexed)**
3. **Abhishek Kumar**, Rajesh Kumar. Enhancing Water Sustainability Through Conical Solar Still Technology: A Comprehensive Review, Paper presented at: International Conference on Renewable Energy and Sustainable Technology (ICREST-2024) July 4-6, 2024 at Jamia Millia Islamia (Central University), New Delhi, India.
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ORIGINAL RESEARCH
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ENVIRONMENTAL PROGRESS & SUSTAINABLE ENERGY

Annual energy, exergy, and efficiency analyses for conical solar still combined with N number of evacuated collectors

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Abstract

The utilization of solar energy technology for obtaining clean water for use of society in remote locations will help in fulfilling the sustainable development goals of the United Nations. Also, promotion of solar energy for the use of society will subside dependency on the fossil fuel or conventional energy. This article deals with the annual energy, exergy, and efficiency analyses of N identical ETCs incorporated conical solar still (NETC-CSS). The thermal model for the proposed system has been developed based on equating input and output heats for different elements. The developed fundamental equations are fed to the MATLAB computational code. The four weather situations in each month of year for New Delhi climate is considered for the annual analysis. The annual energy, exergy, thermal efficiency, and exergy efficiency for NETC-CSS are computed to be 1796.61, 170.19 kWh, 38.79%, and 3.94% under optimized values of mass flow rate and number of collectors. Results are compared with earlier published research. Concludingly, the increase in annual energy, exergy, thermal efficiency, and exergy efficiency for NETC-CSS is 68.03% than modified solar still, 74.14% than conventional conical solar still, 61.12% than modified solar still, and 72.59% than solar still with parabolic trough collector.

KEYWORDS
conical solar still, efficiency, energy, evacuated collector, exergy, yield

1 | INTRODUCTION

The examination of active solar still is essential in the present era to address the freshwater scarcity issue. This technology powered by solar energy offers a sustainable solution without harming the environment. Also, it aligns with the United Nations sustainable goal number 6, which focuses on ensuring clean water and sanitation for all. The greenhouse effect is used by solar still for getting freshwater from dirty water with the help of solar energy.

Solar stills can be categorized as either passive or active. Passive solar stills are straightforward in design but typically produce lower output. To enhance performance, heat can be supplied to the basin of a passive solar still using a solar collector. When a passive solar still is combined with a heat supplying element, it becomes an active solar still. This concept was initially explored by Rai and Tiwari in 1983.[1] Since then, many advancements in design have been made, which are detailed in following sections.

Utilizing an evacuated collector increases the heat provided to the basin of a solar still, as it effectively minimizes convective heat loss, leaving only radiative heat loss.[2] In contrast, other collectors experience both radiative and convective heat transfers.[3] Research incorporating evacuated tubes in a natural circulation mode into a solar still concluded that the optimal number of tubes was 10 and resulted in a freshwater output of 3.8 kg per unit area.[4,5] Esen and Esen[6] studied solar water heater with different refrigerants and concluded that the best performance was obtained using R410A because of its higher latent heat value. Esen et al.[7] investigated heat pump with heat exchanger and reported the efficiency of the system as

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Exergo-enviro-economic analyses and productivity evaluation of conical solar still integrated with evacuated collectors for sustainable solar distillation

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ABSTRACT

Utilizing solar energy for freshwater production offers a sustainable solution to freshwater crisis, aligning with United Nation's sustainable development goals. While recent research has explored conical solar still, there is an untapped potential in active conical solar distillers. Also, the conical solar still has less shading effect as compared to other solar stills which motivated us to work on it. The proposed work focuses on exergo-enviro-economic, productivity, freshwater cost and payback period analyses for conical solar still combined with N number of evacuated tubular collectors (NETC-CSS) under optimized condition. Fundamental equations derived using thermodynamic principle is implemented in MATLAB with supporting data. For N = 0, results of NETC-CSS are validated against existing experimental data. The analysis is done for the whole year of New Delhi, encompassing all four weather conditions in each month. Concludingly, exergy output per unit ₹, annual productivity, freshwater cost and the payback period are obtained as 0.841 kWh/₹, 630.80 %, ₹ 0.79 per kg and 4.03 year respectively at a 2 % interest rate and 30-years life span. The enviro-economic parameter is higher by 84.30 % and freshwater cost is lower by 81.10 % for NETC-CSS when compared with modified water-cooled solar still and dish integrated solar still respectively.

1. Introduction

Analysing solar stills is crucial for addressing freshwater scarcity in remote areas abundant with sunlight and impure water. The solar still has the potential to provide the solution to freshwater scarcity in a sustainable manner because solar still works on solar energy and does not emit any harmful elements that may have detrimental effect on the environment. This technology is environment friendly. The enviro-economic analysis of solar system is important for ensuring the sustainable solution to the freshwater scarcity issue. Also, productivity analysis is needed because it gives information about the feasibility of the system. The solar still may passive or active type. The passive type solar still when combined with some kind of heat supplying element form active type solar still. In 1983, Rai and Tiwari conducted experiments on active-type solar stills, contributing significantly to the advancement of this technology [1]. From that time onwards, many developments in the design of solar still have been reported worldwide. It has been summarised in the paragraphs that follow.

The use of evacuated collector provides higher heat to the basin of solar still because heat loss by convection does not take place. Only radiative heat loss occurs in the case of evacuated collectors [2], whereas other types of collectors involve both radiative and convective heat transfers [3]. In an investigation on solar stills, evacuated tubes were incorporated in natural circulation mode. The study concluded that the optimal number of tubes was 10, with a reported freshwater output of 3.8 kg per unit area [4–6] reported the investigation of solar stills incorporating evacuated tubes determined that the daily optimal freshwater output reached 3.9 kg, surpassing the freshwater output of solar stills equipped with evacuated tubes operating in natural circulation mode. Shafii et al. [7] conducted experiments on solar stills by integrating evacuated tubes and a thermoelectric generator to utilize the heat of condensation from vapor. Their conclusion highlighted that the freshwater production in the described system was 3.13 times greater than that of passive solar stills, attributed to the additional heat supplied to the basin. Sharshir et al. [8] investigated solar still by incorporating evacuated heater and the humidification-dehumidification

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RESEARCH PUBLICATIONS:

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- Kumar, A. and Kumar, R. 2024. Enhancing Solar Distillation Efficiency with Nanofluids: A Comprehensive Review. Energy & Environment Advances 1(4), pp. 178-192; https://doi.org/10.69626/eea.2024.0178.

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Abhishek

Abhishek Kumar