Review

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Solar Heat for Industrial Processes (SHIP): An Overview of Its Categories and a Review of Its Recent Progress

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Review

Solar Heat for Industrial Processes: An Overview of Its Categories and a Review of Its Recent Progress

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Abstract

SHIP (solar heat for industrial processes) refers to the use of collected solar radiation for meeting industrial heat demands, rather than for electricity generation. The global thermal capacity of SHIP systems at the end of 2024 stood slightly above 1 GWth, which is comparable to the electric power capacity of a single power station. Despite this relatively small presence, SHIP systems play an important role in rendering industrial processes sustainable. There are two aims in the current study. The first aim is to cover various types of SHIP systems based on the variety of their collector designs, operational temperatures, applications, radiation concentration options, and solar tracking options. SHIP designs can be as simple as unglazed solar collectors (USC), having a stationary structure without any radiation concentration. On the other hand, SHIP designs can be as complicated as solar power towers (SPT), having a two-axis solar tracking mechanism with point-focused concentration of the solar radiation. The second aim is to shed some light on the status of SHIP deployment globally, particularly in 2024. This includes a drop during the COVID-19 pandemic. The findings of the current study show that more than 1,300 SHIP systems were commissioned worldwide by the end of 2024 (cumulative number), constituting a cumulative thermal capacity of 1,071.4 MWth, with a total collector area of 1,531,600 m^2. In 2024 alone, 120.3 MWth of thermal capacity was introduced in 106 SHIP systems having a total collector area of 171,874 m^2. In 2024, 65.9% of the installed global thermal capacity of SHIP systems belonged to the parabolic trough collectors (PTC), and another 22% of this installed global thermal capacity was attributed to the unevacuated flat plate collectors (FPC-U). Considering the 106 SHIP systems installed in 2024, the average collector area per system was 1,621.4 m^2/project. However, this area largely depends on the SHIP category, where it is much higher for parabolic trough collectors (37,740.5 m^2/project), but lower for flat plate collectors (805.2 m^2/project), and it is lowest for unglazed solar collectors (163.0 m^2/project). The study anticipates large deployment in SHIP systems (particularly the PTC type) in 2026 in alignment with giga-scale solar-steam utilization in alumina production. Several recommendations are provided with regard to the SHIP sector.

Keywords: SHIP; solar heat; industrial processes; solar thermal; collector area

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1. Introduction

1.1. Classifications of SHIP Systems

Solar thermal (ST) technologies refer to the use of solar heat in the form of thermal radiation of electromagnetic waves emitted by the sun [1] in useful applications other than electricity generation. This thermal radiation encompasses a wide spectrum, such as the visible portion and the ultraviolet portion. However, the infrared portion of this thermal radiation from the sun has more contribution to the solar heating power. Solar thermal technologies can be divided into two major branches based on the main use of the collected solar heat [2].

The first major branch of solar thermal (ST) technologies [3] is concentrated solar power (CSP) [4], which aims to ultimately convert the collected solar heat into electricity, in a way similar to conventional heat engines and thermal power plants [5], with the difference being the use of renewable clean solar energy [6] rather than combustible fuels or nuclear fuels [7,8]. In order to meet the high temperatures and intensified heating rates required for electricity generation [9], the concept of concentrating the collected solar irradiance is adopted in CSP collectors [10]. Such concentrating collectors can magnify the incoming solar radiation by a multiplicative factor of 30–80 for line-focused designs (line-concentrators), and by a multiplicative factor of 200–4,000 for point-focused designs (point-concentrators) [11–14].

In Table **1**, I classify various solar concentrating collectors based on the geometric shape of the concentrated reflected solar radiation, which can be either a line or a point.

Table 1. Classification of solar concentrating collectors by focusing zone.

	Line-Focused (Line-Concentrator)	Point-Focused (Point-Concentrator)
Type 1	LFR (linear Fresnel reflector) CLFR (compact linear Fresnel reflector)	PDC (parabolic dish collector)
Type 2	PTC (parabolic trough collector)	SPT (solar power tower) or heliostats

It is worth differentiating here between compact linear Fresnel reflectors (CLFR) and linear Fresnel reflectors (LFR). A solar power system having compact linear Fresnel reflectors (CLFR) in fact resembles the simpler one having linear Fresnel reflectors (LFR), but differs in terms of the ability of these collector mirrors to transmit their reflected concentrated radiation to two or more overhead heat absorbers (receivers), rather than to one absorber only as in the case of the simpler LFR [15,16]. Point-focused CSP systems permit higher temperatures compared to line-focused systems. The solar power tower (SPT) and the parabolic dish collector (PDC) types of point-focused collectors can heat the working fluid in the heat absorber to above 1,000 °C [17–22]; while the parabolic trough collector (PTC) and the linear Fresnel reflectors (LFC) types of line-focused collectors can heat the working fluid in the heat absorber to about half of this, with the possibility of reaching 550 °C [23–26].

The PTC, LFR/CLFR, and SPT types of CSP (concentrated solar power) systems typically utilize the two-phase Rankine thermodynamic cycle [27,28] for converting the absorbed solar heat into mechanical shaft power that, in turn, can be converted into electric power using an electric generator [29,30]. The working fluid can be water with two phases, namely an incompressible liquid [31] and a compressible vapor/gas [32]. The PDC type of CSP systems utilizes the single-phase Stirling cycle and principles of gasdynamics and thermodynamics [33,34], where the working fluid is always in the gaseous phase, and this gas is commonly helium or hydrogen [35–37].

Like photovoltaic (PV) solar power systems, concentrated solar power (CSP) systems generate clean electricity produced without any combustion process [38–40]. This clean electricity can be used in transitioning the economy with its various sectors, particularly the buildings sector [41–43], the transportation sector [44–47], the industrial sector [48–51], and the electricity generation sector [52–56], into a net-zero emission alternative. In addition, this clean (green) electricity allows producing clean (green) hydrogen [57–59] by water electrolysis, and this green hydrogen can be used directly as a clean fuel [60–63] or can be further processed to produce green synthetic fuels.

The second major branch of solar thermal (ST) technologies is the solar heat for industrial processes (SHIP) [64–66], in which the collected solar heat is used in various heat-demanding processes, such as boiling, distillation, wood drying, food drying, paint drying, textile dyeing, nitrate melting, pulping, space heating, water heating for residential use, agricultural greenhouse heating, industrial heat treatment, sterilizing, and solar heating via vapor absorption refrigeration cycles [67–70].

SHIP collectors include those mentioned earlier for the CSP (concentrated solar power) applications, in which radiation concentration allows elevated temperatures. However, for SHIP applications, such concentrator collectors are designed to have a temperature rise below the range needed for electricity generation; with SHIP temperature ranges limited to about 400 °C. It is worth mentioning that higher-temperature SHIP uses are possible, but are not common [71].

There are non-concentrating SHIP collectors, used only for SHIP applications (not commonly used in CSP applications). These non-concentrating SHIP collectors can be divided into three categories based on the operational temperature range (the range of the temperature rise occurring in the heated fluid). This classification is illustrated in Table **2**.

Table 2. Classification of SHIP systems by the temperature rise [71–75].

Collector type	**Low temperature rise (below 75 °C)**	**Medium temperature rise (75–150 °C)**	**High temperature rise (150–400 °C)**
SAC (solar air collector)	✓		
PVT (photovoltaic-thermal)	✓		
USC (unglazed solar collector)	✓		
FPC-U (flat plate collector, unevacuated)	✓	✓	✓
FPC-E (flat plate collector, evacuated)	✓	✓	✓
ETC (evacuated tube collector)	✓	✓	✓
ETC-CPC (evacuated tube collector, with compound parabolic concentrator)		✓	✓
PTC-U (parabolic trough collector, unevacuated absorber)		✓	✓
PTC-E (parabolic trough collector, evacuated absorber)		✓	✓
LFR-U (linear Fresnel reflector, unevacuated absorber); also, CLFR-U (compact linear Fresnel reflector, unevacuated)		✓	✓
LFR-E (linear Fresnel reflector, evacuated absorber); also, CLFR-E (compact linear Fresnel reflector, evacuated)		✓	✓
PDC (parabolic dish collector)		✓	✓
SPT (solar power tower) or heliostats			✓

The explanation for the above classification (by the target temperature rise) is that low-temperature rise SHIP collectors are those without the ability to concentrate the collected solar radiation. On the other hand, SHIP collectors with the ability to concentrate collected solar radiation are intended for either medium or high temperature rises. Their geometric complexity and capital cost do not justify using them for low-temperature rises, while other simpler and cheaper non-concentrating SHIP systems can achieve this target. The extreme solar concentration levels offered by the SPT (solar power tower) design make it a unique option among the concentrating SHIP systems in terms of being more relevant for high temperature rises in excess of 150 °C, rather than for medium temperature rises below that.

The stated temperature rise for each application in the above table is dictated by the heating process involved in the application itself. For example, chemical boiling for distillation purposes is a common separation process for homogeneous liquid mixtures [76]. This chemical process can take place at the low-temperature range (below 75 °C) for distillation processes performed in a partial vacuum (where the boiling pressure is reduced) or for liquids with naturally low boiling points (BP). For example, bio-oil produced from algae can be distilled with vacuum distillation at 50 °C at a

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reduced absolute pressure of 40 mmHg (5.3 kPa), while it may require 120 °C for atmospheric distillation at a normal atmospheric pressure of 760 mmHg (101 kPa) [77]. Crude oil distillation, either in the initial atmospheric distillation unit (ADU) or the subsequent vacuum distillation unit (VDU) [78], involves temperatures above 350 °C [79,80]; making high-temperature SHIP ranges relevant.

Another way to classify SHIP systems is by their solar tracking capability. These systems can be:

(1) Stationary: no sun tracking, no moving parts
(2) Single-axis movable: the collector can tilt with one degree of freedom (DOF) only. The term degree of freedom here refers to an axis of permitting rotation to adjust the orientation [81,82].
(3) Dual-axis movable: the collector can tilt with two degrees of freedom (DOFs). Therefore, the collector can directly orient itself toward the sun [83–85].

The above classification is provided in Table **3**.

Table 3. Classification of SHIP systems by the solar tracking capability.

Collector type	Stationary	single-axis tracking	two-axis tracking
SAC (solar air collector)	✓		
PVT (photovoltaic-thermal)	✓		
USC (unglazed solar collector)	✓		
FPC (flat plate collector)	✓		
ETC (evacuated tube collector)	✓		
PTC (parabolic trough collector)		✓	
LFR (linear Fresnel reflector)		✓	
PDC (parabolic dish collector)			✓
SPT (solar power tower) or heliostats			✓

Like CSP systems, energy storage, using phase change material (PCM), for example, can be incorporated into SHIP systems [86,87]. Such energy storage units enable endured periods of heat supply and compensate for time-dependent variations of the solar radiation during the day, and thus even out fluctuations in their supplied heat [88,89].

1.2. Objectives

The current study has two main objectives, which are:

(1) providing an overview of various designs of SHIP systems

(2) presenting selected data about the recent progress of the deployment of SHIP technologies

Through these objectives, this study serves as a point of reference regarding SHIP technologies and SHIP growth. The study can be used within educational content [90–94] for college or school students to introduce them to solar energy in general, and CSP (concentrated solar power) and SHIP in particular, given the organized and simple way of presenting these concepts here.

2. Method

2.1. SHIP Capacity Relative to Other Power Sources

The global thermal power capacity of SHIP at the end of either 2023 or 2024 is about 1 GWth. In order to identify the scale of this SHIP capacity, I contrast it with other power capacities that span several orders of magnitude in Table **4** (in descending order). From the table, it can be seen that the SHIP capacity is very small (comparable to the small global capacity of ocean/marine power), and contributes a minute fraction to the global power demand and supply. To illustrate this, the worldwide thermal power capacity of SHIP systems is equivalent to the incoming solar irradiance (under a standard test condition of 1 kW/m^2) over a land area of only 1 km^2. Despite this, one should evaluate the contribution of SHIP systems in light of their scope, which is not commercial large-scale electricity generation, but local small-scale heat generation. While being generally small in

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magnitude, these SHIP systems contribute to sustainability through replacing non-renewable heat sources [95,96]with renewable solar energy, thereby reducing greenhouse gas (GHG) emissions [97,98] and helping in combating global warming and climate change [99,100].

Table 4. Examples of various power capacities (from largest to smallest).

Power Capacity Type	Value	Reference(s)
Power radiated from the sun	3.849×10^{17} GW	[101–103]
Solar power reaching the Earth	1.8×10^{8} GW	[104–107]
Global electricity, 2023	8,900 GW	[108]
Global electricity, 2022	8,643 GW	[109]
Global electricity, 2021	8,230 GW	[110]
Global electricity, 2020	7,694 GW	[111]
Global renewable power, 2024	4,448 GW	[112]
Global renewable power, 2023	3,863 GW	[113]
Global solar power, 2024	2,200 GW (almost entirely photovoltaic "PV")	[114–117]
Global hydropower, 2024	1,283 GW	[118–120]
Global wind power, 2024	1,133 GW	
Global bio power, 2024	151 GW	
Global geothermal power, 2024	15 GW	
Global CSP power, 2023	6.7 GW	[121]
Global CSP power, 2020	6.4 GW	[122]
SHIP, 2023	0.951 GW	[123]
SHIP, 2022	0.857 GW	[124]
Global marine (ocean) power, 2023	0.513 GW	[125–128]
Power radiated from 1 m^2 of the sun	0.0633 GW	[129–131]
Standard test condition (STC) of solar radiative power to 1 m^2 of the Earth	10^{-6} GW	[132,133]

2.2. Estimated Solar Radiation Power

It is useful here to justify the computed solar radiation data mentioned in the above table. The listed value (3.849×10^{17} GW) for the power radiated from the sun is computed using the following nonlinear blackbody radiative power law, which is a reasonable approximation for the sun [134–136]:

$$Q_{sun} = \sigma\, T_{sun}^4\, A_{sun} \qquad (1)$$

where (Q_{sun}) is the estimated radiative power from the sun when approximated as a blackbody, ($\sigma = 5.67 \times 10^{-8}$ W/(m^2.K^4)) is the Stefan-Boltzmann constant [137,138], (T_{sun}) is the estimated absolute temperature at the sun surface and it is taken here as 5,780 K (5,506.85 °C) [139–141], and (A_{sun}) is the estimated surface area of the sun when approximated as a sphere with an optical radius (r_{sun}) of 6.957×10^{8} m [142–144]. Thus, I have

$$A_{sun} = 4\,\pi\, r_{sun}^2 \qquad (2)$$

The above expression gives a surface area of

$$A_{sun} \cong 6.0821 \times 10^{18}\ \mathrm{m}^2 \qquad (3)$$

Thus, the estimated total emitted radiative heat from the sun is estimated as

$$Q_{sun} \cong 3.8490 \times 10^{26}\ \mathrm{W} \qquad (4)$$

which is equivalent to the value of (3.849×10^{17} GW) that was listed in the previous table.

The listed value of (0.0633 GW) for the power radiated per unit area (1 m^2) of the sun, this heat flux is denoted here by the symbol (q_{sun}), was computed as

$$q_{sun} = \sigma\, T_{sun}^4 = Q_{sun}/A_{sun} \qquad (5)$$

The above equation gives a value of

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$$q_{sun} \cong 6.3284 \times 10^7 \text{ W/m}^2 \quad (6)$$

which is equivalent to the value of (0.0633 GW) that was listed in the previous table.

It is worth mentioning that the fraction of the solar radiation reaching the Earth (which is 1.8×10^8 GW) of the total solar radiation is about (5×10^{-10}, more precisely 4.68×10^{-10}).

It is also worth mentioning that the solar radiation reaching the Earth (1.8×10^8 GW) is about 20,000 times the global electricity capacity in 2023.

2.3. Outline of the Study

As mentioned in the last section, the current study has two main objectives. In the current subsection, I describe how I achieve them in my study.

To achieve the first objective of contrasting various designs of SHIP, I organized these designs into nine categories. The first five SHIP categories belong to the low-temperature range of operation (below 75 °C) or the medium-temperature (75–150 °C) range of operation. These are mostly non-concentrating systems, where the incoming solar radiation is collected and directed to the absorbing medium or conduit without being focused on a small zone. The other four SHIP categories belong to the high-temperature (150–400 °C) range of operation, and they all use concentrating collectors. Under each category, subcategories may exist due to design variations, such as using evacuation as a method of thermal insulation for better heating. For each of the nine SHIP categories, I describe the design and provide one or more illustrative sketches.

For achieving the second objective related to describing the progress in SHIP technologies, I present informative statistical graphs and tables depicting the historical progress in global SHIP deployment, as well as the recent (2024) status of the global SHIP market. This part also includes some country-based details, but it is mostly concerned with global SHIP use.

2.4. Use of Third-Party Illustrations

The first objective of the current study (contrasting various designs of SHIP systems) required the use of various illustrative schematics. A total of 12 sketches are used for illustration. Three of these sketches are self-made. The remaining nine sketches are taken from one of two external sources provided that they are in the public domain (due to being US government work [145]), and thus do not pose copyright violation and do not require obtaining prior permission from the authoring agency. Sketches taken from an outside source are identified by a dedicated reference to each sketch in their caption. Nine sketches were taken from a public source, five of them were taken from the public website of the United States Environmental Protection Agency (US EPA), and four more sketches were taken from the public website of the United States Department of Energy (US DOE), where the term "Department" here is equivalent to the term "Ministry" in some countries. Other sketches not assigned such a reference in the caption are made directly by us.

2.5. Contribution of the Current Study

While the raw data for these descriptive-statistics graphs and tables were not collected directly by us, I still claim a contribution to the SHIP field through curating, filtering, processing, validating, and visualizing these data and synthesized information not contained in the raw data; making parts of the presented data broader, novel, more valuable, and more informative than their original sources. All raw data were taken from public sources, making them replicable and verifiable by the readers. I provide several references with regard to the data sources used here.

Several questions can be conveniently answered with the aid of the current study, such as:

- What was the SHIP installation in 2024?
- What was the SHIP type with the largest installation capacity in 2024?
- Was the SHIP installation affected by the COVID-19 pandemic?
- What is the historical progress in SHIP between 2017 and 2024?
- What are the top 10 countries in terms of installed SHIP capacity in 2024?
- What are the different types of SHIP systems?

- How are SHIP systems classified?
- Can SHIP systems replace natural gas combustion for enhanced oil recovery (EOR)?
- What is the anticipated size of the SHIP installation for steam installation in mining?
- What are the challenges of small-scale non-SHIP solar thermal systems?
- What are the recommendations for SHIP systems for improved deployment?
- What are the nine main categories of SHIP designs?
- Can the photovoltaic-thermal (PVT) technology be used with bifacial photovoltaic systems?
- What was the average capacity for a parabolic trough collector (PTC) system in 2024?
- What SHIP designs are also used for CSP (concentrated solar power) applications, and why?
- What is the significance of tube evacuation in SHIP systems?
- What are the approaches and tools suitable for modeling SHIP systems?
- Can SHIP systems be used for retrofitting an existing steam generation system, and is there a successful case like this?
- What is the meaning of PV-to-heat configuration (PVH)?
- What is the expected contribution of the (Maaden Solar I) to the SHIP sector, and when?
- What is the technological difference between a transpired solar air collector SHIP system and a plate solar air collector SHIP system?
- What does (Low Temperature) SHIP system mean?
- What are the applications for SHIP systems at high temperatures?
- How does the global SHIP capacity compare to the global capacity of renewable energy technologies as power sources?
- Was evacuation a commonly adopted feature in flat plate collectors in 2024?
- What was the average collector area of an unglazed solar collector in 2024?
- What was the total number of SHIP projects in 2024?
- How big is the disparity in terms of project size among SHIP designs?
- What was the 2024 distribution of new SHIP collector areas by type?
- What was the total collector area of SHIP systems in 2024?

3. Results (Part 1: SHIP Designs)

This section starts with contents pertaining to the first objective of the study, where I provide a technical review of various SHIP systems, particularly the collector designs. I organize these designs into nine categories, starting with the non-concentrating cases (lower-temperature applications) and ending with the concentrating cases (higher-temperature applications).

3.1. Overview of Solar Collectors

A solar collector can be defined as a device that harnesses solar radiation by collecting it, and sometimes concentrating it also, as a source of thermal energy. This collected clean renewable heat is transferred to a working heat-transfer fluid. This fluid can be water or air. The solar-heated fluid can then be transported to a point of use, where a heat demand exists, or it can be stored for subsequent use. The use of solar collectors can be found at a small scale, such as for domestic water heating. Solar collectors can be used at a large scale in the form of sizable arrays in solar thermal power plants to generate green electricity or in commercial facilities to perform industrial processes that require a source of heat. In the current section, we explain the types of solar collectors for industrial applications.

3.2. SHIP Applications

Table 5 lists various applications of SHIP systems, classification by the application sector, and process.

The shown list manifests a wide diversity not only in terms of the sectors (such as agriculture, buildings, and chemical plants), but also in the temperature range. Thus, SHIP systems can meet the needs of many processes.

Table 5. Classification of SHIP systems by application sector and process.

	Application Process		
Application Sector	**Low temperature rise (below 75 °C)**	**Medium temperature rise (75–150 °C)**	**High temperature rise (150–400 °C)**
Agriculture	Greenhouse heating Drying		
Buildings	Space heating Showering Washing Cleaning		Cooking
District heating	Feeding into heat networks	Feeding into heat networks	
Industry	Heat treatment Drying		Distilling Pulping Drying of paint
Chemical	Distilling	Distilling	Distilling
Food and beverage	Drying	Boiling Pasteurizing Sterilizing	
Mining	Copper electrolytic refining Mineral drying processes	Copper electrolytic refining Mineral drying processes	Nitrate melting Alumina production
Textile	Washing	Bleaching Dyeing	Dyeing
Wood	Steaming (steam bending)	Steaming (steam bending)	Drying

3.3. Some Published Works

Different studies were published recently about SHIP systems. In the current subsection, we summarize some of them in Table 6.

Table 6. Summary of selected previous SHIP studies.

Main aim	System type	Main findings	Reference
Integrating solar process heat in industries	Flat Plate, Parabolic Trough, Air Collector	In the (food, beverage, and agriculture) sector, 51% of the solar process heat integration takes place at the supply level, while 27.3% takes place at the process level.	[146]
Integration of solar thermal energy systems into the dairy processes	Parabolic trough, linear Fresnel	The dairy industry has a big potential to utilize solar energy for heating. Parabolic trough collectors and linear Fresnel reflectors are the most suitable solar collectors for this sector. Solar-powered cooling through	[147]

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		the use of solar absorption chillers can be implemented.	
Techno-economic-environmental analysis for using a 5 MWth system	Parabolic trough collector	A SHIP plant in Salt Lake City, Utah, USA, can deliver an annual thermal energy of 15,389.24 MWth/year. Compared to a natural gas plant, the SHIP plant was found to be able to avoid annual emissions of CO_2 at the level of 3,582.4 tonnes/year	[148]
Integration of SHIP systems for meeting low-temperature heat demands in the food processing industry	Flat plate collector	Flat plate collector systems were the most adopted SHIP type in the food industry, with a share of 38%. The most frequent heating applications are pre-heating, cleaning, and pasteurization.	[149]
4E (Energy, Exergy, Economic, and Environment) examination of a small LFR solar water heater	Linear Fresnel reflector	The study was performed in the Blida area in Algeria during the winter season. The optical efficiency was found to exceed 42%. The thermal efficiency was found to exceed 29%.	[150]

3.4. SAC (Solar Air Collector)

I start with the solar air collector (SAC) category of SHIP systems. As the name implies, these systems are used to heat the ambient air, rather than to heat water or another liquid. The temperature rise is relatively small. These systems are limited to specific applications, such as space heating and crop drying [151,152].

There are two versions of solar air collectors (SAC). First, there is the plate version (SAC-P), in which the heat absorber element is a black plate [153,154]. This version is illustrated in Figure 1.

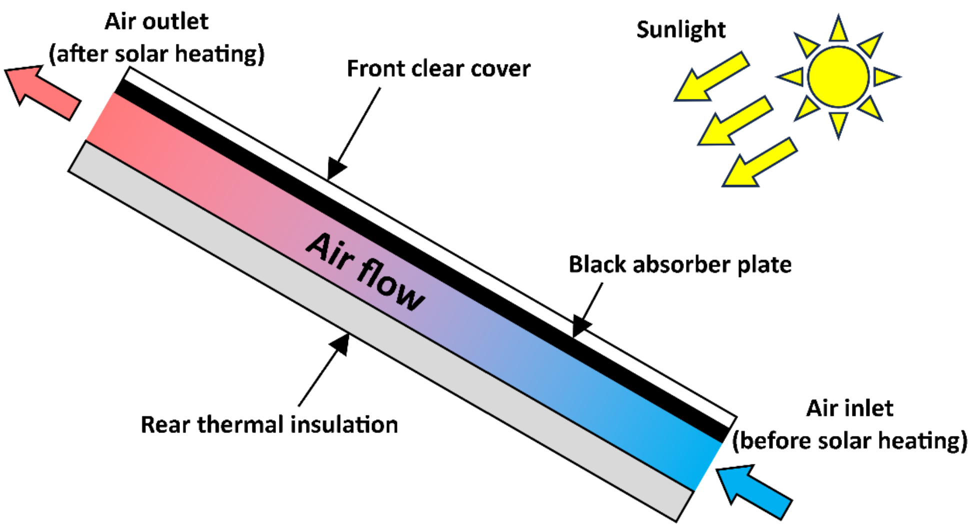

Figure 1. Illustration of a SAC-P (solar air collector, plate version) SHIP system. This sketch is self-made (not taken from an external source).

The other version of the solar air collector (SAC) is the transpired solar air collector (SAC-T), in which air is pulled by a fan through a dark (with high absorptivity and low reflectivity [155,156]) perforated metal cladding layer mounted on an existing exterior wall [157,158]. As a result of the heat transfer from the hotter metal cladding to the colder air, the air is heated before it is distributed to its point of use. This version is illustrated in Figure 2. A similar solution is used for heating and ventilating buildings [159].

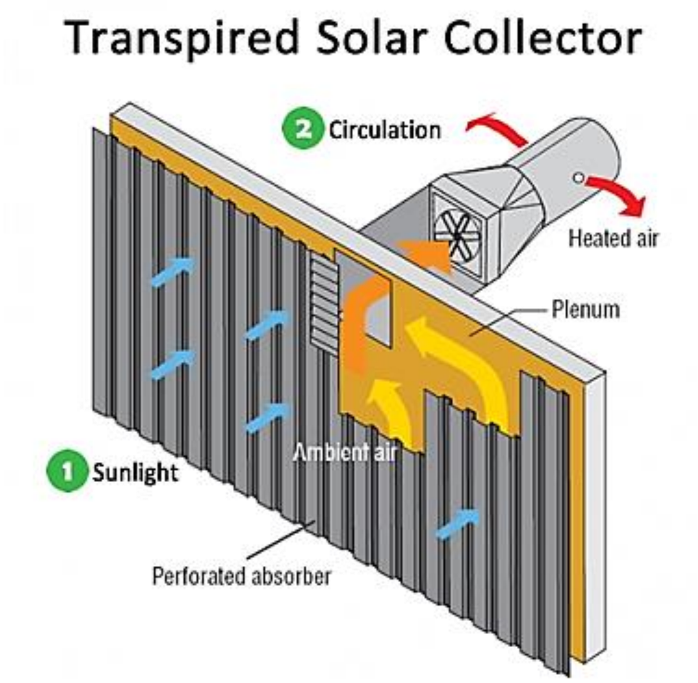

Figure 2. Illustration of a SAC-T (solar air collector, transpired version) SHIP system. This sketch is in the public domain. It was taken from the United States Environmental Protection Agency (US EPA) [160].

3.5. PVT (Photovoltaic-Thermal)

I then move to the second category of SHIP systems, which is the photovoltaic-thermal (PVT) design.

This type takes advantage of the fact that typical crystalline-silicon (c-Si) photovoltaic (PV) cells and modules only convert a fraction (nearly 20%) of the incoming solar radiation (particularly in the visible "VIS" and near-infrared "NIR" spectral bands of light [161–165]) into electricity; while a larger fraction of this incoming solar radiation is either reflected (near 3%) or absorbed (near 77%) by the panel, causing it to heat [166–168]. Thus, this unexploited heat can be collected from the rear side of the PV modules and then used for heating a liquid (such as water). This is illustrated in Figure 3.

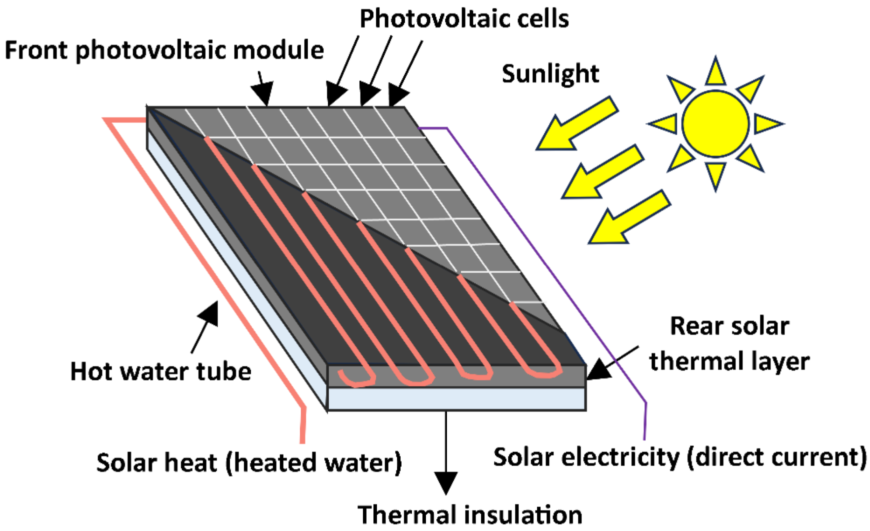

Figure 3. Illustration of a PVT (photovoltaic-thermal) SHIP system. This sketch is self-made (not taken from an external source).

The hybrid PVT design generates both direct solar electricity (from the PV module) and solar heat (in the form of heated fluid), making it a combined heat and power (CHP) system [169,170].

The advantage of the hybrid PVT system is not only in producing additional thermal power, but also in cooling the PV module by directing the absorbed heat to the heated fluid. Such a reduction in the PV cell temperatures improves the energy conversion efficiency of the PV solar cells, because this efficiency drops as the temperature increases; this is reflected in a negative power temperature coefficient [171].

The hybrid PVT design can be used not only with monofacial PV modules, but also with bifacial PV modules, in which the direct conversion of incoming radiation into electricity occurs for both the front face and the rear face of the PV module [172].

3.6. USC (Unglazed Solar Collector)

The third category of SHIP systems I present here is the unglazed solar collector (USC) [173–175]. As the name implies, the main characteristic of this design is the lack of a glazing layer (a front layer of clear glass or plastic). This makes the design simple, but it does not permit the heat-trapping feature provided by the missing glazing. Therefore, this type is intended for small temperature rises, within about 10 °C only. Consequently, this type is especially suitable for heating swimming pools.

Figure 4 illustrates the operation principle of this SHIP design.

The top layer in this figure is a dark-colored sheet of non-glazing heat-absorbing material (metal or plastic) that absorbs incident heat and then transfers it to the collector tubes beneath it. The bottom dark layer beneath the collector tubes in the figure provides structural support and further secondary heat absorption from the rear side.

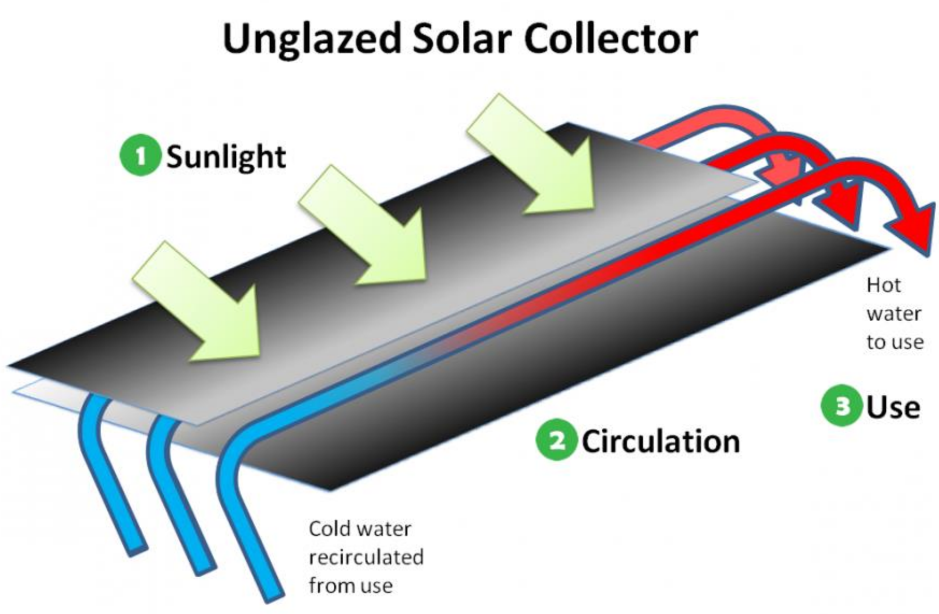

Figure 4. Illustration of the USC (unglazed solar collector) SHIP system. This sketch is in the public domain. It was taken from the United States Environmental Protection Agency (US EPA) [176].

3.7. FPC (Flat Plate Collector)

The fourth category of SHIP systems I present here is the flat plate collector (FPC) [177–179]. This is an upgraded form of the previous unglazed solar collector (USC), where a glazing layer is added at the front. Thus, heat losses are reduced, and a larger temperature difference between the absorber and the ambient air becomes possible. The temperature rise in FPC can be multiples of the one achieved using USC. The operation of FPC is illustrated in Figure 5.

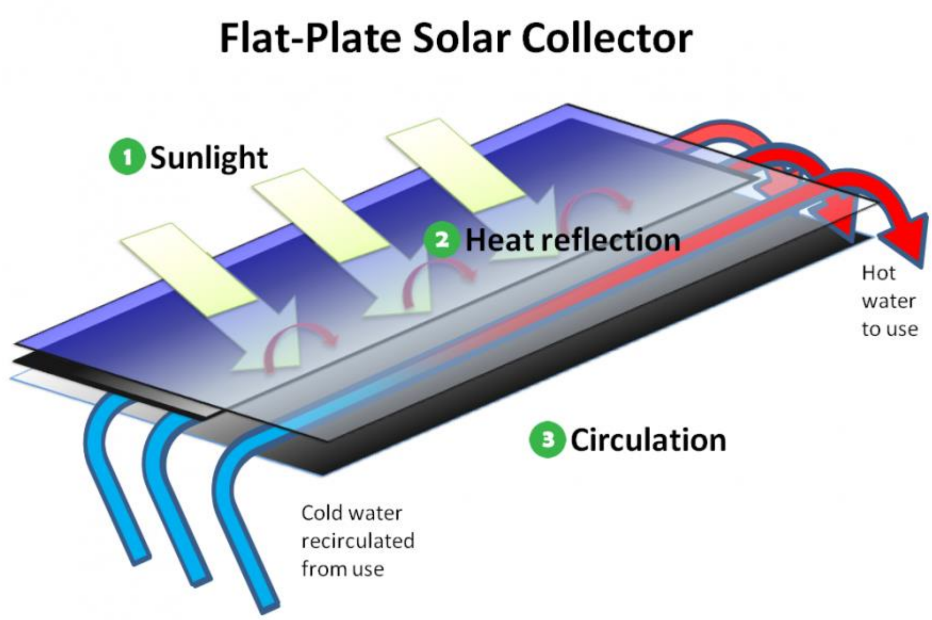

Figure 5. Illustration of the FPC (flat plate collector) SHIP system. This sketch is in the public domain. It was taken from the United States Environmental Protection Agency (US EPA) [180].

The heat absorption zone beneath the glazing layer can be evacuated (vacuum) [181–183], leading to a version called a flat plate collector with an evacuated absorber (FPC-E) or high-temperature flat plate collector [184,185]. Alternatively, the heat absorber space can be unevacuated (ordinary), leading to the flat plate collector with an unevacuated absorber (FPC-U), also called a low-

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temperature flat plate collector. The FPC-E design is more complicated than the FPC-U design, but it offers the advantage of attenuating convective heat loss, and this allows a larger temperature difference between the absorber and the ambient air.

3.8. ETC (Evacuated Tube Collectors)

The fifth category of SHIP systems I present here is the evacuated tube collector (ETC) [186–188].

Through evacuating the tubes that carry the heat transfer fluid (HTF), heat loss is reduced, and thus the HTF temperature can be largely elevated. Also, using individual tubes as absorbers (either the cylindrical surface of each tube is coated with a black heat-absorber coating, and/or a metal heat-absorber fin is attached to each tube [189–191]) has a geometric advantage, where there is more chance of reaching the absorber perpendicularly. The ETC design is illustrated in Figure 6.

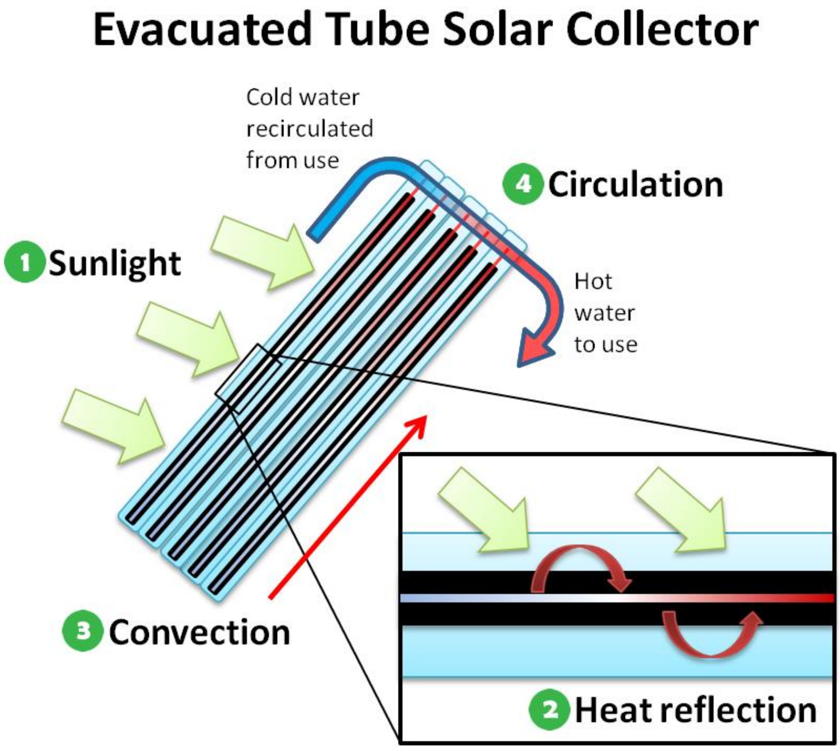

Figure 6. Illustration of the ETC (evacuated tube collector) SHIP system. This sketch is in the public domain. It was taken from the United States Environmental Protection Agency (US EPA) [192].

Instead of having one common large absorber plate (as in the USC or the PFC), the ETC design may have small heat absorber plates (fins) attached to each tube [193].

Depending on the absorber tube, the ETC system can be divided into two versions. The first is the single-phase (liquid) version, and the second is the two-phase [194] (liquid-vapor) heat pipe version [195–197].

Depending on the number of fluids involved in the ETC system, it can also be divided into two versions. The first version is the single-fluid configuration, where the heat transfer fluid within the evacuated tubes (vacuum tubes) is also the heated fluid that is aimed to be heated using solar radiation. This configuration is also referred to as a "wet" connection ETC system. The second version is the two-fluid configuration, where the heat transfer fluid within the evacuated tubes (vacuum tubes) is different from the heated fluid that is aimed to be heated using solar radiation. This configuration is also referred to as a "dry" connection ETC system, where the two fluids are not in contact with each other. The "dry" version has the advantage of the flexibility of choosing the heat transfer fluid (HTF), which can be optimized and controlled independently of the fluid to be heated

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[198–201] using proper computational fluid dynamics (CFD) [202–204] and computer-aided design (CAD) tools [205–207].

Combining an ETC (evacuated tube collector) system with a stationary compound parabolic concentrator (CPC), as shown in Figure 7, allows for concentrating the collected and reflected solar radiation, and this greatly improves the performance of the SHIP system at the expense of added cost and complexity [208].

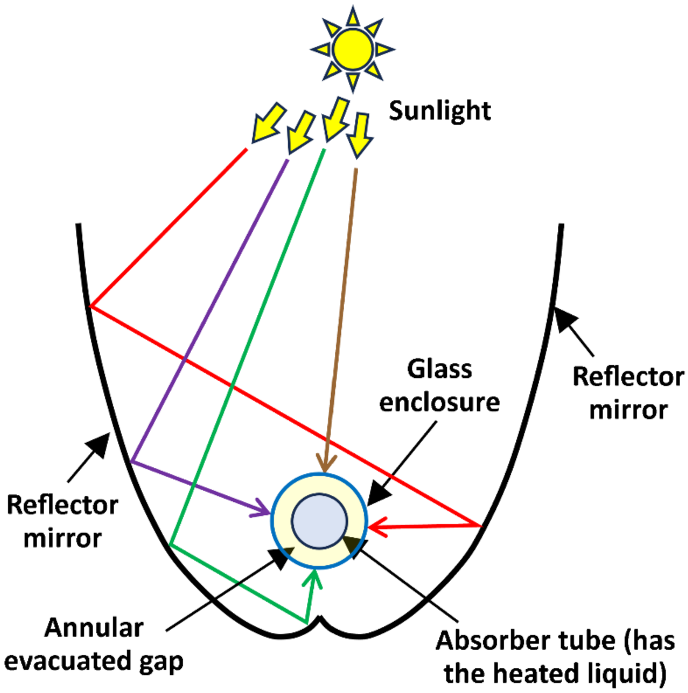

Figure 7. Illustration of an ETC-CPC (evacuated tube collector with compound parabolic concentrator) SHIP system. This sketch is self-made (not taken from an external source).

3.9. PTC (Parabolic Trough Collector)

The sixth category of SHIP systems I present here is the parabolic trough collector (PTC) [209–212].

This SHIP system incorporates a line-concentrator in the shape of a parabola, such that incoming parallel sunlight beams are focused at the tube located at the parabola's focal point, as illustrated in Figure 8.

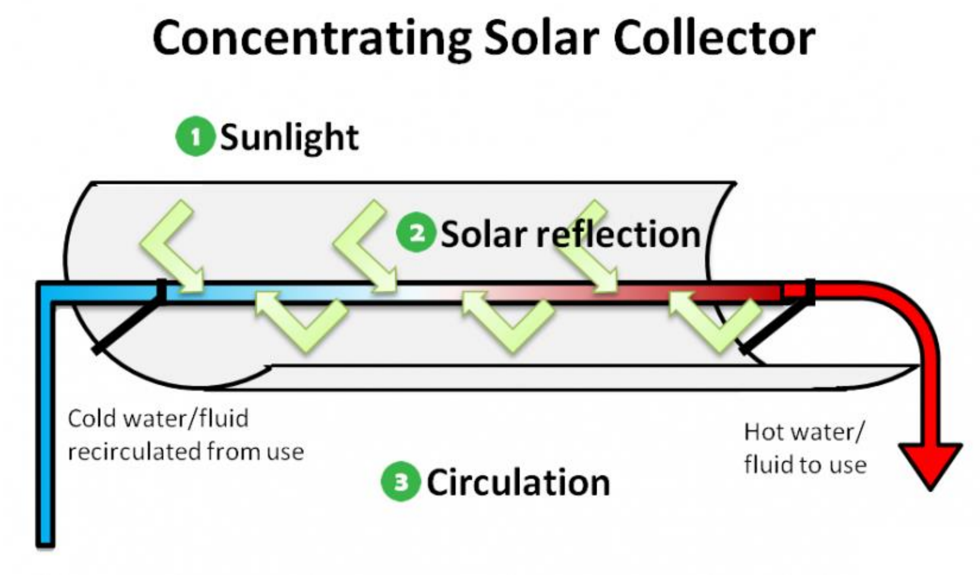

Figure 8. Illustration of the PTC (parabolic trough collector) SHIP system. This sketch is in the public domain. It was taken from the United States Environmental Protection Agency (US EPA) [213].

The parabolic trough collectors are movable with one-degree-of-freedom rotation, such that the aperture angle is optimized during the day to absorb the maximum possible amount of solar radiation.

Depending on the heat absorber tube, the parabolic trough collector (PTC) can be offered in an unevacuated version (PTC-U) or an evacuated version (PTC-E). The evacuated version is better, and it is associated with higher temperature rises due to suppressing convective heat losses from the absorber tube that contains the fluid to be heated. This absorber tube is now encapsulated within a clear enclosure with an annular vacuum gap in between.

The PTC design is commonly used in SHIP applications and CSP (concentrated solar power) applications. The PTC (parabolic trough collector) design is the most mature compared to other CSP options (SPT, PDC, and LFR), which are also used in SHIP applications [214–216].

3.10. LFR (Linear Fresnel Reflector)

The seventh category of SHIP systems I present here is the linear Fresnel reflector (LFR) [217–219].

This is another line-concentrator design (like PTC), but multiple flat-plate reflector mirrors concentrate the incoming radiation to the common heat absorber (instead of having one absorber per reflecting mirror). The linear Fresnel reflectors are movable with one-degree-of-freedom rotation, similar to the PTC mirrors. The LFR design is illustrated in Figure 9.

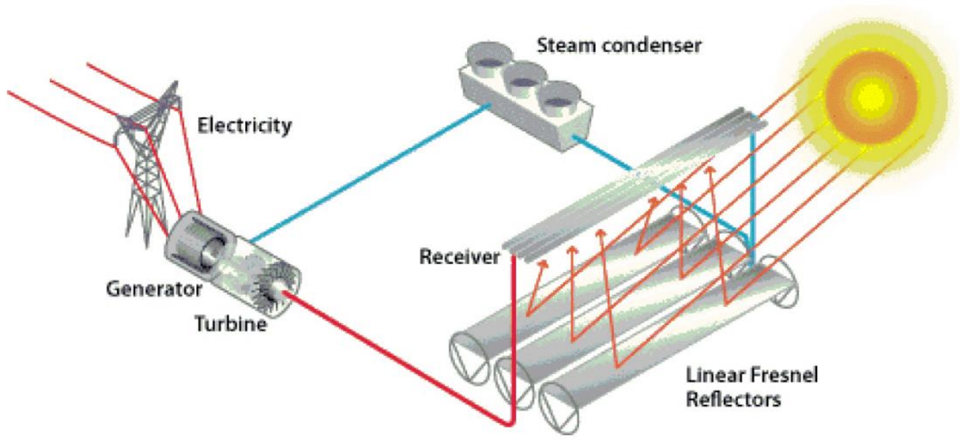

Figure 9. Illustration of the LFR (linear Fresnel reflector) SHIP system. This sketch is in the public domain. It was taken from the United States Department of Energy (US DOE) [220].

When two or more overhead heat absorbers (heat receivers) exist within the same area of the LFR mirrors, this design is referred to as a compact linear Fresnel reflector (CLFR) [221–223]. I may here consider the single-absorber LFR and the multiple-absorber CLFR as one class due to the identical surfaces used for radiation collection/reflection.

3.11. PDC (Parabolic Dish Collector)

The eighth category of SHIP systems I present here is the parabolic dish collector (PDC) [224–226].

Like parabolic trough collectors (PTC), PDC units couple each collector mirror with its own heat absorber. However, instead of using line-concentrators, the PDC units have point-concentrators, as shown in Figure 10.

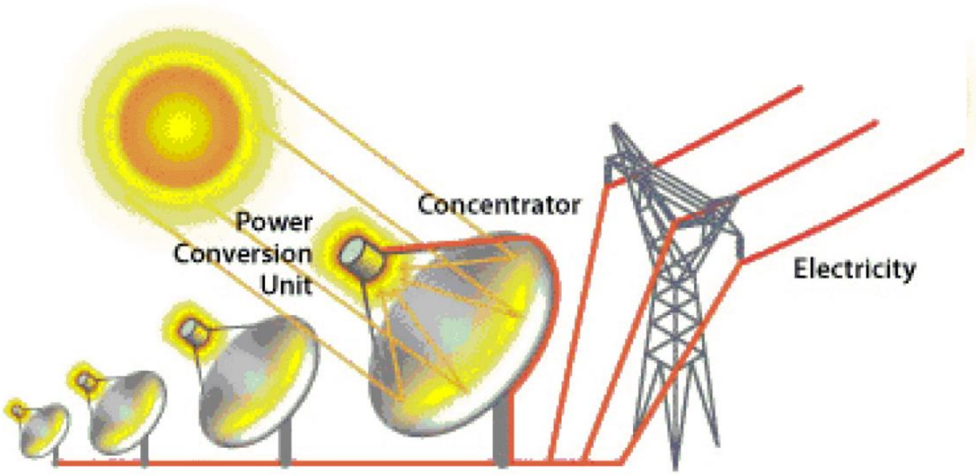

Figure 10. Illustration of the PDC (parabolic dish collector) SHIP system. This sketch is in the public domain. It was taken from the United States Department of Energy (US DOE) [227].

Similar to PTC and LFR, PDC is commonly used in CSP applications. In the case of CSP, the focal point of the parabolic dish has an attached heat engine (Stirling type) that converts the absorbed heat into mechanical rotation (shaft power), which is then converted into electricity using a connected electric generator. Such an engine-generator element is not present in SHIP applications.

Unlike PTC and LFR, the solar tracking mechanism of PDC is two-degree-of-freedom, where both the azimuth and zenith angles (the heading and elevation angles) are adjustable for fully following the sun disc.

3.12. SPT (Solar Power Tower)

The ninth and last category of SHIP systems I present here is the solar power tower (SPT) or simply the solar tower (ST) [228–230]. The solar tower here should not be confused with the solar chimney (SC), which is sometimes called solar tower (ST), solar-wind tower (SWT), or solar updraft tower (SUT) [231–234]. The solar chimney is a very different concept from solar power towers (SPT) for SHIP/CSP applications. In the case of a solar chimney, solar radiation induces an internal upward flow of air inside a chimney-like hollow column (heat energy is converted into kinetic energy), which then operates an indoor wind turbine to produce electricity [235–237].

In the SPT design, a large array of ground-mounted movable mirrors (called heliostats) is tilted such that the solar irradiance can be reflected from them to a common heat-absorber receiver at the top of a centralized tower, as illustrated in Figures 11 and 12.

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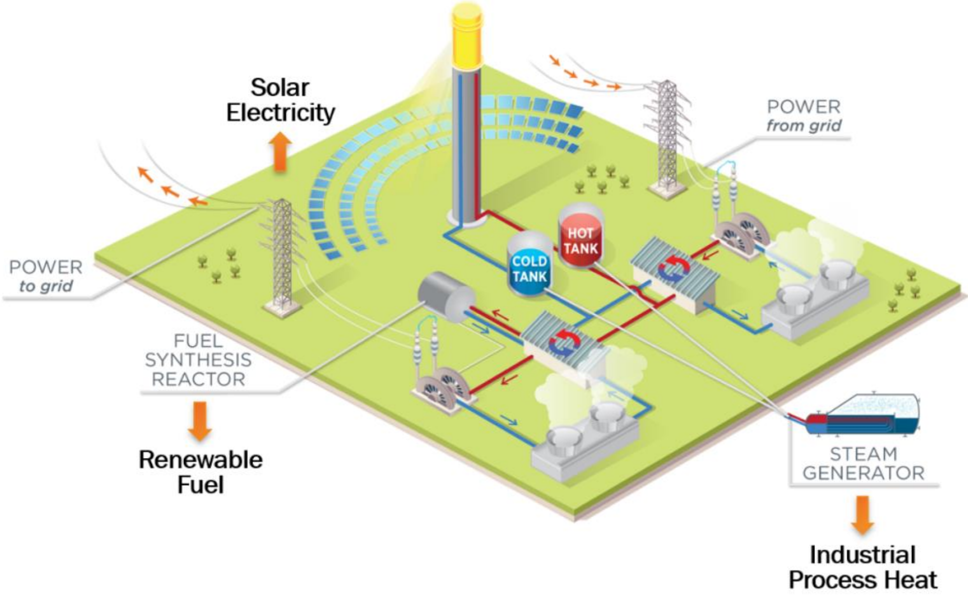

Figure 11. Illustration of the SPT (solar power tower) SHIP system. This sketch is in the public domain. It was taken from the United States Department of Energy (US DOE) [238].

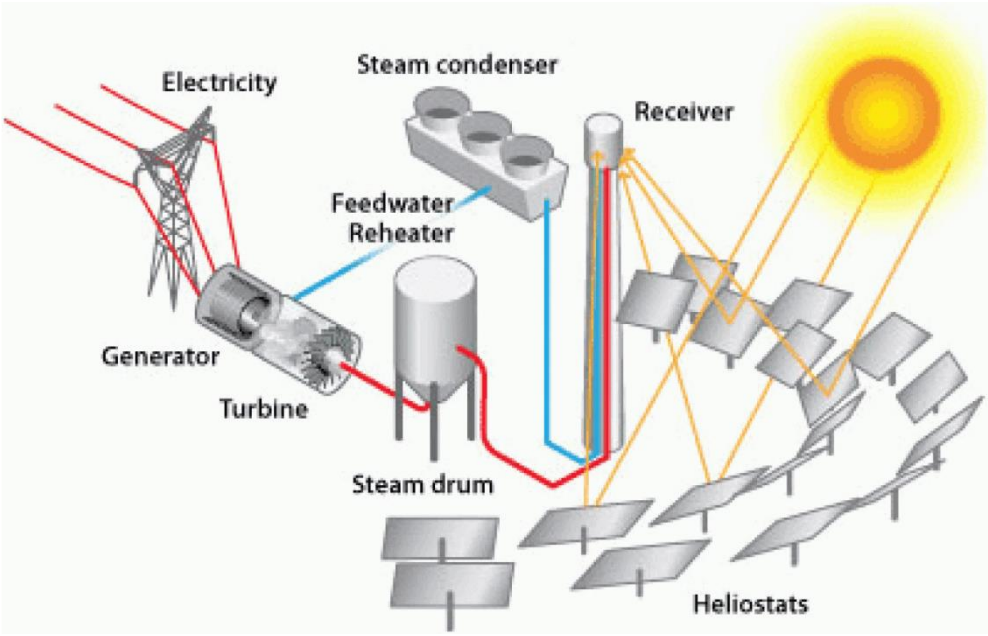

Figure 12. Illustration of the SPT (solar power tower) SHIP system. This sketch is in the public domain. It was taken from the United States Department of Energy (US DOE) [239].

Similar to PTC, LFR, and PDC, SPT can be used for both electric power generation (CSP mode) and process heat generation (SHIP mode).

Similar to PDC, the solar tracking mechanism in the case of SPT is two-axis (two-degree-of-freedom). However, this mechanism is not responsible for tilting a single-piece parabolic dish, but for tilting the heliostats such that they resemble a large parabolic dish (but discretized) whose focal point is the receiver at the top of the solar tower. Due to the lower maturity, larger capital investment, more complex control/optimization of the tilt angles, poor modularity, and heavier demand for land area in the case of SPT projects, PDC and PTC are more suitable for small-scale projects that are frequently encountered in SHIP applications [240–245]. When used as a power plant for CSP electricity generation, a minimum capacity of about 50 MWe (electric) is recommended [246]. One kWe (electric) of CSP power capacity using SPT may require a land area of 45 m^2; while this drops by one-half, to below 25 m^2/kWe (electric) in the case of CSP-PTC [247–249].

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4. Results (Part 2: SHIP Progress)

This section is the second and last part of the two-part results of the current study. This part pertains to the second objective of the current study, where I present selected data regarding the progress of the SHIP systems, particularly the utilization expansion that occurred in 2024. I organize these results into two subsections. I dedicate the first subsection to the historical progress in the global deployment, sampled annually. I then dedicate the second subsection to the expansions in SHIP deployment that took place in 2024 (last year as of the time of preparing this study).

4.1. SHIP Historical Growth

I start with the annual growth of SHIP systems that were installed globally. This growth is expressed here in terms of the number of:

(1) new commissioned SHIP systems per year
(2) new SHIP collector area added per year
(3) new SHIP thermal capacity added per year.

The last growth metric (added SHIP thermal capacity) is actually derived from the added collector area by assuming a reasonable conversion factor of

$$1\ \text{m}^2 \cong 700\ \text{Wth} = 0.7\ \text{kWth} = 7 \times 10^{-4}\ \text{MWth} \quad (7)$$

This conversion factor is reasonably used in solar thermal applications [250–252]. For curved collectors, where the term (collector area) may become ambiguous, the collector area is typically interpreted as the aperture area of the collector mirrors [253–256]. For flat collectors, the collector area can be considered as the total flat area of the collector mirrors (as in LFR) [257].

The source of the data in the current subsection is the web-based platform (Solarthermalworld.org), which was established in 2008 by the International Copper Association Europe (ICA Europe), based in Brussels, Belgium [258,259]. In turn, these data were obtained by Solarthermalworld.org using annual surveys of the suppliers of SHIP systems, and these surveys were conducted by the German agency (Solrico) [260,261].

The historical global counts of SHIP systems are shown in Figure 13 for the period between 2017 and 2024. While this graph does not show a clear trend, it shows that the number of annually commissioned SHIP systems in the last three years (2022, 2023, and 2024) has exceeded 100. The smallest number of new SHIP systems was in 2021, when 73 systems were added globally. Thus, there was a jump from 73 systems in 2021 to 116 systems in 2022.

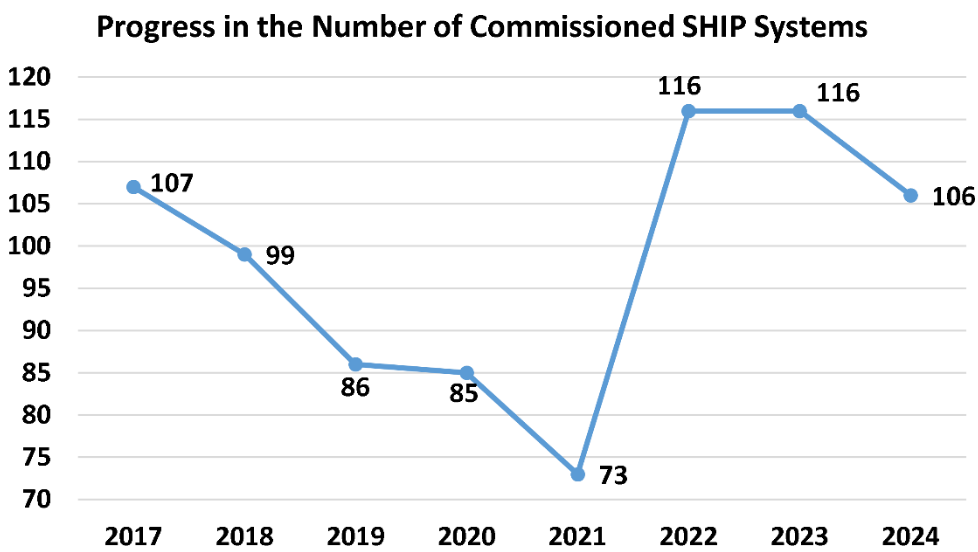

Figure 13. Historical records of annually added SHIP systems, from 2017 to 2024. This graph is self-made (not taken from an external source). Data source [260].

Like any energy system in general, the number of systems by itself is not a good indication of the size of these systems collectively, because there can be a big variation in the capacity of individual systems. Thus, while the above historical graph is useful in expressing the generic interest in SHIP systems as reflected in a continuous demand for them, a better representation should be in terms of the added thermal capacity or the added collector area. The historical values of two alternative metrics are shown in Figure 14. The sharp jump in the number of added SHIP systems between 2021 and 2022 (as observed from the previous graph) is totally altered into a small decline in the collector area (or the equivalent thermal capacity). In the last three years (2022, 2023, and 2024), the added collector area has been increasing. Over the period 2017–2024, the smallest SHIP addition was in 2022 (34,664 m², 30.6 MWth), while the largest addition was in 2019 (358,641 m², 251.0 MWth). Thus, the annual additions varied significantly by one order of magnitude, reflecting the instability of the global demand. However, the sharp decline between 2019 and 2020, and the mild decline between 2020 and 2021 can be attributed to the COVID-19 pandemic, when various business activities were negatively impacted and reduced [262–264]. Despite this decline in the installed SHIP capacity, it has never been zero during the pandemic period.

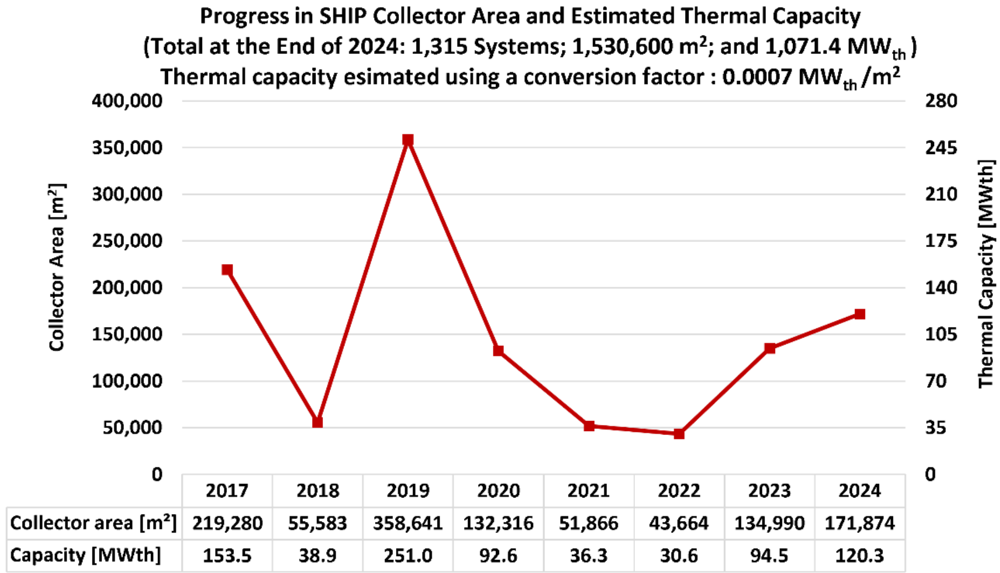

Figure 14. Historical records of annually added SHIP collector area and dependent annually added SHIP thermal capacity, from 2017 to 2024. This graph is self-made (not taken from an external source). Data source [260].

A summary of the 2024 additions, and their percentage relative to the cumulative deployment of SHIP systems at the end of 2024, is listed in Table 7.

Table 7. 2024 Additional and cumulative SHIP deployment at the end of 2024.

Quantity	2024 Addition	Cumulative (end of 2024)	Percentage of the 2024 addition (relative to the cumulative value at the end of 2024)
Number of SHIP systems	106	1,315	8.06%
Collector area [m²]	171,874	1,530,600	11.23%
Thermal power [MWth]	120.3	1,071.4	11.23%

4.2. SHIP Additions in 2024

The final part of the results that I present in the current study is concerned with the new SHIP installations in the last calendar year (2024).

Figure 15 shows the top six countries in terms of the SHIP installed capacity in 2024 [265]. In this figure, I apply a filter to show only the countries having a new capacity of 1 MWth or more in 2024.

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China was by far the leading investor in SHIP technologies, with an added capacity of 84.6 MWth. Then comes Germany with an added capacity of 21.8 MWth. Thus, China and Germany together installed about 106.4 MWth of SHIP systems in 2024, and this represents approximately 88% of the global added capacity in 2024 (120.3 MWth). The other four countries that exceeded 1 MWth of SHIP installation in 2024 are: The Netherlands (3.6 MWth), Austria (2.9 MWth), Mexico (2.6 MWth), and India (1.6 MWth). In addition to these six top countries listed in the figure, 14 more countries also commissioned one or more SHIP systems in 2024, but with smaller capacities below 1 MWth. The total installed SHIP thermal capacity by these 14 countries is 2.9 MWth. These 14 countries with small SHIP installations, along with the six countries with larger installations, are:

1. China
2. Germany
3. Netherlands
4. Austria
5. Mexico
6. India
7. Italy
8. Brazil
9. USA
10. France
11. Panama
12. Jordan
13. Serbia
14. Spain
15. Kenya
16. Ecuador
17. Finland
18. Morocco
19. Colombia
20. Cuba

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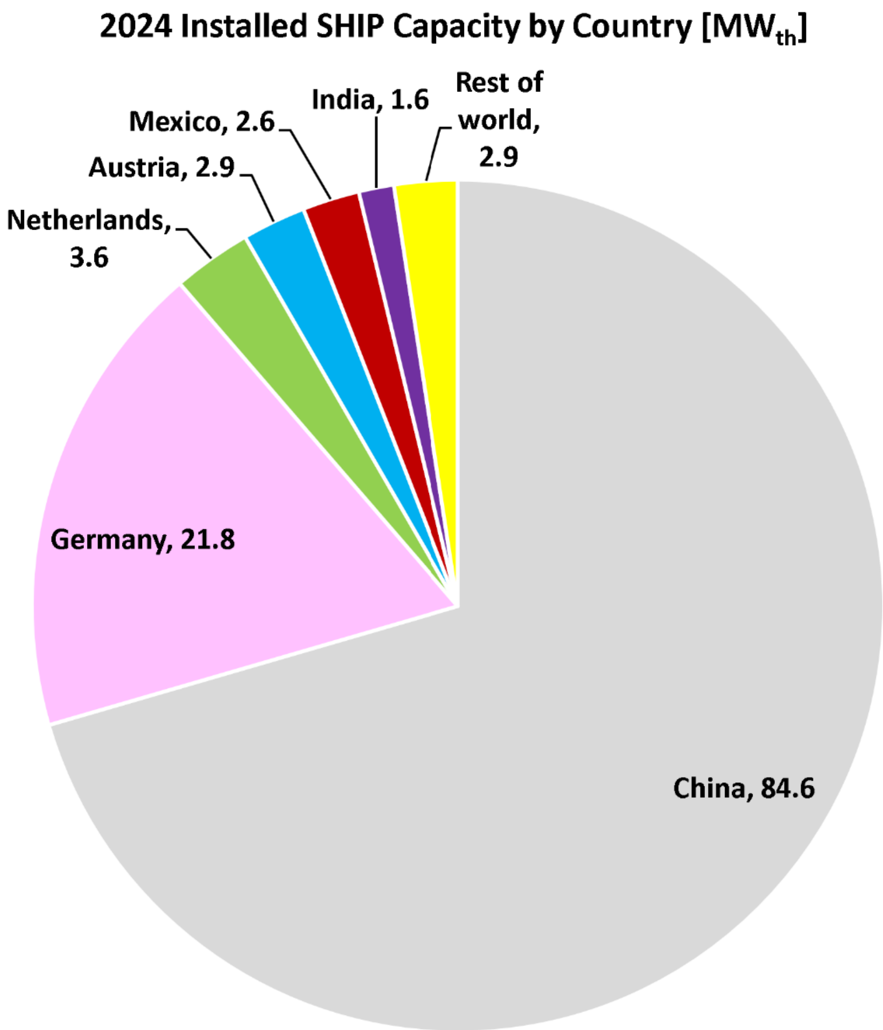

Figure 15. Countries with at least 1 MWth of newly added SHIP thermal capacity in 2024. This graph is self-made (not taken from an external source). Data source [265].

Figures 16 and 17 illustrate the distribution of the 2024 added SHIP collector area globally (171,874 m^2) when divided according to the SHIP category [266]. This distribution is expressed as percentages in the former figure and then as absolute areas in the latter figure. The number of SHIP categories here is 10, which represents the nine categories I discussed in the previous section, but the flat plate collector (FPC) category is split into two categories due to considering the unevacuated FPC version (FPC-U) as a category and considering the evacuated FPC version (FPC-E) as another separate category. The parabolic trough collector (PTC) was the dominant category in 2024, with about two-thirds (65.9%) of the added collector area belonging to this category alone. This testifies to the maturity and reliability of this PTC technology type of SHIP. Unevacuated flat plate collectors (FPC-U) had a share of 22.0% in 2024, which is a considerable portion that also indicates successful operation and wide acceptance of this FPC-U technology type of SHIP. The evacuated version of FPC (FPC-E) had a much smaller share of 1.0% in 2024. If I combine the share of PTC and FPC (both the unevacuated version and the evacuated version), I get a combined share of about 89%. While the evacuated tube collector (ETC) type had an appreciable share of 5.0%, the unglazed solar collector (USC) had the smallest share of only 0.2%. This smallest share corresponded to a USC collector area of 326 m^2. It is noticeable that the other three medium-temperature concentrating technologies, other than PTC (namely, LFR, PDC, and SPT), contributed together about 2.5% only of the added SHIP collector area in 2024.

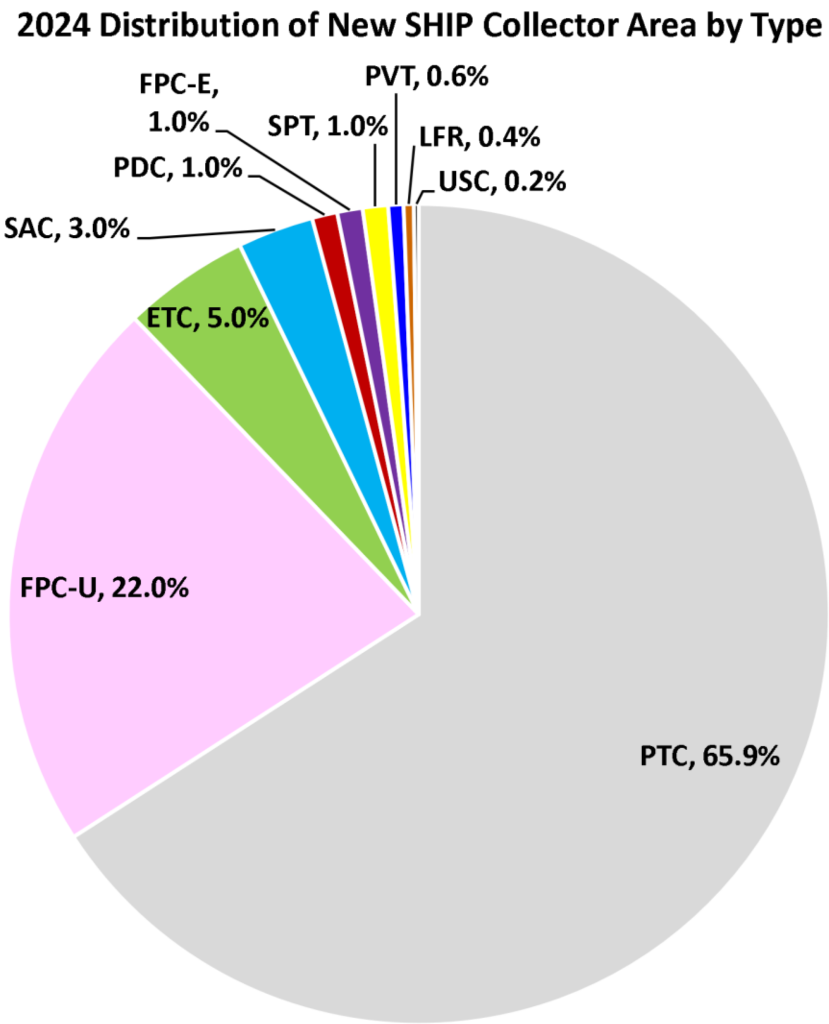

Figure 16. Percentage of added SHIP collector area in 2024, classified by system type. This graph is self-made (not taken from an external source). Data source [266].

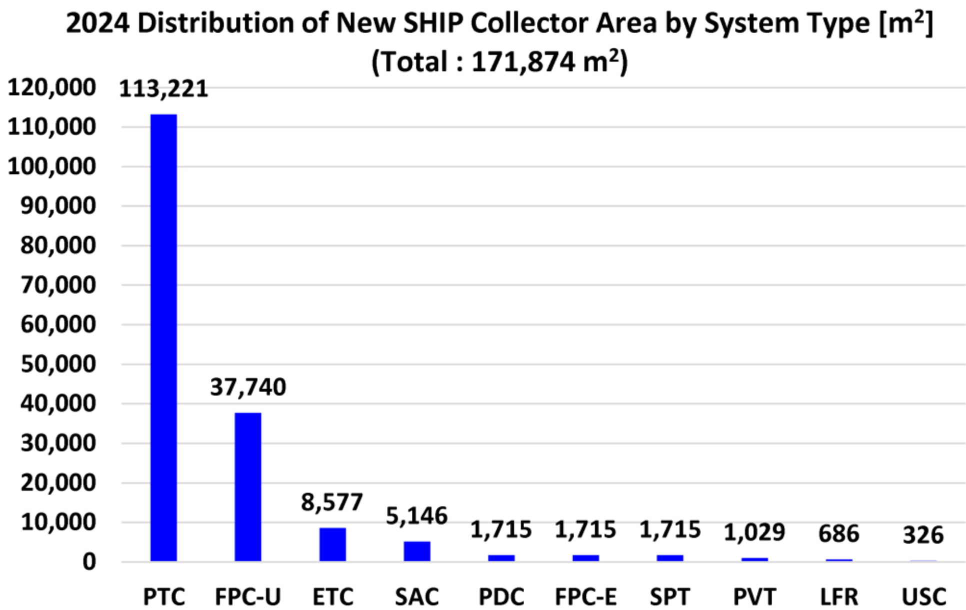

Figure 17. Added SHIP collector area in 2024, classified by system type. This graph is self-made (not taken from an external source). Data source [266].

Figure 18 shows the distribution of the 2024 SHIP systems (a total of 106 globally) over the same 10 SHIP categories as the two previous figures. It is interesting that 48 systems (a count share of 45.3% out of the total of 106 systems) belonged to the unevacuated flat plate collector (FPC-U) category, although this category was responsible for only 22.0% of the total added collector area. When the single evacuated flat plate collector (FPC-E) system that was installed in 2024 is combined with the 48 FPC-U systems installed in 2024, I obtain 49 FPC systems installed in 2024. It is even more interesting that the parabolic trough collector (PTC) category, which was the dominant category in terms of added collector area (area share 65.9%), had only three SHIP projects in 2024. This reflects the large size of individual PTC projects compared to FPC-U projects. When the average collector area per SHIP system is computed for the three PTC systems of 2024, I obtain 37,740.5 m²/project. On the other hand, the average collector area per SHIP system for the 49 FPC projects of 2024 is 805.2 m²/project. Considering the whole 106 SHIP systems of 2024, the average collector area per SHIP system is 1,621.4 m²/project (computed as 171,874 m² divided by 106 systems). Thus, on average, PTC systems tend to be very large (in terms of the collector area), while FPC systems tend to be small.

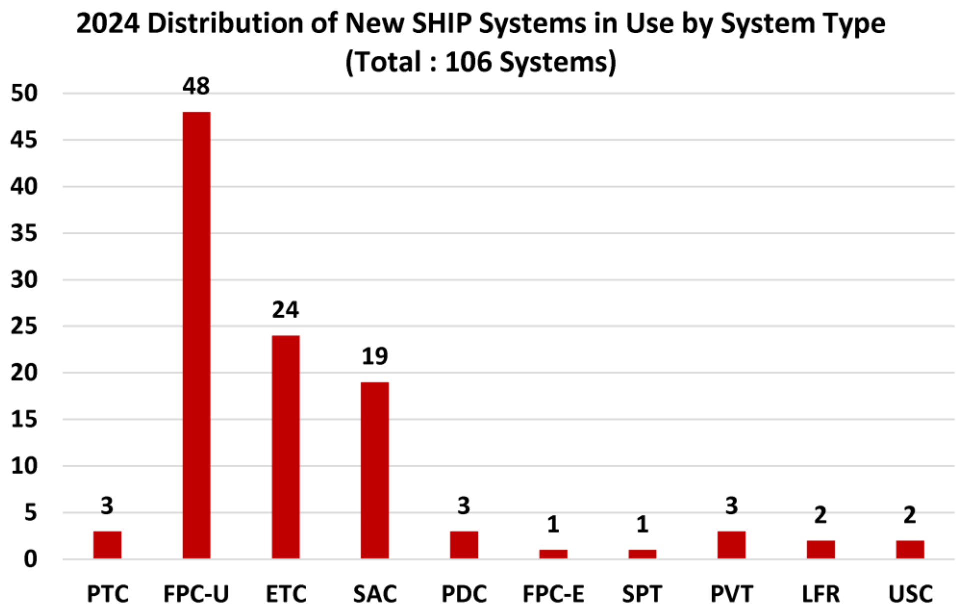

Figure 18. Number of added SHIP systems in 2024, classified by system type. This graph is self-made (not taken from an external source). Data source [266].

In Table 8, I list my computed average collector area per SHIP system for each of the 10 SHIP categories, and the overall average over all 10 categories. I also compute this average area for the flat plat collector (when I treat it as a single category that covers both FPC-U and FPC-E) and consider this combination as an 11th category in the table. Among the tabulated results, the SHIP category with the largest collector area per system (for the installed systems in 2024) is the parabolic trough collector (PTC) category, with a value of 37,740.5 m²/project; while the SHIP category with the smallest average collector area per system is the unglazed solar collector (USC), with a value of only 163.0 m²/project.

Table 8. Computed average collector area per SHIP system based on new 2024 installations.

Category number	SHIP category	2024 Added systems	2024 Added collector area [m²]	Average collector area per system for new systems in 2024 [m²/project]
1	Parabolic trough (PT)	3	113,221	37,740.5
2	Unevacuated flat plate (FP-U)	48	37,740	786.3

3	Evacuated tube (ET)	24	8,577	357.4
4	Solar air collector (Air)	19	5,146	270.9
5	Parabolic dish (PD)	3	1,715	571.8
6	Evacuated flat plate (FP-E)	1	1,715	1,715.5
7	Solar power tower / Heliostats (SPT)	1	1,715	1,715.5
8	Photovoltaic-thermal (PVT)	3	1,029	343.1
9	Linear Fresnel (LF)	2	686	343.1
10	Unglazed (Ung)	2	326	163.0
	Total (Overall)	106	171,874	1,621.4
11	flat plate (FP)	49	39,456	805.2

4.3. Small-Scale Non-Industrial Solar Thermal Applications

While the focus in the current study was on industrial heating processes, because it is the application domain of SHIP systems, the scope of solar thermal applications is much broader. There are numerous low-temperature and medium-temperature solar thermal applications that play a critical role in residential and community settings, especially in developing regions [267]. These important use cases are briefly discussed here to provide a more complete overview of the solar thermal domain.

Solar cookers are one example of such non-industrial solar thermal uses [268]. Many solar cookers were aimed at use as zero-cost alternatives that do not consume fuel or electricity [269]. Several initiatives in different regions of the world promoted and raised awareness about solar cookers as integrated local solutions to problems involved in traditional cooking; such as air pollution, fuel costs, deforestation caused by cutting trees for wood, and the exhausting work for women who spend a lot of time collecting firewood [270,271]. Another important example of small-scale non-industrial solar thermal devices is domestic solar hot water systems [272,273]. The efficiency of domestic-scale solar water heaters can be near 70% [274]. On the other hand, using photovoltaic modules to convert solar radiation into electricity and then converting this electricity into heat via an electric water heater results in a much lower overall energy conversion efficiency of around 17% only [275]. Despite the environmental benefits of domestic solar water heaters; their larger size compared to electric heaters, more expensive capital cost compared to electric heaters, and the need for an outdoor area to collect solar radiation [276,277] hinder the widespread adoption of domestic solar water heaters.

4.4. PV-to-Heat Configuration (PVH)

There is one more method to produce heat using solar radiation that was not listed among the nine main SHIP categories in my classification by design type. This additional tenth method is based on a two-step energy conversion. In the first step, incoming solar radiation is converted into direct current electricity using photovoltaic solar modules (panels). An inverter may be used to further change the electric power from the fixed-polarity direct current (DC) to the alternating current (AC) sinusoidal waveform. In the second step, this electricity is converted into heat using a conventional electric heater [278].

It is true that, in this method, the incoming solar radiation is eventually converted into heat. However, the power generation system remains purely of an ordinary photovoltaic type, rather than a solar thermal type. Primarily, the visible portion of the irradiance spectrum is utilized, not the infrared heating portion, as in the solar thermal concept. The heat is produced through a resistive electric load, irrespective of the solar radiation. Therefore, I prefer not to classify this method as a solar thermal (ST) technology. Instead, it seems closer to the solar photovoltaic (PV) technology. The reader may disagree with this view. In such a case, this (PV-to-heat) or (PVH) configuration is considered the tenth category of SHIP.

4.5. Thermal Modeling Tools

This review can benefit from a summary of thermal modeling approaches found in the literature for SHIP systems. This topic is covered here.

One modeling technique for SHIP systems is the energy balance calculation. This can be in the form of solving a governing scalar equation with hourly or subhourly variations. Specifically, the energy generated by the solar thermal collector can be computed starting from the incident radiation and the active collector's area and collector's efficiency. Part of this energy is lost by conduction and radiation to the ambient surroundings. The net heating rate becomes useful thermal power [279]. This simplified process may be implemented using hand computations, a spreadsheet, or a simple computer code.

Instead of a single overall energy equation, a system of energy balance equations, as well as the mass continuity equations, can be solved to model the various subsystems (such as the water tank, the solar collector, and the pump) of the overall SHIP system, rather than simply focusing on the collector alone [280]. Specialized software tools such as the Modelica object-oriented open-source language [281,282] or the OpenModelica open-source environment facilitate this more-realistic modeling approach [283,284].

Instead, the SHIP modeling can be handled as a dynamic control system using the state space technique of modern control [285]. This modeling option is particularly useful for control purposes and controller-based automation and optimization [286]. The commercial simulation software MATLAB, its block-diagram environment Simulink, and its Optimization Toolbox are very relevant in this approach [287,288].

A more detailed approach to modeling SHIP systems is the computational fluid dynamics (CFD) technique [289], where the governing partial differential equations for the fluid part and the thermal part of the SHIP system are discretized and integrated in both time and space to generate an approximate numerical solution [290]. Specific CFD methods for such thermal problems include the finite difference method (FDM), where the physical domain is approximated as a structured grid of discrete points and the solution is sought only at these points rather than in the whole continuum domain [291,292]. Another CFD method for thermal systems is the finite volume method (FVM), where the spatial domain is split into contiguous three-dimensional finite cells (such as tetrahedra) and the mass conservation law, momentum conservation law, and energy conservation law are numerically enforced at the cell level. The Ansys Fluent commercial software is a powerful tool for implementing this modeling approach [293,294].

4.6. Perspectives and Recommendations

In this subsection, I provide some expectations and suggestions regarding SHIP systems.

As presented earlier, the largest SHIP deployment in 2024 by collector area was in the parabolic trough collector (PTC) type, with an average collector area of 37,740.5 m^2/project. With the rule-of-thumb conversion factor of 0.7 kWth/m^2 or 0.0007 MWth/m^2, the estimated average thermal capacity per PTC project is 26,418 kWth/m^2 or 26.418 MWth/m^2. This is a fairly large capacity. I expect this PTC type to remain the dominant and most successful SHIP type, and expect it to grow significantly. This PTC type enjoys maturity and proven success in medium-scale and large-scale SHIP projects, which supports its ability to attract more interest for these project sizes. For example, this PTC type was successfully demonstrated in the world's first pilot-scale and commercial-scale solar thermal enhanced oil recovery (EOR) projects in the Sultanate of Oman. In these PTC systems, steam near 310 °C is produced using an array of PTC rows that heat water to produce steam for injection in a crude oil reservoir to facilitate production of crude oil that is difficult to extract using conventional methods [295]. Conventional thermal enhanced oil recovery (TEOR) requires burning large amounts of a fossil fuel (commonly natural gas) [296], due to the enormous heat demands in order to supply steam steadily (24/7) [297]. The PTC steam generator operated along with a previous natural gas boiler as an overall hybrid dual-source system because the PTC system is not able to produce steam at night.

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The PTC system was able to reduce natural gas consumption by about 25%. This results in large amounts of avoided CO_2 emissions.

A giga-scale parabolic trough collector (PTC) project is expected to start production in 2026 (construction started in 2024) in the Kingdom of Saudi Arabia. This prospective project is "Maaden Solar I", with an impressive planned peak thermal capacity of 1.5 GWth (1,500 MWth) and a planned annual thermal heat output of 3,000 GWh/year. Maaden Solar I is expected to produce steam at a daily rate of 14,000 tonnes/day, and is expected to occupy a solar field area of 6 km² and a total project area of 7 km² [298]. This project is expected to be the world's largest SHIP plant. It aims to produce solar steam for use in refining bauxite ore into alumina (aluminum oxide, Al_2O_3). This is a preparatory process that precedes the primary operation of aluminum production [299,300] using the Hall-Héroult process that involves the electrolysis of alumina dissolved in molten cryolite mineral (sodium aluminum fluoride, Na_3AlF_6) to produce metal aluminum [301,302]. Maaden Solar I is developed for Maaden (Saudi Arabian Mining Company), which is Saudi Arabia's national mining company (state-owned) and the largest mining and metals company in the Middle East [303].

Given the highlighted challenges facing small-scale domestic solar water heaters when attempted for installation by individual residential users, such systems may not be able to compete with the more convenient, cheaper, and compact options of electric water heaters and gas-fired water heaters. In light of this, I recommend replacing these small decentralized systems with a large centralized one through solar district heating (SDH) [304]. In a similar manner, it is recommended to explore further the potential of solar district cooling (SDC) [305], where central thermally driven (absorption-type) chillers are used instead of conventional compression chillers. Despite the low coefficient of performance (COP) for absorption chillers (about 0.5 only [306], compared to about 3.0 for air-cooled compression chillers and 5.0 for water-cooled compression chillers [307]), their clean solar thermal operation renders them attractive routes to achieve sustainability and national zero-carbon targets. I also recommend governmental subsidies and awareness campaigns for the small-scale (below 1 MWth) SHIP projects.

5. Discussion and Conclusions

In the current study, a technical review of various types of SHIP systems was provided. These SHIP systems were grouped according to more than one classification method. The SHIP systems were grouped based on (1) solar concentration, (2) collector type, (3) temperature rise, and (4) solar tracking. The SHIP systems were divided into nine main categories, and the working principle for each of them was explained with the aid of illustrative sketches. Some of these nine categories can be further divided into subcategories, and this was clarified.

In addition, the recent global thermal capacity of SHIP was contrasted with various thermal and electric power capacities, and this comparison manifested the relatively small size of SHIP. By curating and processing public data about the progress and recent (2024) installations of SHIP systems, useful insights about the development of SHIP systems were given, including the countries that installed more SHIP capacity recently, and the SHIP categories that seem to be more successful and widely adopted than others. This analysis reveals the large disparity in the system size when different SHIP categories are compared.

The current analysis shows that more than 1,300 SHIP systems were commissioned worldwide by the end of 2024 (cumulative number), constituting a cumulative thermal capacity of 1,071.4 MWth, with a total collector area of 1,531,600 m². In 2024 alone, 120.3 MWth of thermal capacity was introduced in 106 SHIP systems having a total collector area of 171,874 m². In 2024, 65.9% of the installed global thermal capacity of SHIP systems belonged to the parabolic trough collectors (PTC), and another 22% of this installed global thermal capacity was attributed to the unevacuated flat plate collectors (FPC-U). Considering the 106 SHIP systems installed in 2024, the average collector area per system was 1,621.4 m²/project. With a generic rule of 0.7 kWth/m², the average thermal capacity becomes 1.135 MWth/project. However, this area largely depends on the SHIP category, where it is much higher for parabolic trough collectors (37,740.5 m²/project), but lower for flat plate collectors

(805.2 m^2/project, equivalently 0.564 MWth/project), and it is lowest for unglazed solar collectors (163.0 m^2/project, equivalently 0.114 MWth/project).

The current did not intend to provide forecasting for the expected deployment of the SHIP systems. It is admitted that the statistical analysis performed here is descriptive, rather than inferential and evaluative. However, the available data are not sufficient to provide reliable predictions. Despite this, the presented analysis here is still considered useful. Also, the current work did not cover economic aspects of SHIP systems, particularly a comparative cost analysis (including metrics such as the levelized cost of heat, payback periods, and operational costs). While this topic is a valuable area, such investigations are major extensions of the current work that deserve a separate study with preferably cooperative institutional involvement, with industrial partners on both the SHIP manufacturers' side and the SHIP users' side.

The current work can be extended in several ways by addressing the above-mentioned limitations. For example, the comparisons between different SHIP designs here excluded the economic aspects. These may be considered to assess the feasibility of the various SHIP options and the suitability of each for a certain capacity range.

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