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Design and techno-economic analysis of a photovoltaic hybrid-Air Source Heat Pump system for a sport center-Nablus-Palestine

Ciemat P.S.A

CIESOL
Centro de Investigación en Energía Solar
CENTRO MIXTO UAL-CIEMAT

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Alumno/a:

Saed B.H Qamhiia

Director/es:
Manuel García Pérez

Acknowledgment

For my father for supporting me and never letting me down.. thanks for believing in me.

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To the planet Earth, sorry for the mess, we are working on it….

Abstract

Sun is an essential energy source for reducing fossil fuel usage and carbon emissions by substituting the conventional manner of producing energy with a renewable approach that can meet daily demands of thermal and electrical energies. This study was intended to give an overview of the photovoltaic-thermal/hybrid solar technology and its applications, by which, the combination between such technology and an air-water heat pump. That’s to cover the thermal and electrical energy needs of a sports center with a swimming pool located in Nablus-Palestine (Mediterranean climate). Such a combination is then compared technically and economically with a PV/ heat pump and a PVT-PV/heat pump. It has been found that a combination between PVT and PV technologies with a heat pump PVT-PV/ HP, can be opted to cover all thermal and electrical energy necessities, and it can show a good performance all along the year, as it increases the COP of the heat pump, bringing more energy savings, and it needs a relatively smaller plant size. Economically, payback period, NPV, and IRR have been calculated and listed for the proposed systems.

Resumen

El sol es una fuente de energía esencial para poder reducir el uso de combustibles fósiles y las emisiones de carbono al ser capaz de sustituir las fuentes convencionales por una fuente de naturaleza renovable capaz de satisfacer las demandas diarias de energía térmica y eléctrica. Este estudio ha tenido como objetivo estudiar una aplicación de la tecnología solar fotovoltaica-térmica / híbrida y la combinación entre dicha tecnología y una bomba de calor aire-agua para cubrir las necesidades de energía térmica y eléctrica de un centro deportivo con piscina ubicado en Nablus-Palestina (clima mediterráneo). A tal fin se han estudiado técnica y económicamente dos propuestas de sistemas constituidos por una bomba de calor-PVT y una bomba de calor PVT-PV. Se ha comprobado cómo la opción híbrida puede cubrir todas las necesidades de energía térmica y eléctrica, y puede mostrar un buen desempeño a lo largo del año, ya que aumenta la COP de la bomba de calor, lo que genera más ahorros de energía y requiere un tamaño de planta relativamente más pequeño. Todos los indicadores económicos del proyecto analizado: el período de recuperación, el VPN y la TIR confirman la idoneidad de la propuesta realizada.

Contents

List of tables

List of figures

Abbreviations

AC: Alternate Current
AM: Air Mass Coefficient
BIPVT: Building Integrated Photovoltaic Thermal
COP: Coefficient of performance
CPC: compound parabolic concentrators.
CPV: Concentrating Photovoltaic.
CPVT: Concentrated photovoltaic thermal.
D: Diverter.
DC: Direct Current.
DHW: Domestic Hot Water.
DX-SAHP: Direct Expansion-Solar Assisted Heat Pump System.
FF: Filling Factor.
FINA: Fédération Internationale de Natation.
HF: Hot Fluid.
HP: Heat Pump.
HTF: Heat Transfer Fluid.
HVAC: Heating, Ventilation and Air Conditioning.
IDEA: Instituto para la Diversificación y Ahorro de la Energía.
IDX-SAHP: Indirect Expansion- Solar Assisted Heat Pump system.
IEA: International Energy Agency.
IRR: Internal Rate Of Return.
M: Mixer.
MPP: Maximum Power Point.
NPV: Net Present Value.
P: Water Pump.
P.W: Pool Water.
PR: Performance Ratio.
PV: Photovoltaic.
PVT: Photovoltaic Thermal.
S.T: Solar Tank.
SAHP: Solar Assisted Heat Pump.
SC: Solar Thermal Collectors.
SC-SAHP: Solar Thermal Collector-Heat Pump Assisted.
SF: Solar Fraction.
SHC: Solar Heating and Cooling Program.
SPT: Simple Payback Time.
STC: Standard Test Conditions.
V: Motorised Valve.

1 Introduction and objectives

Energy is a key factor for development in all sectors. Increased energy consumption has necessitated the use of renewable energy sources to find a solution for also increasing concerns regarding environmental pollution and depletion of fossil-based energy sources.

For the past decades, many energy technologies were developing, especially the technologies that specialize in renewable energies, such as wind, geothermal, sun and so many others. Sun radiates, or sends out, an enormous amount of energy and is considered one of the very abundant energy sources that can be employed to fulfill human necessities of power in its various forms, and it has helped to form and shape a lot of renewable technologies such as solar heating, photovoltaics, solar thermal energy, solar architecture, and artificial photosynthesis.

Most buildings worldwide are served with conventional fossil fuel-based technologies as gas or electric heaters for the coverage of the hot water demand, and with the improvements on the quality of life, we can see that the demand for hot water is increasing for both residential and industrial sector, so we must keep developing and searching for new and innovative techniques for us to harmonize our energy needs with the energy that we can harvest from the different resources and especially from renewable sources [1]

Among the above techniques, photovoltaic modules are best known as a method for generating electric power by using solar cells to convert energy from the sun into a flow of electrons by the photovoltaic effect. Photovoltaic systems amongst all the sustainable energy sources are considered as the most popular for their lower operational cost and maintenance [2] and also for being pollution-free energy [3]

But as we know, radiation that the sun emits increases the temperature of PV modules, resulting in a drop of their electrical efficiency. With proper circulation of a fluid with low inlet temperature (or other usable heat sinks), heat is extracted from the PV modules and so, the extracted heat can be used to support other practical heating applications while photovoltaic efficiency is increased. This is the abstract idea behind the development of the so-called photovoltaic/thermal (PVT) systems [4] [5] [6]. In Figure (1) we can see an overall view of an example of this type pf hybrid PVT modules [7] [8]

The combination of the conventional photovoltaic collectors (PV) and the conventional solar collectors in a single component has made the PVT collectors promising particularly, while the PV layers produce electricity, the formerly-considered wasted thermal energy can be distributed to a fluid [9] [10] (typically air or water [11] [12] [13] [14], and that can lead to the simultaneous production of heat and electricity as an overall result, that’s also with fulfilling higher electrical and thermal efficiencies if we compare with the conventional ones [15]

The range of applications of PVT collectors can be divided according to their temperature levels, and that depends on collector design and make [16]. PVT can be employed in a wide range of different (low-temperature) applications as in residential buildings for example, but for being able to get a higher working fluid outlet temperature without a decrease in the electrical efficiency and to widen the possibilities where the system can form a suitable option, a photovoltaic-integrated solar heat pump (a merge of the photovoltaic/thermal and solar assistant heat pump technology) is here proposed as a sustainable alternative [9], [10] [17].

Figure 1 Overall view of a hybrid PVT module [7]

In addition to the above, once solar heat and electricity are available thanks to PVT systems, it seems reasonable to combine then with heat pumps, which are devices consuming, initially, conventional energy (electricity) to output two to six times thermal energy through the absorption from renewable and “free” energy sources, such as air or water. Therefore, these heat pumps are a significant energy-saving technology widely used in domestic hot water production, space heating, swimming pool heating, etc.

In a basic approach, a heat pump is an energy transformation device involving both heat and mechanical work. A heat pump allows transferring heat from a cold source (air, water…) to a hot source (air or water heating system) thanks to certain thermodynamic process feed by mechanical work, its working principle is depicted in figure (2). The coefficient of performance (COP) represents the efficiency of the overall energy balance, relating the obtained useful heating energy Q_H to the used energy W. As advanced, the cold source of the process can be air or water, but as transfer efficiency will be higher as higher value of T_C, heat pumps can also benefit from use of other sources as the underground or solar thermal energy. Practically, most of the heat pumps works using an inverse compression refrigeration cycle feed by electricity, which, in turns, it could have a renewable origin.

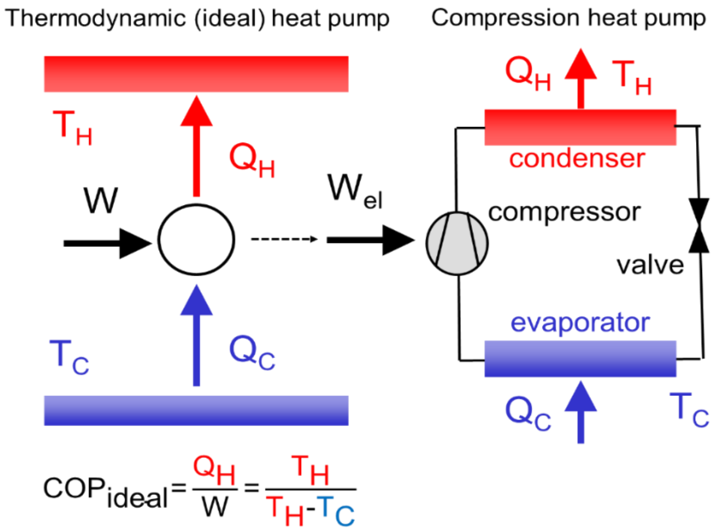


Figure 2 Net transferred energy and the COP of the heat pump

Accordingly, a heat pump that is assisted with a hybrid PVT collector could form an independent and integral system, allowing multiple operation modes , that is, the thermal part of the PVT collector uses solar energy as an evaporating heat source, thus the heat pump can achieve a high coefficient of performance (COP), and the electrical side of the collector, that represents the power source for the heat pump [18] [19] [20]

In this master’s thesis, the case study is the fulfillment of the energy demands of a sports center, located in Nablus-West Bank, in the city of Nablus (solar irradiation average above 1800 kWh/m^2).The center energy demands are the thermal energy needed to heat a swimming pool and to cover the sanitary hot water needs for the sports centers’ members, and the electrical energy needed to power the thermal systems and to operate the everyday routines of different electrical equipment, as the energy used to power air HVAC systems.

The main objective of the work is to practically design and evaluate a hybrid system, consisting of a heat pump with photovoltaic/thermal (PVT) collectors aiming to obtain reasonable values of solar fractions of the building energy demands. The system is called the photovoltaic thermal solar-assisted heat pump (PVT-SAHP) system. We are going to focus on both actual demand and energy savings, the system will be designed that’s to be capable of operating in two different modes, PVT thermal to operate solely and/or to assist a heat pump being the low-temperature inlet point. In addition, we will compare the system with an on-grid PV system that just produces electricity to see how our system would be of favor for enhancing the efficiency of the heat pump. Another system to be compared with, a system that combines PV and PVT modules also with a heat pump.

As advanced, the unity of PVT collectors and HP (heat pump) can take advantage of solar thermal energy being used to enhance the coefficient of performance (COP) of the traditional HP by providing hot water at the low-temperature inlet, which from the perspective of the heat pump technology, this is can cause an increment of the evaporating temperature of working fluid at the evaporator–collector, and from the point of view of solar technology, the refrigerant undergoes phase change at a relatively low temperature in the evaporator, which moreover makes the conversion efficiency improve. [21]. Although, the electricity from the PV part helps driving the compressor with renewable solar energy, which gives a further enhancement for the overall efficiency of the whole system [22].

For a high-density city in West-Bank, the design area of solar systems is such an important factor to be put under consideration. Installing any system imposes many constraints, so when the final objective is to cover the most possible energy needs for a facility, we must consider the ability to achieve a higher overall energy output per unit collector area. So, having such a hybrid system not just better than side-by-side systems (PV+SC) concerning area regulations, but also a reduction of the number of systems' components, which makes our design much more compact, in addition, multiple requirements of water heating and space air conditioning in the public facilities can be catered for. [23].

The primary function of the proposed PVT-SAHP is to produce heat to reduce the operating time of both installed systems, the heat pump, and the electric heater, and therefore to save money and reduce greenhouse gas emissions.

The main objective in this thesis is to evaluate the design of an innovative system that consists of an air-water heat pump that is assisted with a photovoltaic hybrid thermal collector (PVT-HP) with the goal of fulfilling the demand (both thermal and electrical) of a covered swimming pool, and the domestic hot water for a sports center located in Nablus-Palestine. For the fulfillment of this main objective, the following sub-objectives have been tackled:

- Assessing the available knowledge on the different PVT collector technologies and manufacturers, showing the types, models, characteristics of each, that's to show the selection criteria of each one of them as the most proper and adequate from economic, availability and other different aspects.

- Estimating the yearly and monthly electric consumption profile of the facility, swimming pool's thermal demands, and daily domestic hot water usage.

- Providing a basic design of a PVT-SAHP for the fulfillment of the center energy demands.

- Comparing such a system with other solutions such as photovoltaic system that just can produce electrical energy to supply the center’s electrical demands, that the heat pump is considered one of them, and the combination between PV and PVT solar modules as another configuration to be differentiated from different points of view, like efficiency, best COP for the heat pump installed, performance ratios, cost effectiveness.

2 Technical Specifications

2.1 Solar collectors' technologies

As we aim to investigate and to compare different technologies, an overview of the main characteristics and technical parameters for solar collectors are assessed, starting from the two mainstream technologies, solar thermal and solar photovoltaic technologies, and ending in hybrid PVT collectors.

2.1.1 Solar thermal collectors

In SC collector systems, incident solar radiation is converted purely into heat energy, and a heat transfer fluid such as air or water has to be circulating in the tubes to carry the heat that comes with the solar radiation. This energy in a form of heat (thermal energy) can be employed in many applications, some examples are space and water heating, generation of steam, or also can be used later after being stored properly by different storage technologies. Classifications of solar thermal collectors can be based on the type of fluid circulating: air-heating type and liquid-heating type, or also can be according to the concentration technology, as some types come with a concentrating mirror such as CPC (compound parabolic concentrators) or simply as non-concentrated; flat plate [24].

In addition, for medium and high-temperature applications (250-2500°C), tracking devices can effectively help collectors reaching much higher temperatures, this is for concentrated collector systems, though, for low-temperature applications (less than 100 °C) no need for any complications, so stationary collectors would comply with their duty perfectly [25].

Flat plate solar collector components are as follows: absorber which is the main part of the collector, made typically of aluminum or copper, transparent cover to let through the maximum amount of solar radiation, frame to set different parts together, and insulation placed at every side and at the back for assuring the minimum thermal losses to the ambient. Serpentine-shaped tubes are attached to the surface of the dark absorber, which makes heat transfer between absorbed heat from solar radiation and fluid as good as possible [26]. Figure (3) shows different collector types and applications.

A good solar thermal collector must accept the maximum solar radiation (high transmittance), absorb most of it (high absorptivity), emit as little as possible (low emissivity), and let out as little as possible (low long wave transmittance) [27].

As long as applications where this type of collector employed staid within the range of 40-70°C (low temperature) it can be of favor with good suitability and can reach good thermal efficiencies of about 40-60%. But once temperatures start to increase more and more, a significant decrease in efficiency occurs [27]

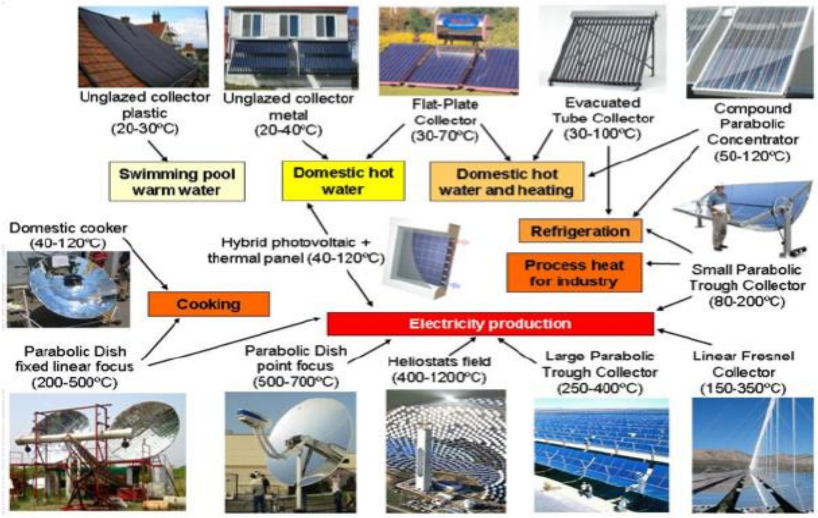


Figure 3 Solar thermal collectors' types and applications [27]

When it comes to defining the parameters of the collector, different areas are mentioned and is crucial to clearly define every one of them, which come as gross surface area (collector area) which is the minimum amount of area required for mounting, aperture area that corresponds to the light entry area of the collector, and effective collector area which is the actual area of the absorber panel. The choice of collector for an application depends upon the resultant temperature range desired. Other considerations include the amount of radiation expected, weather conditions, and the space available. [28]

The efficiency of a solar thermal collector is the usable thermal energy divided by the received solar energy and it depends on several factors including the type of collector, the spectral response of the absorbing surface, the collector insulation, and the temperature difference between the collector and the ambient air.

Collector's efficiency can be expressed as follows;

$$\eta_{\mathrm{th}} = \frac{P_{\mathrm{th}}}{G_{\beta}A} = \frac{\dot{m}C(T_{\mathrm{out}} - T_{\mathrm{in}})}{G_{\beta}A}$$

Where η_{th} , $\dot{m}$, C, T_{out}, T_{in}, G_{β}, A are instant efficiency of the collector, mass flow rate, specific heat capacity, working fluid temperature at the inlet and the outlet, incident solar irradiance normal to surface, collector aperture respectively. Figure (4) illustrates the parameter that define the efficiency of a solar thermal collector.

Solar collector’s efficiency depends on several constructive and environmental factors being expressed, as regulated by international standards [29], as

$$\eta_{th} = \eta_0 K(\theta) - a_1\left(\frac{T_m - T_a}{G_\beta}\right) - a_2\left(\frac{(T_m - T_a)^2}{G_\beta}\right)$$

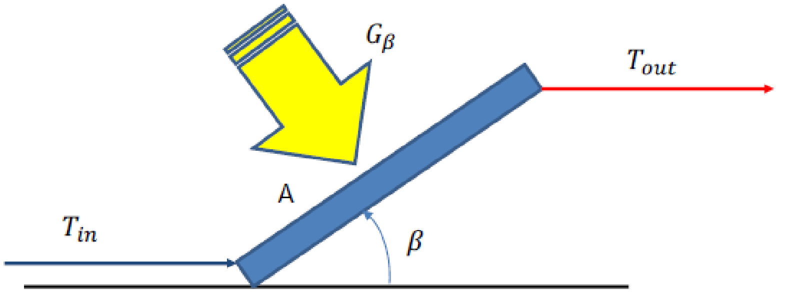


Figure 4 Efficiency define parameters of a solar thermal collector. [28]

where η_0 is the optical efficiency, $K(\theta)$ is the incidence angle modifier, a_1 is the heat loss coefficient, a_2 is the temperature dependence of the heat loss coefficient, G_β is the global solar irradiance on the aperture plane, T_a is the ambient temperature and T_m is defined as the average temperature between the input and output temperatures.

Normally, T_m is unknown. Its value is determined by the load, as well as the design and components of the system (collector area and efficiency parameter, storage capacity, heat losses, control, and so on), i.e. the real system and the actual operation circumstances at a particular moment in time. When the collector and location are recognized, the power output is calculated at every point in time by eq. below, using the same value of T_m at all times [30].

$$P_{th} = A_m * (\eta_0 K(\theta) G_\beta - a_1(T_m - T_a) - a_2((T_m - T_a)^2)$$

All manufacturers must explicitly express the value of the efficiency equation parameters as they serve as a reference for thermal power calculations and comparative performance estimations at operation temperatures and irradiances.

In addition to the above, Solar Fraction (SF) is a very important parameter to look for when designing a solar thermal system, which is the ratio between the energy supplied by the solar part of an installation and the total energy supplied by it, it can be expressed as [28]

$$SF = \frac{Y_{solar}}{Y_{solar} + Y_{aux}} \text{ x } 100$$

Where Y_{solar} and Y_{aux} are solar heat yield (KWh) and the auxiliary heat that come from a nonrenewable energy source (KWh) respectively.

Reports showed growth of installed capacity by a factor of 7.7 since 2000, by end of 2018, accumulated thermal capacity in operation was more than 450GW$_{th}$, which is approximately 680 million square meters of installed collectors' area worldwide. Despite this, the solar thermal market is facing challenges in recent years, and this happens because these conventional systems are being pressured from heat pump systems and photovoltaic systems [31]. Flat plate collectors are considered as the most convenient type in the most of studies to be combined with PV systems to reuse thermal energy wasted in many different applications. [32].

2.1.2 Solar photovoltaic collectors

A photon from the sun's light with an energy higher than or equal to the band gap of the cell material can release an electron from its place once it hits it, so this electron starts move in the electric circuit. This is the abstract idea of the photovoltaic effect that was first noted by a French physicist in the 90s of 19th century. For this process to be effective, these cells have to be electrically connected forming a PV module, in this way, a sufficient amount of electricity will be produced, and having this module connected with many others forming an array that can effectively support a system with its needing of electrical energy [33].

We refer to the grouping of solar cells based on the requirements of voltage and current, so it's preferable having series and parallel connections combined; a series connection will add up the voltages to the value we desire, the same for a parallel connection that helps to reach the desired current levels. Modules that are formed by combining several cells are further grouped to meet the system's requirements of voltage. Installations in most solar plants have a wide range of voltages that can be chosen from 48 to 600V. Then the string is formed by connecting these modules in series to further increase the levels of voltage. [34]

Mono crystalline and poly crystalline silicon cells are the most common types of cells utilized for electricity generation, quite good efficiency levels can be reached, as for polycrystalline material-based cells, an efficiency range varies from 12-21%, and that what has helped these types of cells compete among many other technologies in the market of PV. Thin-film photovoltaic cells had their opportunity to appear, being cost-effective and having an acceptable efficiency range [35].

The key parameters of a solar panel, which should always be measured under an international standard operating environment known as Standard Test Conditions (STC) represented by 1000 W/m^2 of irradiance (peak solar hour definition), an AM 1.5 spectral distribution, and a temperature of 25°C [36] are:

- Short-circuit current (I_{SC}), which is the value of the current that circulates through the solar panel when the voltage at its terminals is zero, V =0, and it is the maximum current that could be obtained (in an ideal case) of the solar panel when it works as a generator.

- Open circuit voltage (V_{OC}), which is the highest voltage that can bias the device when working as a generator.
- The maximum power point (MPP), which is a working point in which the power delivered by the solar panel to the external load is maximum.
- The Filling Factor (FF), is the product of I_{SC} and V_{OC}. Its value is higher the better the cell. In general, a low FF value is associated with the existence of efficiency losses in the device, while a good quality cell usually has FF values higher than 0.70.
- The efficiency is usually expressed as a percentage and is the ratio of the electrical power delivered by the panel and the power of the incident radiation. A standard efficiency would be around 15-17%, and a high-efficiency panel would be from 19-20% .

Rated efficiency of solar modules is defined at STC conditions (asterisk) and it is estimated as:

$$\eta_{PV}^{*} = \frac{P_{PV}^{*}}{A_m G_\beta^{*}} = \frac{V_{MP}^{*} I_{MP}^{*}}{A_m G_\beta^{*}}$$

According to the above, existing standards require manufacturers to provide the specifications of their modules allowing assessing the efficiency and the rest of electrical performance characteristics for any condition of operation, that is, any ambient temperature and irradiance, both also determining module surface temperature, T_c. [37]. While also these parameters can be obtained from the I-V that the manufacturer provide, a typical cell's I-V is shown in figure (5). [38]

$$I_{sc} = I_{sc}^{*} \frac{G_\beta}{G_\beta^{*}} [1 + \alpha(T_c - T_c^{*})]$$

$$V_{oc} = V_{oc}^{*}[1 + \beta(T_c - T_c^{*})]$$

$$\eta_{PV} = \frac{P_{PV}}{A_m\, G_\beta} = \eta_{PV}^{*}[1 + \delta(T_c - T_c^{*})]$$

In the above equations, the asterisk means manufacturer specifications at STC, and α, β, and δ are thermal coefficients, also provided by manufacturers.

PV system works on generating electrical energy from incident solar radiation, but this cannot happen without much-dedicated work between the different subcomponents that are function together to make this process achievable. Although there are lots of different types and applications in the field of photovoltaic systems, we can categorize the components of the system into four groups, PV part, power part, energy storage (optionally added), and mechanical and electrical components [34]

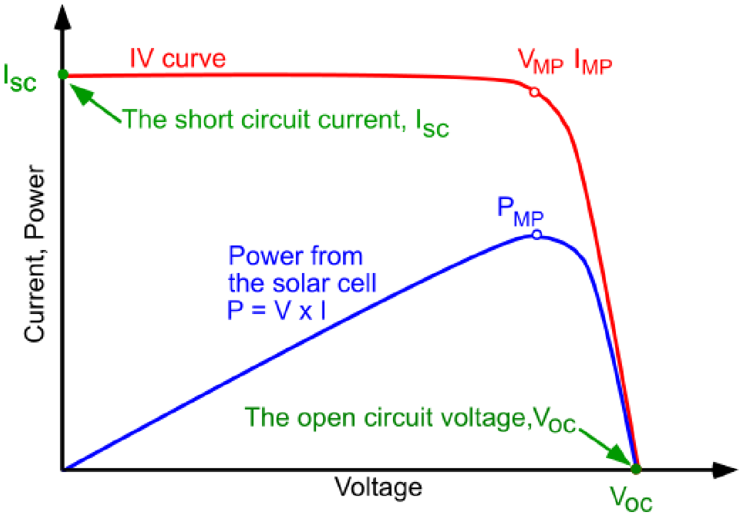


Figure 5 I-V curve of a solar photovoltaic cell [38]

Generally, we can distinguish three types of PV systems, grid-connected, stand-alone, and hybrid PV systems (combines both of them). In grid-connected PV systems, electricity generated is directly fed into the public electricity grid, and this system consists generally of an inverter, transformer, and the utility grid. Another type is what is called stand-alone PV systems, here, electricity generated is directly consumed by the facility in which is installed and excess energy is to be stored in storage systems which are battery bank. Hybrid PV systems are typically a combination of those two systems, so the electricity generated even it is directly consumed or can be stored in batteries, excess is fed into the grid [39].

PV systems through their various types use components of power electronic, the most popular for using are power conditioning units, inverters as an instance. Current produced from the arrays is direct current (DC), so to be used in the different applications has to be converted to alternate current (AC), so inverters are responsible for this conversion, which makes its selection very crucial and so what decides the operating voltage of our system [34]

There are a wide range of types and sizes of inverters, so the selection process has to be very effective because it is critical for the performance of the system, and the choice has to be based on the peak power rating required and as formerly mentioned on the system’s voltage. Three different types of inverters can be installed based on the size and the output power ratings; microinverters, string and central inverters. [34]

The evaluation of a PV system's performance varies depending on its features, and it is more or less dependent on the plant's location, PV-specific technology, and the type of installation. The energy yield for each array and the final yield for the entire power plant, capture loss, performance ratio, capacity factor, and the efficiencies for the different components of the system, such as module efficiency, invertor efficiency, battery bank efficiency, and the overall efficiency of the PV power plant, according to the International Energy Agency are the most important parameters that evaluate the system. Plant operation and maintenance choices can be made using these indications [40]

The environment has a direct impact on the output power ratings of a PV system, thus weather variables like temperature, wind, light intensity, and soil in each region where the system will be installed must be taken into account while choosing the module type. The module's performance degrades as the temperature rises. Each module's sensitivity to temperature is defined by its temperature coefficient. We may also regulate the temperature of the module by providing it with technology that actively cools it so that it maintains its performance [41] According to the above, parameters to be considered regarding the efficiencies of the components of the whole photovoltaic systems are as follows [42]:

$$\eta_{PV} = \left(\frac{E_{DC}}{H_{\beta} x A_{g}}\right) x\ 100\%$$

$$\eta_{system} = \left(\frac{E_{grid}}{H_{\beta} x A_{g}}\right) x\ 100\%$$

$$\eta_{inv} = \left(\frac{E_{AC}}{E_{DC}}\right) x\ 100\%$$

$$PR = \left(\frac{Y_{F}}{Y_{R}}\right) x\ 100\%$$

Where η_{PV} is the generator’s efficiency, η_{system} system’s efficiency, η_{inv} inverter’s efficiency and PR is the performance ratio. E_{DC} and E_{AC} are the DC and AC energy generated by the PV array system [KWh], respectively, and H_{β} is the available irradiation, that is the irradiance integration, on the plane of aperture [KWh/m^2], A_g is the array surface, Y_F and Y_R are the final and reference yield respectively.

Of all the above parameters, the more important for calculation is performance ratio, PR, which allows to directly relating system AC output with rated DC power from generator. Performance Ratio for grid connected systems ranges, usually from 70% to 90%.

2.1.3 Photovoltaic Thermal (hybrid)-collectors

A photovoltaic/thermal hybrid solar system (or PVT system for simplicity) can produce electricity and thermal energy simultaneously, as being an integrated system, such a system is necessarily be formed after a combination between photovoltaic (PV) components and solar thermal components.

The efficiency of electrical conversion from incident radiation for any conventional PV module varies between 15 and 17 % depending on the cell type used and the environmental conditions in which the system is installed; in other words, the incident radiation that remains, which is greater than 50 percent, will be directly converted as heat dissipated in the module structure. The cell experiences an extremely high increase in working temperature, which in some cases can reach 50°C above ambient temperature, and this temperature increase can have unfavorable consequences, including a drop in cell’s efficiency and the possibility of permanent damage to the module's structure if the thermal stress persists for a long time [43]. So PV-thermal technology can solve this issue as it removes the heat which can prolong the module’s lifespan.

There are various types of PVT collectors, and the principles are so distinct that discussing ‘PVT systems' without additional clarification is nonsensical [44]. In general, PVT collectors with liquid heat transfer medium can be distinguished from those with air or water as a coolant, with the option of utilizing special refrigerant fluids such as R-134, which may also flow naturally or be forced mechanically. Furthermore, PV technologies along with monocrystalline silicon, polycrystalline silicon, and even thin-film PV can be part of the collector. Flat plate collectors, evacuated tube collectors, and heat pipes are among the various solar thermal methods available. [45]

This type of systems can serve in various applications, as it can be installed in a solar field (standalone) or connected to the grid. It can be installed as an independent field or it also can be integrated into a building façade. Available designs vary from pre-heating water and/or air, to supplement hot water that results from a heat pump integration, and many others [9]

Plenty of design decisions can effect on the mode of operation, the temperature at which the system process, and efficiency. So, in addition to selections formerly mentioned above, thermal to electrical production ratio, as well as the solar fraction, are very important factors for the optimization process of the overall benefits. [46]

Since the 1970s, extensive research and development have been carried out, with activity levels continuously growing year after year. For the past 40 years, experts have documented theoretical and practical studies of the PVT system, and they have found important design characteristics. Both coolant fluids (water-based and air-based) technologies and key principles were covered [47] [48].

The attractive features and advantages of PVT are listed in review studies [49] [50]:

- The combined photovoltaic–thermal collectors system functions as a dual-function system, providing both electrical energy and heat.
- A photovoltaic module with a solar thermal collector has greater combined efficiency than two independent systems of equal size. That's to say, one hybrid PVT solar collector is able to produce more energy than two separated modules (PV and SC). For example, 2 m^2 of both modules, 1 m^2 photovoltaic module that is able to produce 72 kWh of electricity, and another 1m^2 thermal collector that is able to produce 520 kWh of thermal energy. But on the other hand, a hybrid PVT of 2 m^2 produces 720 kWh of thermal energy and 132 kWh of electricity, which is 44% more energy than two separated systems.
- PVT can have a shorter payback period than separate systems. According to research conducted in Greece, a combined PVT system lowered the payback period for c-Si modules by 10 years and for a-Si modules by 6 years.
- Because it produces no hazardous waste or radioactive material and decreases greenhouse gas emissions, the PVT system is considered a quiet and clean technology.

2.1.3.1 Liquid-type PVT system

Researchers have focused for the first 30 years on improving the performance-cost ratio for the PVT systems, and many investigations were conducted to try competing for conventional systems with the same resulted production having both photovoltaic and solar thermal systems operating apart. PVT-water collector types were confirmed to be having higher efficiency, nevertheless, the adoption of air-based PVT in Europe and North America was more rapid than water-based collectors for an economic motive [51]

A detailed physical model for the evaluation of water-based PVT collector performance was presented in [48], and the range of the total efficiency of the system was found to be 60-80%, and for the prediction of the performance quantitatively, mathematical algorithms were proposed. The ratio between the diameter of the tubes and the width of the fins was also investigated. Although numerous different PVT configurations are now under development, the most popular PVT configuration is the “sheet-and-tube’’ [52], in which a standard SC thermal collector is equipped with a PV layer encased in the absorber [9], [10] [52] [53]

Various PVT collector design performances were investigated for the long-term in steady-state circumstances and it was found that thermal efficiency can be improved using a collector of a single-covered design and can be better than that of an uncovered one, but for the same collector, not any observable improvement for the electrical efficiency to be mentioned, yet double-covered design can cause an incrementation for the thermal efficiency but that can affect inversely the electrical efficiency [54]. Worth to be mentioned, more or less, the cell’s area doesn’t have any affection on its efficiency, however, it does influence its thermal efficiency. As the system comes attached to a tank reservoir, system performance is significantly affected by the amount of water in the tank [9].

In a water-based flat plate collector, solar cells have to be thermally contacted perfectly with the absorber plate, that’s to assure a good heat transfer between both, hence, they have to be insulated electrically. Figure (6) shows the main features of a flat-plate PVT collector [48].

There is a risk that water-based systems will attain dangerously high temperatures, especially when there is a low demand for hot water. The PVT may achieve a temperature of 170°C, resulting in reduced fluid heat transmission and increased pressure in the heat transfer loop [55]. Turning on the PVT collector after it has been switched off for a long period and the temperature has reached the stagnation point might cause internal thermal shocks, resulting in the production of steam and a rapid non-uniform thermal decrease of the absorber [56]. A temperature control function should be included to avoid the negative effects of the stagnation point.

The use of a liquid PVT system has drawbacks, including higher costs for thermal pipes, heat exchanger components, and pumps for water circulation, as well as freezing issues in cold climates [49]. As a result, anti-freezing fluids like propylene-glycol/water combination must be used in solar systems built for very cold locations like Canada [55].

The electrical performance of a PVT system can be directly assessed, that’s because electricity generated is consumed immediately or it optionally can be stored. When it comes to thermal performance, things are a bit more complicated, as the

PVT collector is just a portion or sub-system of a bigger and complete system for a heat supplement, as an instance, storage, auxiliary boiler or electrical heaters, and many other mechanical equipment that can include pumps and measuring devices, in addition, many other design parameters have to be taken under consideration, like the solar fraction for example, that's all to be able to achieve best benefits. [57].

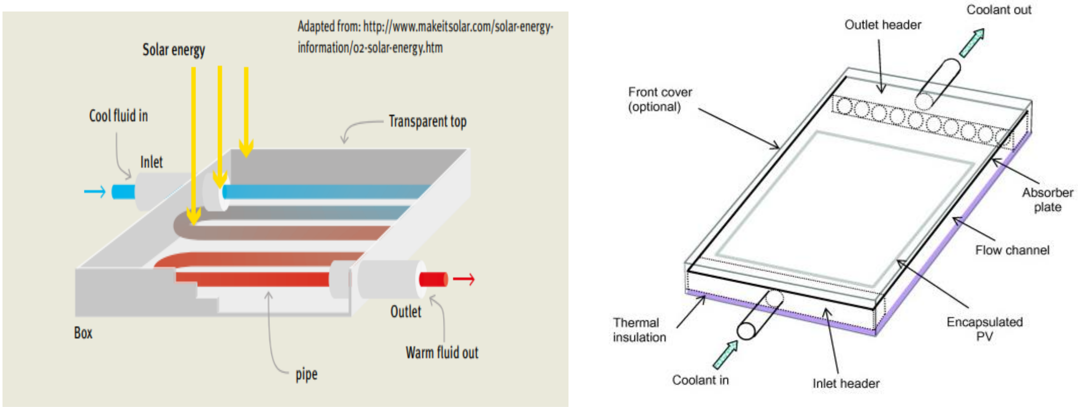


Figure 6 Main features of a flat-plate PVT collector. [48]

The use of PVT-liquid collectors allows the PVT system to be integrated into thermal heating systems in buildings, allowing for low-temperature heat sources to be used. The collectors can be linked to a storage tank and used in conjunction with other heat sources such as heat pumps or biomass boilers. Space heating, DHW preparation, or both are possible with these devices. A variety of countries have examples of these types of systems. [45]

In regard to efficiency, the overall system performance η_{PVT} can be calculated as the direct sum of thermal and electrical efficiency [57] [58] [59]

$$\eta_{PVT} = \eta_{th} + \eta_{PV} = \frac{P_{th} + P_{PV}}{G_{\beta} A}$$

Another important aspect to be considered for a poly-generation system is the exergetic efficiency (ε), exergy as it is known; the maximum work that can be produced from the given energy with certain ambient conditions, and is the ratio between the total of exergy output and input. When the working temperature rises, the electrical efficiency of PV drops. The performance drop-off due to temperature increase is normally not too high: for crystalline silicon, it is typically approximately 0.45%/K [60]. In any event, lowering the operating temperature of PVT collectors improves both electrical and thermal efficiency. As a result, PVT systems are most commonly employed in low-temperature applications including residential hot water supply, under floor heating, and swimming pool heating [61], [62].

High ambient temperature in summer doesn't affect the efficiency of the thermal part badly, conversely, it does reduce the cell's electrical efficiency by about 30%. In winter, a deterioration in the thermal efficiency can be observed yet the PV side has shown better performance [8].

The PV cells encapsulated in the PVT panel produce energy based on solar irradiation and cell temperature T_c, as well as the physical properties of the photovoltaic material. The equation below calculates the power provided by PV modules by taking into account the module's peak power ($\mathrm{P}^{*}_{\mathrm{PV}}$), solar irradiation ($\mathrm{G}_{\beta}$), temperature coefficient losses (δ) and cell temperature ($\mathrm{T_c}$)

$$\mathrm{P}_{\mathrm{PVT(el)}} = \mathrm{P}^{*}_{\mathrm{PV}}.\frac{\mathrm{G}_{\beta}}{1000}.\left[1 - \delta(\mathrm{T_c} - 25)\right]$$

The temperature of the absorber plate, that is, the temperature of the flow moving in and out of the panel, is directly related to the temperature of the cell $\mathrm{T_c}$. The temperature at which the cell operates is governed, in turns, by the flow in the solar circuit, which is a key distinction between standard PV modules and PVT modules.

2.1.3.2 Air-type collector systems

A PVT-air module is just a flat-plate air collector with being pasted solar cells on the interior face of the absorber. A poly-generation of electricity (high grade) and warm air (thermal low-grade energy) can be yield using the same unit, which is cheaper than two separated ones [9].

For the sake of cooling the PV module, air-type collector design can be an economically accepted solution and less complicated, so in this type of collector, air temperature levels can be controlled by natural or forced flow, although in the natural flow electrical consumption that fans in the forced flow consume, wouldn't be required, but for the circulation being forced, a better convective and conductive heat transfer make it more efficient [63]. Flat plate air collectors exist in many designs, but the most common models are shown in Figure (7). [64]

Overall efficiency performance for an unglazed PVT-air was evaluated for a collector in a tropical area, and the results were given, as the ideal flow rate of the air, depth, and length of the ducts, and many other parameters [65], exergy and energy instant efficiencies ranges were found of 12-15% and 55-66% respectively [66]. And an evaluation of the effect of the filling factor was also conducted [67].

Utter characterization for the performance of a PVT-air collector can be defined within its rise in the air temperature, efficiencies for both thermal and electrical energies, the power demanded for pumping (circulating) the flow and the available net electricity production [67].

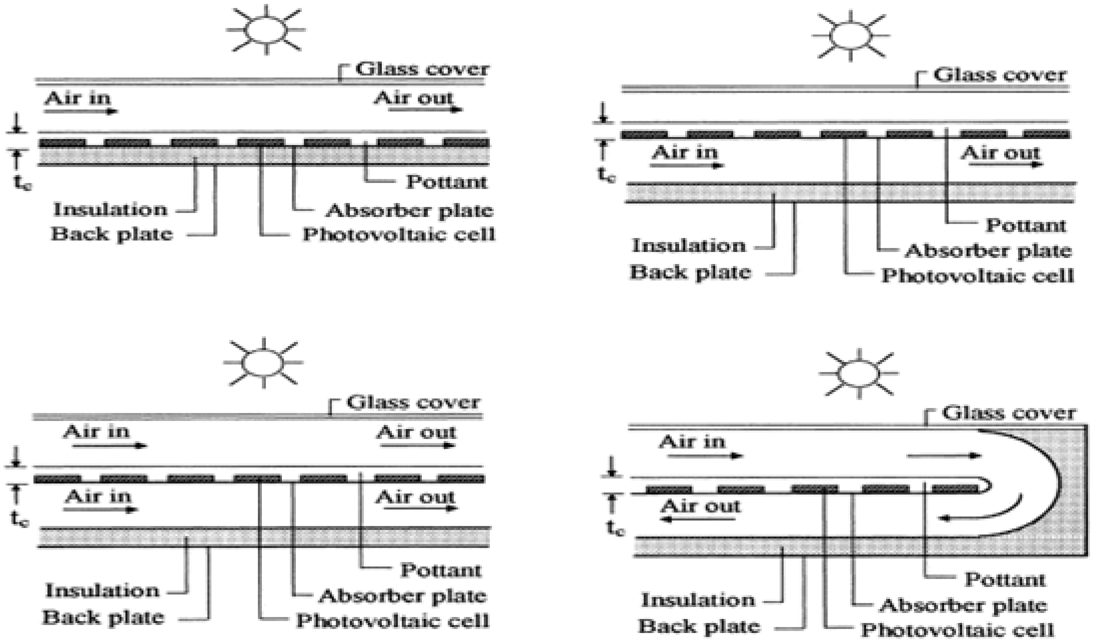


Figure 7 Schematics of the various PVT-air models. [64]

Air offers benefits and drawbacks over water as a working fluid [49] [50]:

Advantages:

- Preventing the collection fluid from freezing and boiling.
- Corrosion is less of a problem.
- There are no concerns about leaking causing harm.
- There is no requirement for high-pressure protection.
- The system is less difficult and straightforward to set up.

Disadvantages:

- A low heat transfer rate is caused by poor heat capacity and thermal conductivity.
- Due to the low density, a higher volumetric flow rate is required.

2.1.3.3 Concentrated photovoltaic thermal (CPVT)

Concentrated photovoltaic thermal (CPVT) solar collectors have been garnering growing interest from the scientific community and industry developers, due to their promising ability to lead the way for solar energy penetration into present-day power-generating technologies. The versatility, manufacturability, high efficiency, and multi-output nature of CPVTs prompted a slew of new designs and enhancements [68].

CPVT is a photovoltaic-thermal system that combines concentrated photovoltaic (CPV) and photovoltaic thermal (PVT) systems. [69]. The absorber, concentrator, solar radiation tracker, and thermal absorber are the four components of a concentrated photovoltaic thermal system (CPVT). Because the CPVT uses beam radiation, the absorber and concentrator should track the sun's position to optimize incident beam radiation. Fresnel lenses and parabolic concentrators are two primary technologies that may be used to concentrate radiation [70].

The solar energy is focused on the PV cells in Concentrating Photovoltaic (CPV) systems, which generates more power than a typical flat panel. [71]. One of the drawbacks of a CPV system is that as the intensity of the radiation increases, the temperature rises, lowering even more the cell's electrical efficiency. Other constraints of the CPV system include its restricted application scope and the need for effective PV cell cooling. CPV systems were adapted to use thermal energy to overcome the foregoing constraints, and are now known as Concentrated Photovoltaic Thermal (CPVT) systems [72].

CPVT, like the CPV system, employs low-cost optical components and is multijunction cell compatible. Due to the concentration of the optical element, the PV cell's surface area is decreased. A thermal method uses the heat created on the PV cell owing to the concentration of radiation. The use of thermal energy in the CPVT system can boost overall system efficiency (electrical and thermal) to about 90% [68].

2.1.3.4 Building-integrated PVT

A photovoltaic thermal array integrated inside the building structure is referred to as BIPVT. Instead of installing each component separately, the system integrates a building's roof or façade, solar cells, and heat collector into a single product. The BIPVT substitutes traditional building materials, making it less expensive than having several items. BIPVT can be used for both the roof and the façade. It serves a variety of functions in addition to providing power [73]:

- Acoustic isolation.
- Generating thermal energy for room heating or hot water production in the winter.
- Incorporating natural airflow into PV glass designs that might be utilized for heating or cooling.
- Visual cover with one-way mirroring.
- A more appealing perspective than traditional PV and solar collectors.
- Provide waterproof and windproof protection to the structure.

Figure (8) depicts a classification diagram for the BIPVT system. [74]

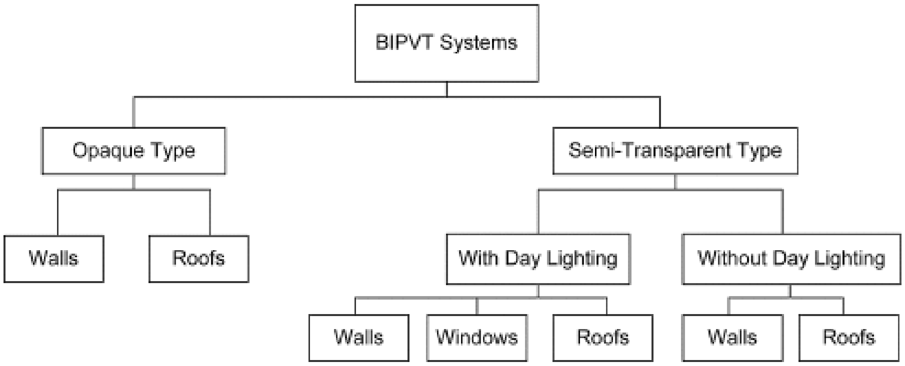


Figure 8 Classifications of the building integration PVT systems [74]

Experimental and theoretical studies on the building envelope should be conducted to determine the performance of an integrated photovoltaic-thermal system, taking into account the heating and cooling load, building type, location, and other factors. By combining the electrical and thermal efficiency of the BIPVT, the overall efficiency is calculated. The working fluid in construction applications is chosen based on the ambient temperature and sunlight intensity of the site. The liquid type is recommended for regions with high ambient temperature and solar radiation intensity because it has a larger thermal capacity than air. To create a more efficient system in locations with low ambient temperature and solar input, air might be employed as the working fluid [63].

2.2 Solar Assisted Heat Pump Systems (SAHP)

2.2.1 SC-SAHP

SC-SAHP is an integration of a traditional solar thermal panel with a conventional heat pump. Normally, these technologies are used apart and can be placed separately but working in parallel to produce hot water for the same application. In this system, hot water produced by the solar collector is fed directly to the low-temperature point of the heat pump. The purpose of this integration is to increase the coefficient of performance (COP) of the heat pump, so energy production can be less expensive and much more efficient. The solar thermal collector can increase the evaporation temperature acting as the heat pump evaporator [75]

Many different applications can be supported by a SAHP system, such as water heating, air conditioning, and many others. A solar thermal collector not just can take advantage of the incident solar radiation, but also of the energy that exists in the environment due to its low operating temperature. Solar collector’s efficiency can reach high values of about 80-90%, not surprisingly, a higher COP is also attained and it can reach a value as high as 8.0 [76]

Two different configurations can be distinguished for such a system, indirect expansion (IDX-SAHP), and direct expansion (DX-SAHP), which depends on the presence of a working fluid. DX-SAHP for water heating consists of a refrigeration cycle (Rankine cycle) that is coupled with the solar collector that acts as an evaporator, figure (9) shows a cross-sectional view of the PV evaporator. [77]. As the working fluid circulates in the refrigeration cycle, and once it passes through the evaporator it directly expands and absorbs the solar energy. [76]

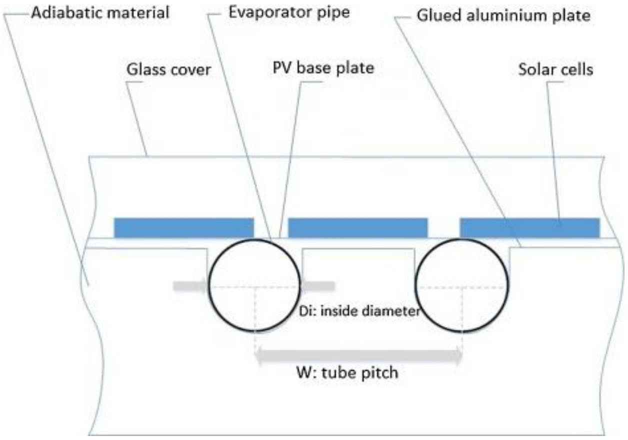


Figure 9: Cross-sectional view of the PV evaporator model. [77]

Indirect type SAHP systems are unlike direct systems in that the solar collector does not operate as an evaporator for the heat pump; rather, the heat pump is designed as a closed unit and the panel is integrated into the design. The heat pump is useful to the system in theory for a variety of reasons; first, it will pre-cool the fluid that is supplied to the collector, enhancing collector efficiency and extending the periods (both daily and seasonally) during which solar energy may be gathered. It will also post-heat fluid exiting the collector, ensuring that the fluid sent to the storage system is at a greater temperature. Furthermore, heat pumps with relatively warm domestic storage temperatures have a higher coefficient of performance (COP) [78].

There are three types of IDX-SAHP systems: series systems, parallel systems, and dual systems. Antifreeze solution, water, or air are commonly used as heat transfer mediums. The use of solar energy improves the heat pump performance in series and dual systems. A parallel system works as when enough solar radiation is available, the solar collector loop can meet the heating demand, but when there is insufficient solar energy available (during the night or on cloudy days), the heat pump kicks in. Solar radiation or the open-air environment are used to power this particular type of device [23]

Thermal losses from solar panels towards the environment can be considered additional thermal energy available to the heat pump, that’s because generally, a heat pump can evaporate at temperatures way below the ambient, which generates a better thermal distribution of the collectors even below that temperature, and by this, the thermal efficiency of the solar panel sometimes would reach 100% [79]. In a comparison between SAHP and a geothermal-based HP, SAHP is better from complexity and economic point of view, because it doesn’t require drilling pipes in the soil, which accounts for about half of the system’s cost [80].

2.2.2 PVT-SAHP

Renewable solar energy with the combination of a heat pump can effectively reduce the consumption of nonrenewable energy sources, also global warming is reduced significantly, that’s because of its ability to exploit ambient energy and solar energy [81].

A single solar assisted heat pump (PVT-SAHP) system combining PV/Thermal collectors and a heat pump. These systems have been widely employed for a variety of purposes, including water heating, space heating, and various residential and industrial applications. According to the International Energy Agency's Solar Heating and Cooling (IEA SHC) Program Task44, there is a growing interest in the most efficient usage of solar heat pump systems for residential usage [40].

This system combines photovoltaic/thermal (PVT) and solar assistant heat pump (SAHP) technologies in a scientific way, using this combination of PVT and solar-assisted heat pump (SAHP) technologies, greater hot water supply temperatures can be achieved, and PV cells cooling is improved. This is one of the long-term development goals specified in the PVT Road Map 2006, which was issued by the European PV Catapult project's PVT Forum [82].

Unlike traditional solar thermal collectors, hybrid photovoltaic/thermal (PVT) collectors allow for greater energy outputs per unit surface area due to the simultaneous conversion of absorbed solar radiation into electricity and useful heat. [83]. Additionally, the HP's compressor can be powered by the renewable electrical energy produced by the PVT collectors, further improving the system's overall efficiency [84].

The use of PVT in conjunction with a SAHP is a handy approach to ensure that both systems operate at their best. The lower the operating temperatures of PVT collectors, the greater their performance: thermal efficiency is higher because convection losses are reduced, and electrical efficiency is also higher since the PV cells are cooler. The temperature of the PV cells will be reduced because the absorber plate is connected to the PV cells, and the operating temperature of the flow in the solar circuit is lower. When the heat pump is running in heating mode, however, high temperatures increase its performance since the compressor's consumption is reduced as the cold storage temperature rises. [85]

Both thermal and electrical methods are used to integrate the solar panels. Solar thermal panels generate heat water, which is used to warm the cold side of the heat pump's circuit. The HP then operates more efficiently with a smaller temperature disparity.

This system also can operate in two different ways such as the conventional SAHP systems; indirect expansion (IDX-SAHP) and direct expansion (DX-SAHP), in the direct expansion system, working fluid vaporizes at the tubing under the flat-plate collector, which is the PVT evaporator. And in the IDX-SAHP system, the PVT collector helps rising the inlet temperature to the low-temperature inlet point of the heat pump, which by this, an enhancement of the performance of the system can be attained. DX-SAHP & IDX-SAHP systems illustrations are depicted in figure (10). [86]. The combination of PVT and a water-water heat pump is particularly convenient due to their physical behavior: the operating parameters of both systems make their connection ideal. [87].

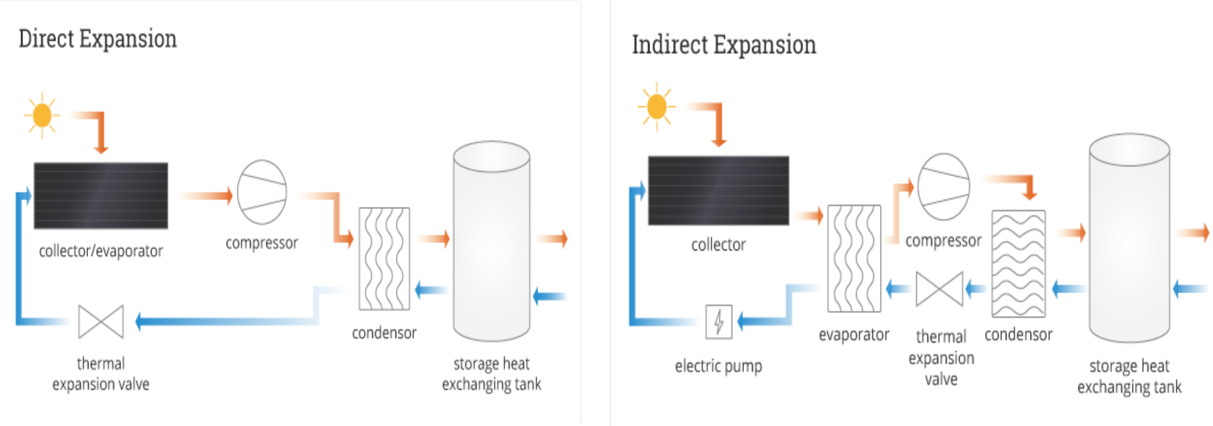


Figure 10 Animated design for an Indirect & Direct expansion design system. [85]

2.2.3 PVT-SAHP-Swimming Pool

The use of solar energy for public swimming pool heating might be quite interesting, but unlike residential hot water, which requires temperatures of around 60°C, swimming pools simply need to be heated to a few degrees above ambient air temperature. Solar collector arrays, require a big rooftop or open area in a structure to provide all of the criteria of an indoor swimming pool and this creates architectural restrictions. From this perspective, the photovoltaic solar thermal assisted heat pump (PVT/SAHP) system appears to be the best option, since it not only saves building space but also meets the needs of water heating, space heating, and electrical energy [88].

Many research projects on the direct use of solar thermal collectors for swimming pool heating have been conducted in recent decades [89] [90]. Also, a lot of researches has tested the conventional SAHP systems for general applications as mentioned earlier in this research. However, from the literature review, one research on the coverage of the thermal energy demands for a swimming pool comprising a conventional SAHP system has been conducted [88].

Although solar hybrid systems based on PVT collectors have received a lot of attention in the scientific community as seen above, their application to swimming pools has received less attention. Based on what has been searched, very few studies on the adoption of such an innovative system configuration for sports centers' applications have been published. A published study has included an indoor swimming pool's prospective water heating application (the thermal behavior of the swimming pool and its heat requirement were not considered) based on theoretical studies of a hybrid PVT solar-assisted heat pump system [91]. Another study has presented an analysis for a PVT solar plant serving an existing indoor/outdoor swimming pool [91]

2.3 Market potential and commercial PVT modules overview.

2.3.1 Market potential

The current market for both solar thermal and photovoltaic is quickly developing. PVT has the potential to increase at a similar rate, and its market share could surpass that of solar thermal collectors in the future [9]. Although the PVT industry is currently tiny in comparison to the markets for purely photovoltaic or solar thermal systems, there has been a rise in the number of widely viable solutions over the previous decade. The increased interest in PVT is most likely fueled, at least partially, by the growing global need for energy-efficient buildings and building energy regulations that are becoming stronger, with the European Commission aiming for all new buildings to be "almost zero energy buildings" by 2020, This puts pressure on the construction sector to find solutions for on-site sustainable energy production [92].

The highest potential market for PVT, based on the current Roadmap [82] released by the European PV Catapult project's PVT Forum, is in the household sector (about 90% of the current market). Customers for domestic hot water systems may first come from single-family homes; however, this will eventually be extended to multifamily complexes, where the hot water demand will be more consistent. The investment might be included in the building's mortgage. Collective tap water systems, direct space heating, swimming pool heating, autonomous applications, and heat pump integration are all conceivable niche markets in the intermediate future [93].

Then, in the commercial, agricultural, and industrial domains, applications will emerge. When tracking becomes commercially practical, PVT will become an inherent component of the building design because of the solutions that will be found. Eventually, using PVT in solar cooling could be beneficial [3].

In a market survey conducted by IEA SHC Task 35, it was discovered that markets in different countries have their features and that installers and planners in European nations have different perspectives on the combination of heat and electricity for energy generation. The high energy production per unit collector surface is a distinct benefit when it comes to low-energy building design, where sun-facing regions should be utilized to their best potential [93].

The absence of economic feasibility, public awareness, product standardization, warranties and performance certification, installation training, and experiences are the key barriers to the commercialization of PVT technology at the current time. The technology's dependability must be extensively evaluated. This necessitates further product development and innovation as well as established testing techniques and standards, as well as well-supervised demonstration initiatives [45].

During the classification of PVT collectors, it was discovered that a more specific language regime should be specified in terms of the design and function of PVT collectors. That means that existing language will need to be updated or altered. This suggestion applies to both the realm of standards and financing guidelines [44].

As available product information has shown to be insufficient in many situations, certain minimum standards for product information should be established and included in the certification. This pertains to the data sheet requirements as well as the design characteristics. A PVT collector's data sheet should at the very least provide the following information [44]:

- Types (e.g., covered/uncovered with/without rear thermal insulation)
- Dimensions.
- All needed electrical and thermal characteristic values for performance characterization.
- Mode of operation during the measurement.
- Materials used.
- Limit temperatures.
- Maximum operating pressure.
- Quality label.

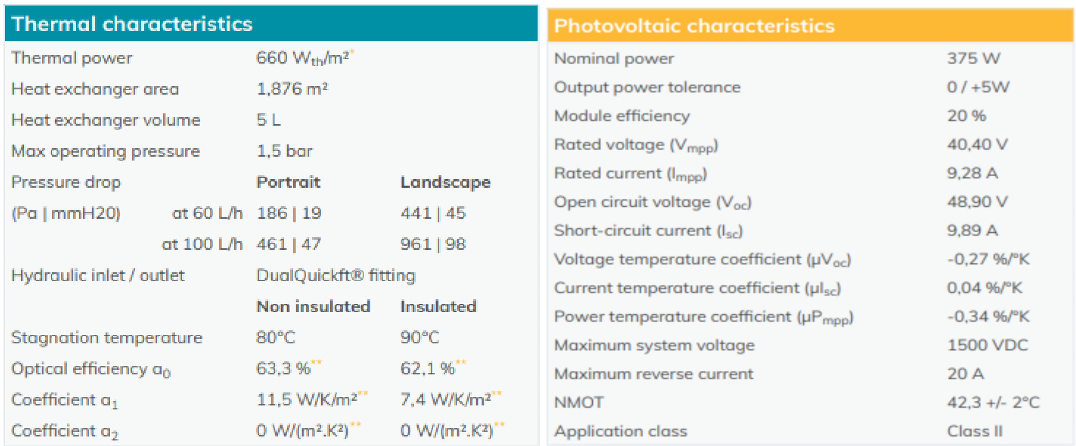
2.3.2 Overview of PVT manufacturers and modules

A market survey published in Task 35 in 2007 revealed ten commercial PVT product producers, with six of them have gone out of business. In addition, the investigation discovered 25 work principles. Previous research in Germany's PVT-Norm project discovered 41 PVT collector manufacturers, indicating a considerable rise in commercially accessible devices. Most of them, about 80% were uncovered, PVT collectors. Even though Chinese firms dominate both the PV and solar thermal sectors, many PVT producers discovered in the survey were European. [94].

There are a lot of PVT producers all around Europe that manufacture several types of panels as mentioned earlier, some of what has been found in this research and which can be considered as suitable options for our specific case study are mentioned in this section, a list of other producers is shown in annex (2).

1. DualSun-France

The company has around 30 monitored installations throughout France and around the globe. Most of its installations are in the range of 6 to 12 modules (1.5-2 kWp), but there are also larger installations, including residential and commercial, such as hospitals, schools, sports centers, and many others [96]. DualSun manufactures photovoltaic, thermal, and hybrid solar collectors. Its hybrid collectors (Spring-Hybrid) have an electrical nominal power in the range of 300-375W and thermal power output in the range of 620-660Wth/m^2, the efficiency of its modules can reach 20% as they claim. The thermal and Photovoltaic characteristics of its Spring-Hybrid 375 collector are shown in figure (11). [96]



Thermal characteristics			
Thermal power		660 W_{th}/m^{2*}	
Heat exchanger area		1,876 m²	
Heat exchanger volume		5 L	
Max operating pressure		1,5 bar	
Pressure drop		**Portrait**	**Landscape**
(Pa | mmH20)	at 60 L/h	186 | 19	441 | 45
	at 100 L/h	461 | 47	961 | 98
Hydraulic inlet / outlet		DualQuickft® fitting	
		Non insulated	**Insulated**
Stagnation temperature		80°C	90°C
Optical efficiency a_0		63,3 %**	62,1 %**
Coefficient a_1		11,5 W/K/m²**	7,4 W/K/m²**
Coefficient a_2		0 W/(m².K²)**	0 W/(m².K²)**

Photovoltaic characteristics	
Nominal power	375 W
Output power tolerance	0 / +5W
Module efficiency	20 %
Rated voltage (V_{mpp})	40,40 V
Rated current (I_{mpp})	9,28 A
Open circuit voltage (V_{oc})	48,90 V
Short-circuit current (I_{sc})	9,89 A
Voltage temperature coefficient (μV_{oc})	-0,27 %/°K
Current temperature coefficient (μI_{sc})	0,04 %/°K
Power temperature coefficient (μP_{mpp})	-0,34 %/°K
Maximum system voltage	1500 VDC
Maximum reverse current	20 A
NMOT	42,3 +/- 2°C
Application class	Class II

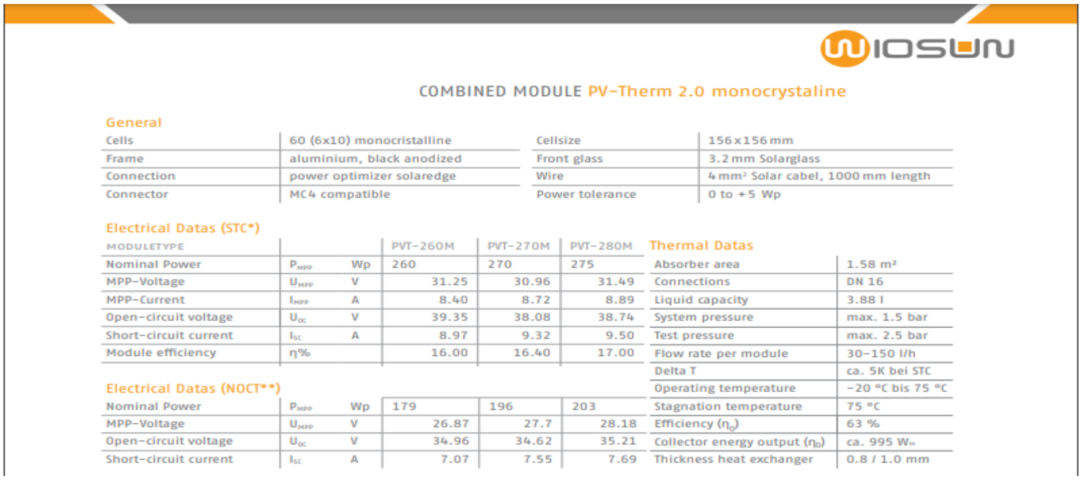
Figure 11 Thermal and photovoltaic characteristics of a hybrid PVT collector. [96]

2. Abora-Spain

Abora is a Spanish company located in Zaragoza, they specialize in PVT solar solutions. According to Abora, a hybrid solar panel with an aHTech innovation which is an innovative technology that consists of a series of insulating layers whose design and arrangement manage to minimize the panel's thermal losses while maximizing electrical production, can produce the same amount of energy as five photovoltaic solar panels, and because of this high efficiency, a hybrid installation pays for itself in a short time, being the most cost-effective solar technology available in the market. Abora has its simulation software that can help calculating the energy needs, as well as the size of the solar hybrid field that could cover those demands. [95]

3. WIOSUN-Germany

WIUSUN is a Jordanian-German company, they manufacture photovoltaic and PVT solar modules. Its hybrid collectors ‘’PV-Therm 2.0 monocrystalline’’ have a nominal power range of 260-270 Wp electrical, and with a thermal energy output that can reach 995 Wth. The specification sheet of a WIOSUN made collector is shown in figure (12). [97]



COMBINED MODULE PV-Therm 2.0 monocrystaline

General

Cells	60 (6x10) monocristalline	Cellsize	156x156 mm
Frame	aluminium, black anodized	Front glass	3.2 mm Solarglass
Connection	power optimizer solaredge	Wire	4 mm² Solar cabel, 1000 mm length
Connector	MC4 compatible	Power tolerance	0 to +5 Wp

Electrical Datas (STC*)

MODULETYPE			PVT-260M	PVT-270M	PVT-280M
Nominal Power	P_{MPP}	Wp	260	270	275
MPP-Voltage	U_{MPP}	V	31.25	30.96	31.49
MPP-Current	I_{MPP}	A	8.40	8.72	8.89
Open-circuit voltage	U_{OC}	V	39.35	38.08	38.74
Short-circuit current	I_{SC}	A	8.97	9.32	9.50
Module efficiency	η%		16.00	16.40	17.00

Electrical Datas (NOCT)**

Nominal Power	P_{MPP}	Wp	179	196	203
MPP-Voltage	U_{MPP}	V	26.87	27.7	28.18
Open-circuit voltage	U_{OC}	V	34.96	34.62	35.21
Short-circuit current	I_{SC}	A	7.07	7.55	7.69

Thermal Datas

Absorber area	1.58 m²
Connections	DN 16
Liquid capacity	3.88 l
System pressure	max. 1.5 bar
Test pressure	max. 2.5 bar
Flow rate per module	30-150 l/h
Delta T	ca. 5K bei STC
Operating temperature	-20 °C bis 75 °C
Stagnation temperature	75 °C
Efficiency (η_0)	63 %
Collector energy output (η_0)	ca. 995 W_{th}
Thickness heat exchanger	0.8 / 1.0 mm

Figure 12 Specification’s sheet for a monocrystalline PVT collector. [97]

4. NewForm Energy-UK

Is a company that specializes in solar energy solutions and especially PVT technologies, based in Ireland. As the company claims, hundreds of installations, ranging from tiny systems to major multi-source energy installations have been completed in the United Kingdom. Most of the systems are grid-connected in the range of (2- 10 kWp) and are installed on residential buildings, according to the available case studies [98]. NewForm Energy manufacture two types of PVT collectors:

- *Volther PowerTherm:* has been designed to maximize the panel's thermal return. This panel's electrical and thermal peak outputs are 180/680 watts, respectively.

- *Volther PowerVolt*: This collector is designed to maximize the electrical return. Peak electrical/thermal outputs are 200/460 watts respectively.

3 Materials and methods

3.1 Case Study

A sports center with a swimming pool located in Nablus-Palestine is selected as a reference case. The floor area of the sports center is 1000 m^2 corresponding to 25 m (L) by 40 m (W). An indoor swimming pool, one general-games sports hall, many general minigames rooms, one gym, and relevant service spaces such as changing rooms, canteen, lobby, and office are included in the supplies. The swimming pool hall is placed near the gym's structure with a total floor space of 573 m^2. The solar field will be erected on the roof of the hall. The heat pump and all mechanical and electrical equipment will be built in a dedicated chamber on the ground level. The geographical location and the climate data are represented in the following sections.

3.1.1 Localization

The location of the sports center is in Nablus-Palestine, the position as shown in the geographical map is shown in figure (13). The exact coordinates of the location are shown in Table (1).

Location characteristics of the PVT-SAHP system	
City	Nablus
Country	Palestine
Latitude	32.22°
Longitude	35.25°

Table 1 Location characteristics.

Figure 13 The geographical position of the center as appears in the map.

A SketchUp 3D design with the dimensions of the hall and the swimming pool is shown in figure (14).

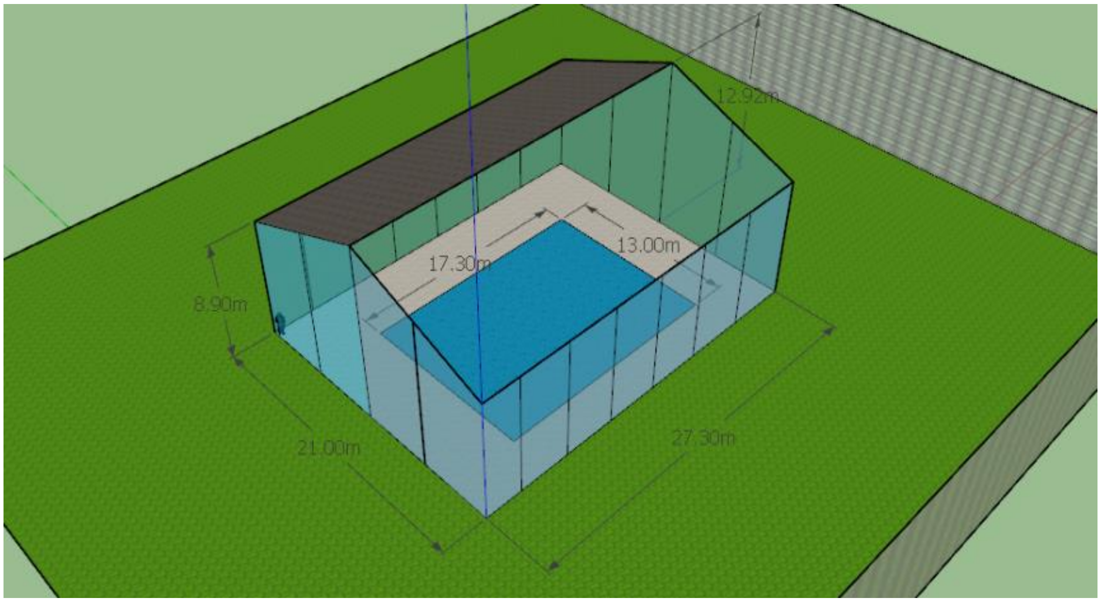


Figure 14 3D design with the dimensions of the hall and the swimming pool.

Figure (15) shows the perspective view (real) of the swimming pool hall structure and the rooftop of the hall where the PVT solar field will be installed. The rooftop total area is of about 290 m^2.

Figure 15a: Perspective view of the swimming pool hall structure (real)

3.1.2 Meteorological data

Meteorological data such as solar radiation, ambient temperature, relative humidity, wind speed, air pressure, and sunshine duration play a very important role in solar systems and are considered as the major parameters to look for to design a sufficiently effective system. There are a lot of databases and software that can provide us with these parameters, for this study, data was obtained from Meteonorm and PVGIS.

In this location, ambient temperature obtained from the Meteonorm software, and the average cold-water temperatures that are supplied monthly from Nablus's municipality water-sector are those shown in table (2).

	Ta (c)	**T_{cold}- ºC**
January	9.1	8
February	10.3	9
March	13.7	11
April	17.6	13
May	21.4	14
June	24.5	15
July	26.3	16
August	26.1	15
September	24.3	14
October	21.3	13
November	15.3	11
December	10.7	8

Table 2 Ambient air temperature and Average cold-water temperatures supplied from Nablus's municipality water-sector

Figure (16) shows the average annual ambient temperature.

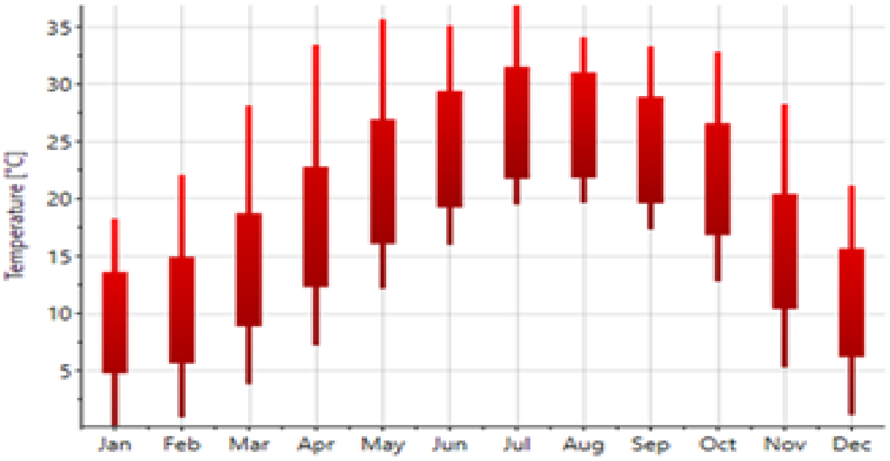


Figure 16 Average ambient temperature

Daily and monthly global radiation in KWh/ m^2 and MJ/ m^2 over inclined surfaces with an optimum tilt angle of β-42.25° (latitude plus 10°) for the design location, obtained from PVGIS meteorological database are shown in table (3). Figure (17) shows the global and diffuse radiation on the tilted surface.

	Global radiation- Monthly		Global radiation- Daily	
	KWh/m^2	MJ/ m^2	KWh / m^2.day	MJ/ m^2.day
January	126.70	443.46	4.09	14.31
February	129.48	453.18	4.62	16.19
March	176.83	618.89	5.70	19.96
April	198.39	694.35	6.61	23.15
May	216.45	757.59	6.98	24.44
June	224.91	787.17	7.50	26.24
July	234.91	822.20	7.58	26.52
August	230.27	805.95	7.43	26.00
September	206.91	724.19	6.90	24.14
October	183.25	641.39	5.91	20.69
November	145.75	510.12	4.86	17.00
December	124.98	437.43	4.03	14.11

Table 3 Daily and monthly global radiation in KWh/m2 and MJ/m2 β (42.25°)

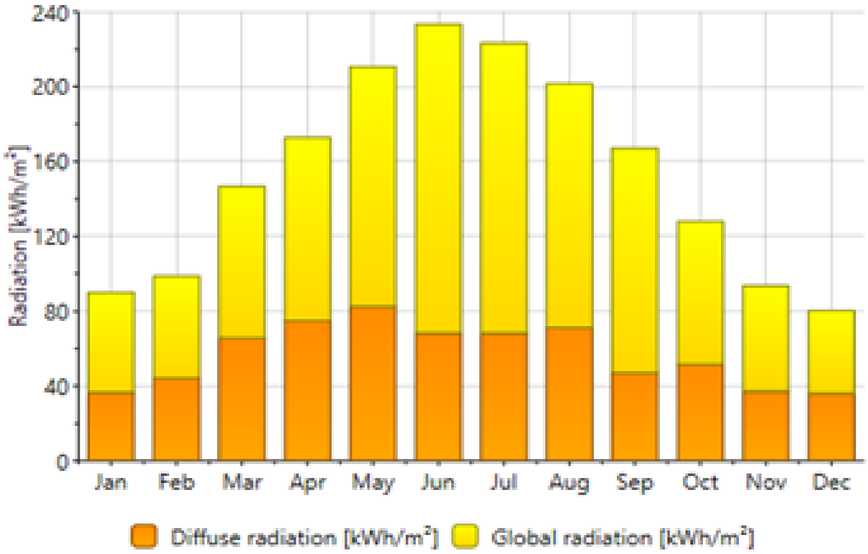


Figure 17 Average diffuse and global radiation

3.1.2.1 Energy demands

3.1.2.2 Electrical demand

As the sports center is a real case study, and it is operating for a year until now, a real electrical consumption profile was acquired from the utility company for the entire year. All electrical energy needed for the different electrical applications, as space heating and cooling, swimming pool, and domestic hot water heating, are all included within this energy demand, because all of the heating applications are running on electrical power.

Energy consumptions in KWh for the year 2020 are shown in table (4) and figure (18).

Total Electricity demand	
	KWh/month
January	7,574.81
February	7,824.87
March	7,735.91
April	6,573.34
May	7,216.25
June	7,116.64
July	7,682.02
August	7,243.98
September	7,119.94
October	6,217.21
November	6,801.92
December	8,033.81
Total	87,140.70

Table 4 Electrical energy consumption of the center (year 2020).

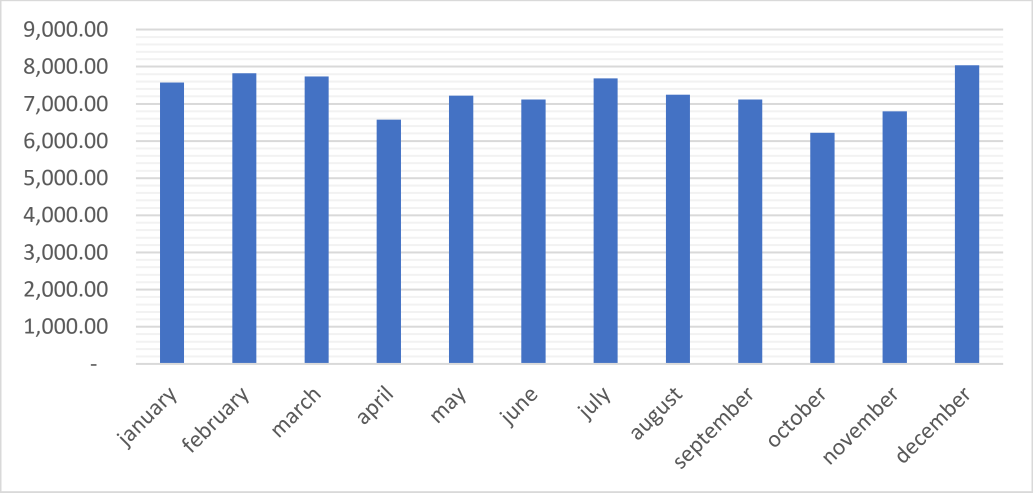


Figure 18 Electrical energy consumption of the center (year 2020).

3.1.2.3 Swimming pool thermal demand

There are a lot of different approaches to calculate the thermal energy needed for heating a swimming pool, and they vary on the level of complexity due to their accuracy and precision. So, depending on the available data, the model used in this project is the one recommended by Spanish institution (Instituto para la Diversificación y Ahorro de la Energía) IDAE [99].

The energy demand necessary to maintain the temperature of the water in the swimming pool can be considered as constituted by the thermal losses with the environment $\mathrm{Q_{loss}}$ and by the energy demand for heating the makeup water $\mathrm{Q_{m.u}}$. Thermal losses in covered swimming pools are produced by the evaporation of the water, by radiation towards the walls of the hall, and by conduction through the walls and bottom of the basin:

- Evaporation losses represent between 70% - 80% of total losses.
- Radiation losses represent between 15% - 20% of total losses.
- Conduction losses between swimming pool and the ground are to be negligible.

To calculate the power of energy losses $\dot{\mathrm{q}}_{\mathrm{loss}}$ in covered swimming pools, the following empirical formula can be used:

$$\dot{\mathrm{q}}_{\mathrm{loss}} = \left(130 - 3.\mathrm{T_{hw}} + 0.2.\mathrm{T_{hw}^2}\right).(\mathrm{A_p}/1000)$$

Where $\mathrm{T_w}$ is the desired temperature of the pool water °C and $\mathrm{A_p}$ is the surface of the pool (m^2).

The calculation of the daily thermal losses of the $\mathrm{Q_{loss}}$ (kWh) for the conditions established, $\mathrm{T_w}$ = 24-29 ºC (depending on the season) According to FINA (International Swimming Federation) facility rules, the water temperature should be maintained between 25 and 28 ◦C for standard and Olympic competition pools. Considering that during non-operation hours (to be considered 12 hours) a thermal blanket is used, so thermal losses are reduced to 20% of the total. For this, thermal losses can be determined, according to the above, by the formula:

$$\mathrm{Q_{loss}} = 2.4.\mathrm{A_p}$$

The demand for thermal energy corresponding to make-up water $\mathrm{Q_{m.u}}$ produced by the renewal needs, is the amount of energy necessary to increase the temperature from the cold-water inlet temperature ($\mathrm{T_{cw}}$) to the wanted temperature (27-29ºC) of the renewed water mass, we can take the rate of water loss to be around 2% – 5%, with higher make-up required for a higher rate of water loss depending on the number of swimmers using the pool per day. For colder months (November- March) is assumed to have fewer users than warmer months (April -October), and this was considered for proposing makeup water factor. The characteristics of water are represented by its density ρ and by the specific heat C_{PW} at constant pressure and is calculated by the expression:

$$Q_{m.u} = (V_{sp}.(2\% - 5\%)).\rho.C_{PW}\ (27/29°\,C - T_{cw})$$

The total daily demand for thermal energy of the pool would be the sum of both:

$$Q_{s.p} = \ 2.4.A_p + (Vsp.(2\% - 5\%)).\rho.C_{PW}\ (27/29°\,C - T_{cw})$$

Using the previous method to determine swimming pool thermal needs, we were able to obtain swimming pool energy demand, table (5) and figure (19) show the annual thermal energy demand for pool heating.

Q $_{\text{Pool}}$ KWh/month	
January	13,825.13
February	11,914.33
March	11,872.33
April	9,604.57
May	9,268.60
June	7,714.77
July	6,664.88
August	7,315.81
September	8,344.70
October	9,919.54
November	11,494.37
December	13,825.13
Total	121,764.15

Table 5 Heating demands of the swimming pool.

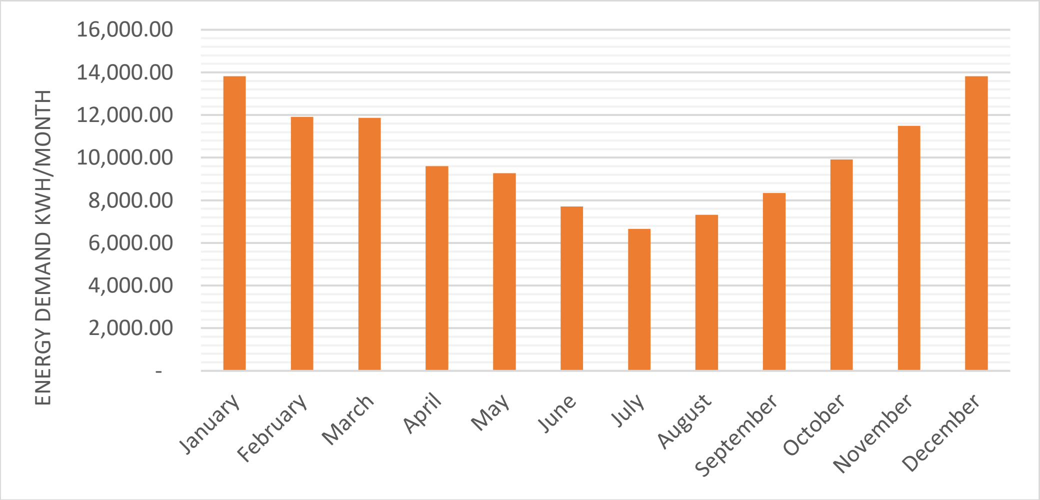


Figure 19 Heating demands of the swimming pool.

3.1.2.4 Domestic hot water demand

According to the practical design guides of sports center hot water heating, the water load can be determined by: [88]

- the daily average hot water consumption per person
- the hourly water consumption per shower faucet and lavabo.

In our study, the hot water load is calculated by using the daily water load $\mathrm{Q_{DHW}}$, which depends on the number of showers faucets, and lavabos in the provision, hence

$$\dot{\mathrm{m}}_{\mathrm{dis}} = \sum \mathrm{q_h n_0 b}$$

Where $\mathrm{q_h}$ is the hourly water consumption of shower faucets and lavabos, in kg/h; $\mathrm{n_0}$, is the number of the shower faucets and lavabos, b is the simultaneous using factor of the shower faucets and lavabos within one hour, which is usually taken as 100% for the sports center cases. [88]

The hot water demand is then calculated by:

$$\dot{\mathrm{m}}_{\mathrm{h}} = \mathrm{k_r} \dot{\mathrm{m}}_{\mathrm{dis}}$$

Where $\mathrm{k_r}$, is the hot water mixing factor. This is determined according to the designed hot water temperature at the outlet of the heat pump system and the delivery temperature, as follows:

$$\mathrm{k_r} = \frac{\mathrm{T_{dis} - T_{cw}}}{\mathrm{T_{DHW} - T_{cw}}}$$

where $\mathrm{T_{dis}}$ is the delivery water temperature after mixing, in °C; $\mathrm{T_{DHW}}$ is the hot water temperature at the outlet of the tank, in °C; $\mathrm{T_{cw}}$ is the feedwater temperature, in °C.

The required heating load is then calculated based on:

$$\mathrm{Q_{DHW}} = \dot{\mathrm{m}}_{\mathrm{h}}\ \mathrm{C_{PW}}\ (\mathrm{T_{DHW} - T_{cw}})$$

Using the previous method to determine domestic hot water thermal needs, we can obtain monthly and annual thermal energy demand. Table (6) and figure (20) show annual thermal energy demand for domestic hot water.

Total monthly thermal demands as mentioned earlier, are covered by a heat pump, the electrical energy that a heat pump would require to meet that quantity of thermal demands has to be measured empirically, but it can also be calculated approximately by dividing the thermal energy required monthly by the heat pump's COP, so, a value of 4.5 was assumed for this purpose.

	KWh/month
January	10,708.00
February	10,418.60
March	9,839.78
April	9,260.97
May	6,077.51
June	5,788.11
July	5,498.70
August	5,788.11
September	6,077.51
October	6,366.92
November	9,839.78
December	10,708.00
Total	96,372.01

Table 6 Thermal energy needs for the DHW.

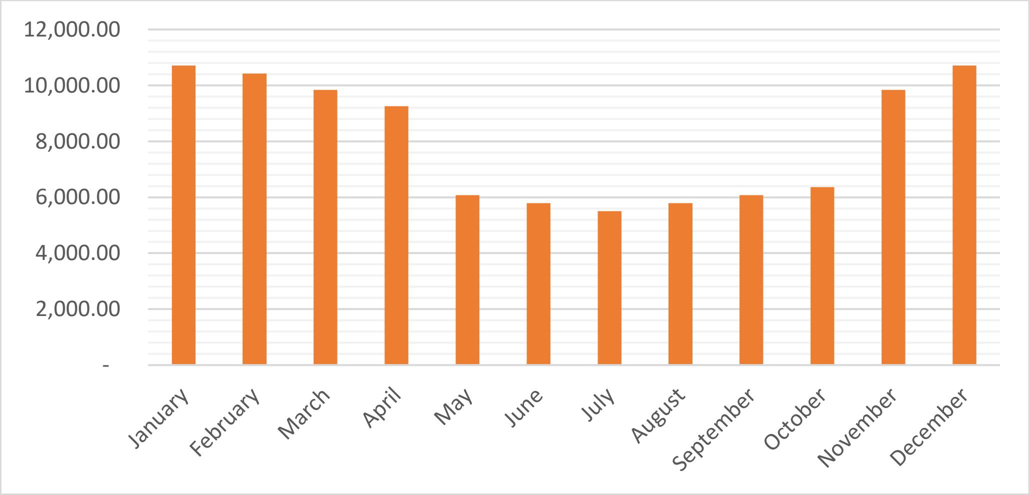


Figure 20 Thermal energy needs for the DHW.

Total thermal energy and its equivalent as electrical energy is listed in table (7) below.

January	**24,533.13**	**5,451.81**
February	22,332.92	4,962.87
March	21,712.12	4,824.91
April	18,865.54	4,192.34
May	15,346.12	3,410.25
June	13,502.88	3,000.64
July	12,163.58	2,703.02
August	13,103.92	2,911.98
September	14,422.22	3,204.94
October	16,286.46	3,619.21
November	21,334.16	4,740.92
December	24,533.13	5,451.81
Total	**218,136.16**	**48,474.70**

Table 7 Total thermal demands and the equivalent as in electrical energy.

Figure (21) shows the monthly thermal and electrical energy demands, thermal demands have been converted to their equivalent value of electrical energy. Center electrical loads are that any electricity needed apart from that needed for heating purposes (swimming pool& DHW).

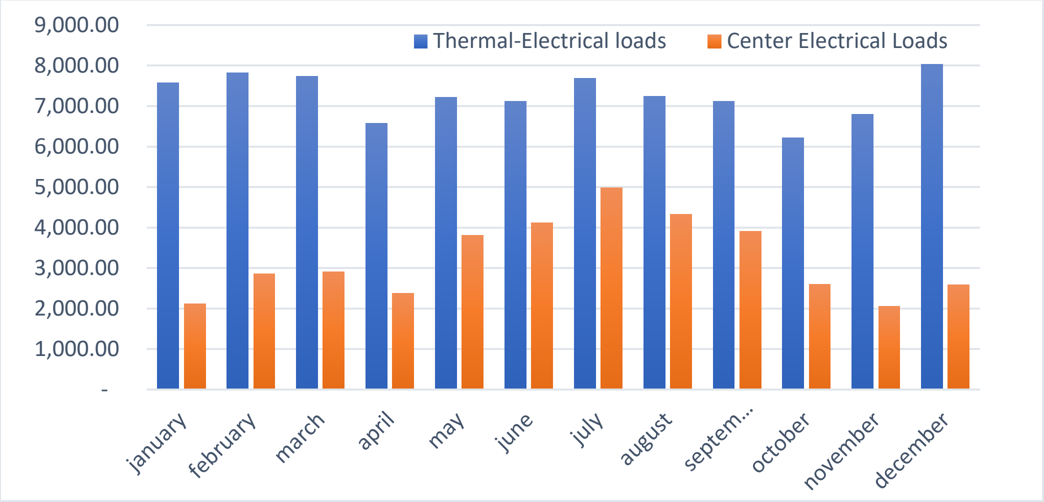


Figure 21 Thermal and electrical annual energy demands for the center.

3.2 PVT/SAHP system

In our case, we have two different configurations: a PV solar system that will be designed to meet the electrical energy demands of all different applications, these demands are represented by thermal demands, which specified by, heating an indoor swimming pool and domestic hot water, and electrical demands that are any miscellaneous appliances that need electrical power to function. In this PV system, thermal demands are always to be obtained through a heating pump which is considered as an electrical dependent machine. The other configuration is the innovative PVT-Heat Pump system. In this configuration, PVT solar modules are adding two values, one is covering part of the thermal energy demand, lowering by that the electrical energy that to be consumed by the heat pump for the same reason, and two, supplying electrical energy to cover heat pump’s electrical needs, making thermal energy needed fully covered by solar renewable source all along the year. Any other electrical requirements could also be fed by the electrical output of the PVT solar modules.

PVT's ability to produce electrical and thermal energies simultaneously, serving two different necessities at the same time in just one single device, and is theoretically equivalent to two separated systems operating to comply with the same results but with double the area of the plant.

See figure (22) and (23) that compare the configurations of the two different systems, it can be noticed that in order to fulfill the thermal and the electrical needs simultaneously, SC and PV collectors have to be installed to work side by side in the PV plus SC system, but for the hybrid PVT system, it will only be needed to have one single collector to function as it was two separated systems.

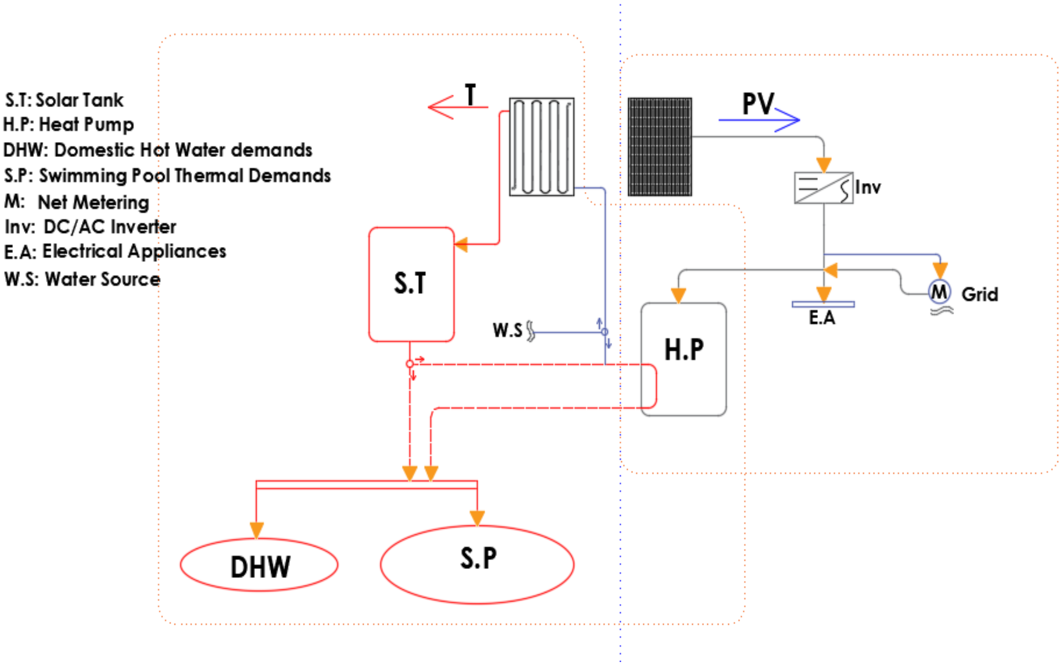


Figure 22 Photovoltaic and solar thermal collectors design configuration.

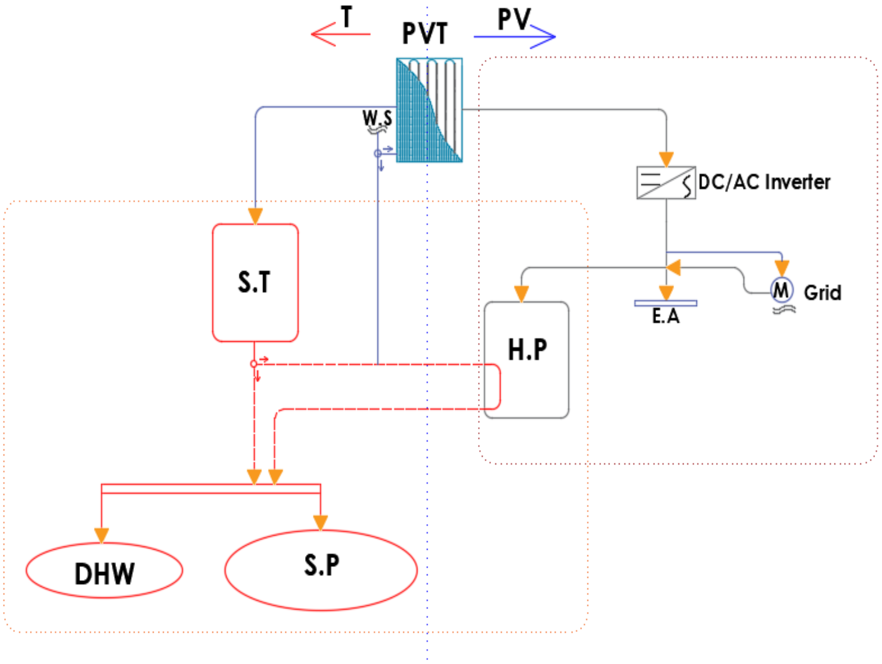


Figure 23 Hubrid PVT collector design configuration.

3.2.1 System layout

The proposed solar cogeneration system will heat the indoor swimming pool to provide appropriate thermal comfort and to meet a portion of the facility's domestic hot water demand. In addition, the system provides simultaneous electrical energy generation. The following are the major components that will form the system:

- PVT solar field
- A solar tank S.T that accumulates hot water produced from the PVT solar panels
- Hot water accumulator with an internal heat exchanger for the DHW.
- A heat pump that is integrated into the system and positioned after the solar system to put to work when there is no sufficient solar energy
- A heat exchanger that provides hot water to the swimming pool
- Three circulation pumps, P1 for the solar circle, P2 for the heated water circle, P3 for the swimming pool water
- A rectangular shape swimming pool with a fixed volume and temperature.
- A heat sink that prevents the fluid in the solar circle from overheating and allows maintenance to be done without causing the panels to overheat.
- An inverter that converts the solar energy generated by the panels from DC to AC so that it can be used by the facility and the utility grid.

In the system, four liquid circuits may be recognized, including:

- HTF-SOLAR, which is a heat transfer fluid that is a combination of water-glycol and used to transmit the heat running from the PVT panels to the solar tank S.T.
- HF-SOLAR/HP, hot fluid of water and glycol, flows from S.T and/or from the heat pump to the heating elements; swimming pool heat exchanger, and DHW accumulator.
- P.W, pool water that is recirculated between the swimming pool and its heat exchanger.
- DHW, domestic hot water and refers to the water that supplies a pool facility's household equipment.

System’s schematic design is depicted in figure (24) below, and annex (1).

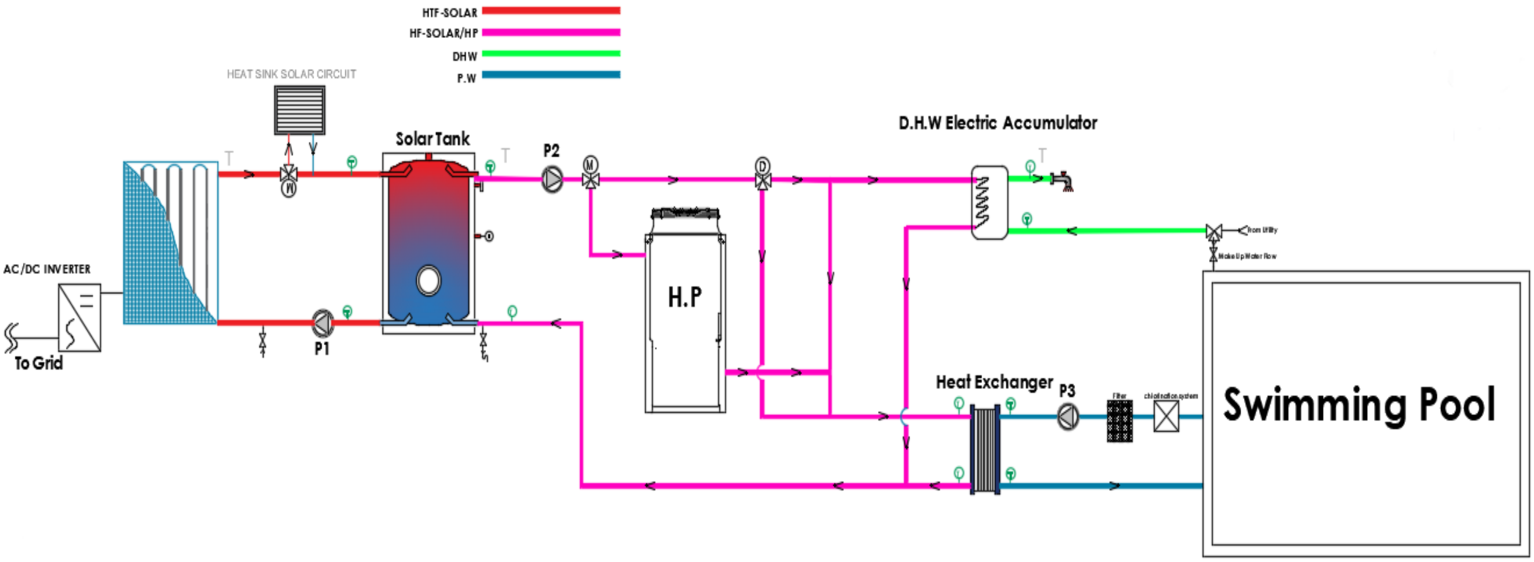


Figure 24 Schematic design of the propsed PVT/Heat pump

The system's operational concept may be summarized in the following way. The photovoltaic panel and absorber in the PVT solar collectors convert solar irradiation into electric and thermal energy, respectively. The sports center uses all of the generated electric energy, while the thermal energy warms the PVT outlet water temperature. HTF-SOLAR by the pump P1, which is controlled by a solar radiation sensor, is circulated from the PVT collectors to S.T where it will be accumulated. In the tank, a thermally stratified fluid distribution occurs, ensuring that the solar circuit operates uniformly.

The fluid HF-SOLAR/HP is pushed from the load side of the S.T to the hot side of the swimming pool heat exchanger and the internal heat exchanger of the DHW accumulator, or it is delivered to the heat pump as needed. This flow is controlled by a motorized valve, a diverter, and a mixer, designated by the letters V, D, and M, respectively.

P2 is controlled by a sensor that monitors the temperature of the HTF-SOLAR fluid exiting S.T. If the temperature is lower than desired (45.0 °C for swimming pool heating and 55.0 °C for DHW production) and a thermal demand happens, the HF-SOLAR/HP is pumped out of the S.T through the motorized valve to the heat pump, where it is heated to the desired temperatures and thus meets the thermal demands of the swimming pool and DHW. If the temperature of the fluid departing the S.T exceeds the desired temperature, the HF-SOLAR/HP is pushed out of the S.T to directly fulfill the swimming pool and DHW thermal demands.

In other words, there is a minimum temperature at which P2 may be activated. The control system transfers the flow of hot fluid HF-SOLAR/HP from S.T to the HP through the motorized valve V, then the diverters D1/D2 deliver the hot fluid HF-SOLAR/HP to the heat exchanger of the swimming pool if the pool temperature dips below 27.0 °C, and until the pool temperature reaches 28.0 °C. When the pool is heated, the diverters D1/D2 direct the hot fluid HF-SOLAR/HP to the DHW accumulator's internal exchanger to meet the demand. Water recirculating back from both the swimming pool and the DHW accumulator is mixed with the mixer M and directed to the bottom of the S.T to continue its circle. Due to heat losses in the distribution piping system, the temperature set point will be slightly higher than the ultimate pool water supply temperature.

The energy generated by the PVT system is provided to the user in the form of pool heating, residential hot water, and power. The heat generated by the solar field is primarily utilized to heat the pool, with DHW generation coming in second.

3.2.2 Technical configuration.

The technological configuration in this project is intended to cover thermal energy demand for domestic hot water (DHW) and swimming pool heating. The heat required for the swimming pool can be deliverable by a traditional heat pump and an electric heater for the DHW is recommendable as the desired temperature of it is a bit higher than the output set point of the heat pump. The addition of solar hybrid panels (in tandem with the existing system) should results in considerable energy and cost savings, making its adoption within the planned energy hub appealing.

The low-temperature heat flow supplied into the heat pump originates from S.T storage and makes up the heat pump's cold side. WHP stands for the electricity that feeds the HP and is determined by the heat fluxes and operational circumstances (the working temperatures of the evaporator and condenser). The manufacturer provides the heat pump's functioning characteristics, which could be used in the simulation.

3.3 Methods for system design

3.3.1 PV system design: average monthly production method

The most important stage of PV deployment is designing and sizing PV systems, which requires a methodical methodology. The following is a five-step method for developing a solar PV system:

- Site assessment and planning.
- Determine the amount of energy required.
- Determine the availability of solar resources.

- Sizing of the PV system's major components.
- Selection of the PV system's major components

The system is grid-connected, whose power is directly fed into the utility. The method to be used will be the average monthly production dimensioning method [100]. The following parameters must be defined to professionally design the system.

$\mathrm{Panel\ generation\ factor\ (P.g)}$; which determines the peak watt rating of the PV plant. It also gives information on the number of PV panels required and the actual peak sunshine available at the installation site.

$$\mathrm{P.g} = \frac{\mathrm{H_\beta}}{\mathrm{G_\beta^*}}$$

Where $\mathrm{H_\beta}$is the average solar irradiation of location kWh/ m^2, $\mathrm{G_\beta^*}$ is the Standard Test Conditions irradiance, 1000 W/ m^2. This value is equivalent to the well-known concept of Peak Solar Hours.

The energy required from the PV modules $\mathrm{E_t}$ may be calculated using the data from the load assessment phase. Once the $\mathrm{P.g}$ has been determined, the overall peak rating of the PV is estimated using the following relationship based on the energy need value.

$$\mathrm{Total\ Watts\ Rating} = \frac{\mathrm{E_t}}{\mathrm{P.g}}$$

Based on the obtained total watt rating, the number of PV modules required to meet the load is estimated as follows:

$$\mathrm{NO.Modules} = \frac{\mathrm{Total\ Watts\ Rating}}{\mathrm{Panel\ Peak\ Capacity}}$$

After estimating the quantity of PV modules, inverter sizing is completed. In most situations, the inverter size is estimated to be to 25–30 percent lower than the PV array's peak rating, depending on location solar irradiation.

3.3.2 STC system design: f-Chart method

The F-Chart method allows determining the solar contribution of an installation to determining energy demand, $\mathrm{D_{Total}}$ is calculated based on the functional parameters that are related and the procedure that is described to determine the monthly values of the dimensionless parameters $\mathrm{X_i}$ and $\mathrm{Y_i}$, that allows calculating the monthly value of the solar fraction $\mathrm{f_i}$ using the indicated correlation.

Functional parameters

The functional parameters of the installation necessary to perform the energy performance calculations with the f-Chart calculation method are;

- The total area of the collector's system (A_c in m^2) which is defined by;
  - the number of solar collectors.
  - aperture area of each solar collector (m^2).
- collector performance, which can be defined by;
  - The optical efficiency factor of the collector $F_R(\tau\alpha) = \eta_o$
  - Global coefficient of losses U_L in W/(m^2.K). When the collector loss factors are available, linear a_1 and quadratic a_2, it is determined: $U_L = a_1 + 40a_2$.
- Specific accumulation volume V/A in Liters/m^2
- Flows and exchange:
  - Mass flow in the primary circuit m_1 in kg/s.m^2
  - Mass flow in the secondary circuit m_2 in kg/s.m^2
  - Specific heat in the primary circuit Cp_1 in J/kg.K.
  - Specific heat in the secondary circuit Cp_2 in J /kg.K.
  - Effectiveness of the exchanger $\mathcal{E}$.

Process

For each month of the year (value of i from 1 to 12), the dimensionless parameters X_i and Y_i are determined, which are representative, respectively, of the losses and gains of the installation:

$$X_i = [A_c\,.\,U_L\,.\,U_{HEX}\,.\,(100 - T_a).\,\Delta t_i.\,C_{V.}C_{Ti.}]/Q_{Total}$$

$$Y_i = [A_c.\,F_R(\tau\alpha).\,U_{HEX}\,.\,K(\theta).\,I_{inc}.\,N_i]/Q_{Total}$$

The following correction factors have been defined:

- Heat exchanger correction factor U_{HEX}, ($m_1Cp_1 = m_2Cp_2 = mCp$ is assumed):

$$U_{HEX} = 1/[1 + (U_L/mCp).(1/\mathcal{E} - 1)]$$

- The volume of the solar tank S.T correction factor:

$$C_V = ((V/A)/75) - 0.25$$

- Correction for hot water temperature $C_{Ti.}$, where T_p (ºC) is the preparation temperature, T_{fi} (ºC) is the cold-water temperature and T_{ai} (ºC) is the monthly mean ambient temperature:

$$C_{Ti} = (11.6 + 1.18.\,T_p + 3.86.\,T_{fi} - 2.32.\,T_{ai})/(100 - T_{ai})$$

- Incidence angle modifier $K(\theta)$ for which the value $K(50)$ of the sensor test will be adopted
- The rest of the parameters involved are:

- Δt_i is the number of seconds in the month (s).
- Q_{Total} is the monthly energy demand (J).
- I_{inc} is the monthly average daily incident solar irradiation (J/m^2).
- N_i is the number of days in the month.

With the values of X_i and Y_i, the factor f_i is determined for each month of the year:

$$f_i = 1.02.Y_i - 0.0065X_i - 0.245.Y_i^2 + 0.0018.X_i^2 + 0.0215Y_i^3$$

We must take into account the limit values of X_i ($0 < X_i < 18$) and Y_i ($0 < Y_i < 3$) that establish the range of validity of the function f_i.

The factor f_i which results from the previous expression, is the value of the solar fraction per one of the months considered and will always be $f_i \leq 1$. The solar contribution, for each month, will be determined by the expression:

$$Y_{solar} = f_i.D_{Total}$$

Carrying out the same operation for all 12 months, the annual mean solar fraction will be obtained from the expression:

$$f = \sum(f_i.D_{monthly})/\sum D_{Total}$$

The needed collector area is determined by several criteria, including the sports center's daily heating demands for pool and hot water for showers and sinks, collector characteristics, and climatic circumstances. In the direct heating mode, the area of the solar collector directly affects the solar fraction. So, we must size the collector's area to reach a value of $f_i \leq 1$.

The solar tank S.T is used to heat and store the solar hot water and provide the re-heated pool water to the swimming pool. The volume of the tank has to be determined based on the volume/area ratio, which is the ratio between the volume of the solar tank and the total area of the collectors. V/A ratio must be in the range between (50-80).

3.3.3 Hybrid system design: energy balance method

The thermal and electrical energy balances have to be considered when it comes to design a co-generative hybrid system such as a PVT-SAHP system. The PVT panels produce both thermal and electrical energy, so, the whole integration between the PVT panels and the heat pump can reach an energy balance more effectively. As the system can support the heat pump electrically and thermally, at the same time when there is a shortage in the production of any of these two, the system becomes supported by the HP thermally. By this, it can be considered that the heat pump is the one major component that needs to be analyzed to fulfill the electrical and thermal energy balances.

So, a thermal energy balance can be analyzed as that the total energy $\mathrm{D_{Total}}$ demanded by the facility should be always fulfilled, this demand can be met through the net contribution of the solar thermal energy $\mathrm{Y_{solar}}$ and the heat pump $\mathrm{Y_{HP}}$. Energy balance can be carried out employing the following expression:

$$\mathrm{D_{Total}} = \mathrm{Y_{HP}} + \mathrm{Y_{PVT}}$$

From the previous expression, it can be deduced, firstly, that a certain consumption of thermal energy can be met with multiple combinations of net energy contributions from the solar installation and the installed heat pump.

For the electrical energy balance, is assumed that the heat pump is fed by the energy generated by the PVT panels (WPVT-HP), so, it's possible that the output WPVT will be more or lower than the HP electricity demand at any one time. The additional power goes to other electrical users in the building if WPVT exceeds WPVT-HP, and this quantity of energy is represented as WPVT-GRID. It's also possible that the situation may be reversed, in which case the variable WGRID will be defined. To summarize, there are two fundamental electrical energy balances [85]:

$$\mathrm{W_{PVT}} = \mathrm{W_{PVT-HP}} + \mathrm{W_{PVT-GRID}}$$

$$\mathrm{W_{HP}} = \mathrm{W_{PVT-HP}} + \mathrm{W_{GRID-HP}}$$

The first equation shows that the PVT panel’s power generation fulfills the HP electricity requirement and may ultimately meet additional demands. The second equation focuses on the HP electricity need, stating that it is met by photovoltaic generation in PVT devices and, if necessary, energy from the grid.

The system's background analysis is based on the primary components’ basic performance equations: the heat pump and the PVT modules. The HP is in heating mode, which requires electrical energy to drive the mechanical compressor and the preheat source from the PVT panels to produce hot water. The heat pump's coefficient of performance, is a measure of its efficiency.

$$\mathrm{COP} = \frac{\mathrm{Q_{HP}}}{\mathrm{W_{HP}}}$$

Where $\mathrm{Q_{HP}}$ (KWh) is the thermal energy that the heat pump can produce and $\mathrm{W_{HP}}$(KWh) is the electrical energy needed to produce that energy.

To select an adequate size of the heat pump that is to be able to operate properly when necessitated, the solar contribution has to be calculated as previously indicated with its representative factor, solar fraction. After calculating the total amount of thermal energy produced in KWh for the month that will be less supported by the solar energy, and then by that, finding the rate of energy $\mathrm{E.R}$ in kW needed for the heat pump by dividing the quantity of energy that the solar energy cannot support, which can be found by suppressing the total amount of energy produced by the PVT panels from the total energy demand for each month, and divide it by the number of hours for that month as follows:

$$\mathrm{E.R} = \frac{\mathrm{Y}_{\mathrm{non-solar}}}{\mathrm{N}_{\mathrm{D}}.24}$$

Where $\mathrm{Y}_{\mathrm{non-solar}}$ in KWh, is the quantity of energy remains not fulfilled after the maximum solar contribution has been applied, and N_{D} is the number of days of that month.

4 Results and discussion

4.1 Energy balance

After calculating the electrical and thermal demands for our case, and applying the above design methods for both thermal and electrical parts of the hybrid solar panels and photovoltaic panels [99], we can come up with initial sizing results as for the PVT and PV solar fields, the size of the storage tank and the rated power of the heat pump, that's based on the thermal and electrical features of the panels that are considered for this project particularly. A system that consists of a PVT solar field and that is coupled with a heat pump is designed, and its initial results are given. This system is then to be compared with a PV/Heat pump system economically and technically. This work is confined to a theoretical examination due to a lack of available actual data for a comparable system, so these results were obtained with some assumptions and hypotheses for the sake of simplicity.

Regarding temperature of the photovoltaic cells for both photovoltaic and photovoltaic/thermal modules, starting from a value of 25°C which is at the standard test conditions and knowing that this temperature depends on the ambient temperatures and the solar irradiance, corresponding loss factors have been applied accounting for the possibility of better photovoltaic performance in the case of heat removal. Hence PVT solar modules' loss coefficient is considered to be 0.25% per degree of difference with cell temperature, as it has a heat removal circuit within its structure, moreover, modules are connected to a heat pump, which makes the circulation of the heated fluid in the modules more rapid which dissipates its heat more effectively. For the PV solar modules, this coefficient was considered to be 0.4%, as no heat removal technology applies here. Distribution losses in the hydraulic system were considered to be 3%. Regarding collector's thermal efficiency close to optical efficiency can be considered in hybrid mode as feeding HP allows the solar thermal collector operation at lower temperature and, consequently, lower thermal looses

The value of the COP of the heat pump is seasonal dependent, as the temperature of the ambient air from which a heat pump will extract the heat to raise the temperature of the working fluid from the cold inlet to the desired outlet, will require more work to be done by the heat pump's compressor than the work required to obtain the same thermal output in a warmer climate, which by this, the ratio between the thermal energy to be acquired and the electrical energy supplied depends on the climatic conditions of where the heat pump installed. Anyway, for the case of PV-solar assisted heat pump, a COP's value of 4.5 was assumed. But for heat pump-PVT assisted, water enters the low-temperature inlet of the heat pump has a higher temperature than that in the case of the water entering directly from the cold-water source (the utility), and this means, less temperature difference and less work to be done by the heat pump to increment water's te6mperature to the desired point, which consequently gives a higher value for the heat pump's COP. For that, it was assumed that the heat pump in this case can reach a COP of 5 all along the year, that's to evaluate its performance, and to approximately estimate its electrical demands. It is important to mention, that these values were assumed based on other climatically and technically similar studies because for obtaining instantaneous and real values of COP, the system will need to be simulated and checked against environment-like circumstances by a sophisticated software like TRNSYS, which can give more accurate results based on real weather inputs. Specifications' sheet of the heat pump installed can be seen in Annex (4). [101].

The solar storage tank is sized based on the V/A ratio, which is the volume of the tank to the total area of the PVT modules and needs to be in the range of [50-80]. So, a storage tank with a volume of 6.5 m^3 is sized, which meets the acceptable range.

The PVT solar field is to be composed of 65 modules, each of them has a total area of 1.96 m^2 and a catchment area of 1.88m^2 so the total area of the catchment is around 122.2 m^2. The specifications sheet of the PVT selected for this specific case can be seen in Annex (2). [102]. The main thermal features of the PVT modules are $\eta_0 = 0.7, a_1 = 5.89\ \mathrm{W/m^2K}, a_2 = 0.00\ \mathrm{W/m^2K}$. The electrical peak power is 350 Wp, so the whole field reaches 22,75 kWp. The inclination of which the PVT modules are mounted is β-42.25°, facing the south and with an azimuth angle of 0°.

This number of panels can produce an annual thermal energy QPVT of 129,205.17 KWh/year, and an annual electrical energy WPVT of 34,407.25 KWh/year. The thermal output of the PVT modules, on one hand, can cover up to 59% of the total thermal energy demanded by the facility, lowering down electrical energy needs prominently. As in all cases, hot water required for swimming pool and domestic hot water will still be gained through the heat pump, which needs annual electrical energy requirements of 17,786 KWh/year if to be assisted by the PVT solar field, but in the case of not being assisted by the PVT solar panels, its annual electrical energy needs will be much higher of up to 48,474.7 KWh/year. Having the PVT solar field can lower this insanely huge difference between electrical energy needed for both cases, so, 64% of electricity to be needed in the traditional approach is already covered only by the thermal energy contributed to the system by the PVT solar panels. On the other hand, PVT's electrical energy production (WPVT=34,407 KWh/year) meets 61% of the yearly electricity demanded by the facility, part of it will directly cover the heat pump demands WPVT-HP, and what remain will be feeding any other electrical demands within the sports center or will be fed to the grid. It could happen that the heat pump's electrical demands not fully obtainable from the PVT electrical production WPVT-HP, in this case, its demands are met by the grid WGRID-HP.

In the periods that happen to have less solar power and colder weather conditions, coincide with more thermal needs, taking the month of January as an example, thermal balance is described as; 31% of its total thermal energy needs (QJanuary = 24,533.13 KWh/month) can be acquired by the PVT thermal output (QPVT =7,483.3 KWh/month), the other 69% comes from the heat pump, the electricity demanded by the heat pump to fully cover month’s thermal necessities is (WHP =3,409 KWh/month). PVT electrical output in January (WPVT-January) covers 50% of that demand for the heat pump WPVT-HP, and the other 50%, comes from the grid WGRID-HP. Not surprisingly, this energy balance is distinct in the months that happen to have warmer ambient air temperatures and more incident solar radiation as what is the situation in June for example, the abundant solar radiation hitting the surface of the solar hybrid module, makes the solar fraction reaches up to 95%, which means, almost all of its thermal needs are directly fed by the thermal output from the PVT solar field QPVT. Lowering significantly heat pump’s working hours and by that less electrical energy consumption. Electrical needs in this month for cooling purposes and daily routines are 4,116 KWh/month, WPVT can cover 94% of its energy demands.

Table (7) and figure (25) below, show the portion of the thermal demands that the PVT thermal output can cover directly, and the other portion that the HP covers.

Month	**Q_{Total} KWh/m**	**PVT**		H.P	
		Q_{PVT} KWh/m		Q_{HP} KWh/m	
January	24,533.13	7,483.30	31%	17,049.83	69%
February	22,332.92	8,514.71	38%	13,818.22	62%
March	21,712.12	11,530.38	53%	10,181.73	47%
April	18,865.54	13,351.04	71%	5,514.50	29%
May	15,346.12	12,550.76	82%	2,795.36	18%
June	13,502.88	12,793.50	95%	709.38	5%
July	12,163.58	12,182.57	100%	-	0%
August	13,103.92	12,917.99	99%	185.93	1%
September	14,422.22	12,464.67	86%	1,957.55	14%
October	16,286.46	9,787.29	60%	6,499.17	40%
November	21,334.16	8,301.61	39%	13,032.54	61%
December	24,533.13	7,327.36	30%	17,205.76	70%
TOTAL	**218,136.0**	129,205.17	57%	88,930.98	41%

Table 7 Monthly coverage percentages of the PVT solar modules and the heat pump for the thermal loads.

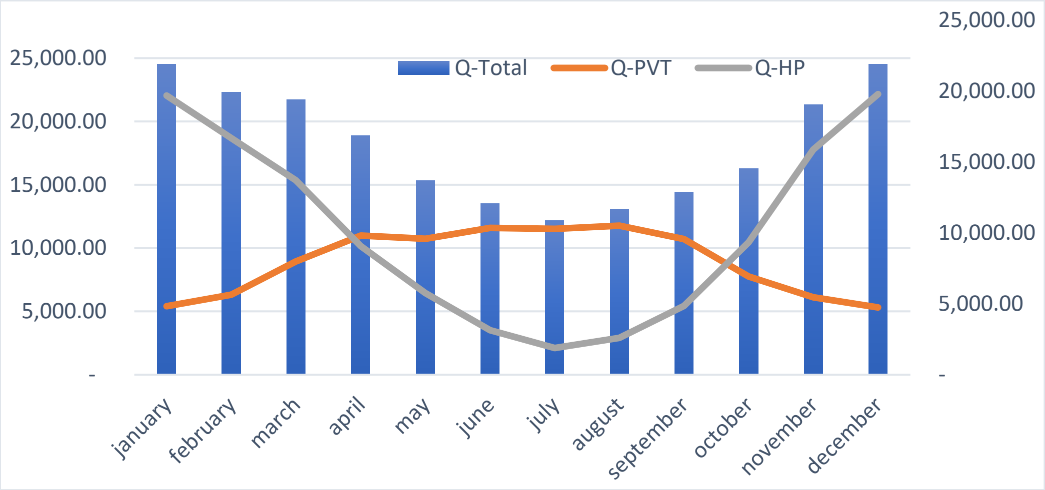


Figure 25 Monthly PVT coverage vs heat pump coverage for the total thermal loads

So, for the rest of the thermal demands that the PVT thermal output unable to cover directly, the integrated heat pump will handle them. That's to say, at any given moment, if the solar radiation is not enough and PVT isn't able to produce sufficient thermal energy, the heat pump will put to work. Anyway, once the heat pump starts to operate, it has electrical requirements which have to be fulfilled. However, the photovoltaic part of the PVT modules will still be producing electrical energy, this electrical energy here is complementary to the system, making the integrated system of heat pump and PVT modules reaching to a point that all of the thermal energy needed is covered completely from the solar source.

Table (8) below shows the percentages of the thermal and the electrical energies (needed for heating purposes) that the PVT solar modules are capable to cover.

Month	Q_{PVT}/Q_{Total}	$W_{PVT}-W_{HP}$
January	31%	50%
February	38%	67%
March	53%	100%
April	71%	100%
May	82%	100%
June	95%	100%
July	100%	-
August	99%	100%
September	86%	100%
October	60%	100%
November	39%	75%
December	30%	48%
TOTAL	57%	85%

Table 8 The percentages of the thermal and the electrical energies PVT modules cover.

That was for the thermal part of the facilities' demands, as can be seen, these percentages of full coverage (100%), means that all the electrical energy demanded the heat pump can be supplied from the PVT solar modules, but it doesn't necessarily mean that all of the PVT output is consumed by the heat pump. In other words, in many months, WPVT is way more than the needs of the heat pump only, which by this, this energy produced is going to be directed to the other electrical demands within the facility. In table (9), it can be seen the total electrical power produced by the PVT modules versus that needed for the facility, In the values of WTotal, electrical energy that is exclusively demanded by the heat pump is included with the electrical energy demands of the whole facility.

Month	**W_{Total}**	**W_{PVT}**	**$W_{PVT-Total}$**
January	5,532.97	1,714.55	31%
February	5,625.64	1,858.82	33%
March	4,947.35	2,694.69	54%
April	3,483.90	3,213.99	92%
May	4,365.07	3,705.05	85%
June	4,257.88	3,990.63	94%
July	4,975.20	4,101.07	82%
August	4,369.19	3,782.00	87%
September	4,306.51	3,157.10	73%
October	3,897.83	2,597.59	67%
November	4,667.51	1,942.89	42%
December	6,023.15	1,648.88	27%
TOTAL	56,452.20	34,407.25	61%

Table 9 Percentages that PVT electrical output can cover of the total electrical demands.

In figure (26) below, it can be seen the total PVT electrical production all along the year, versus the total electrical energy needed for the center, of which, electrical energy is needed exclusively for the heat pump.

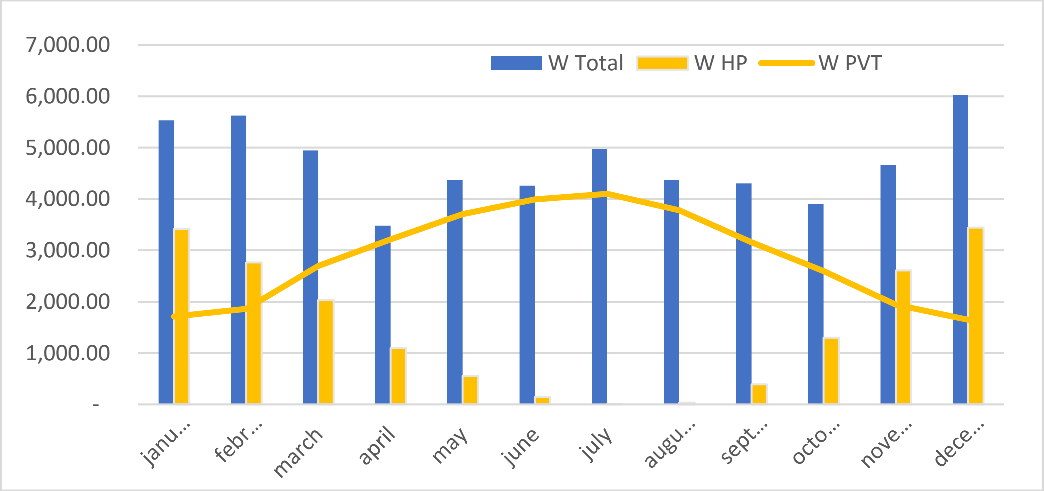


Figure 26 PVT electrical output coverage of the total electrical demand and heat pump electrical demand.

As it has been discussed, electrical demands are much lower with installing the PVT solar modules, this is because of the ability of the hybrid solar module to produce thermal and electrical energy, with the thermal energy produced, heat pump won't still be needing to work at the same level to meet thermal energy required from it. Figures (27) & (28) below, shows energy requirements the facility and the heat pump need in the case of having PVT solar panels installed versus in a contrary case.

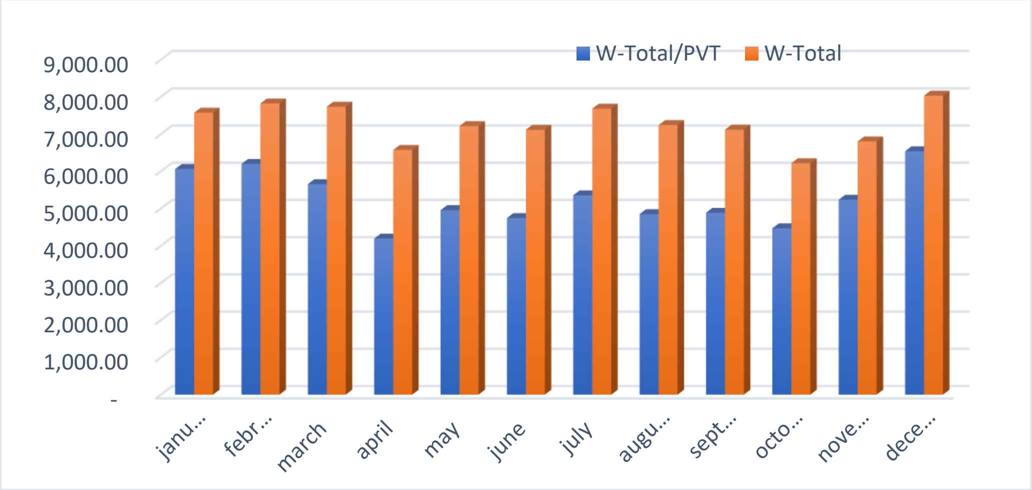


Figure 27 Facility's electrical demands with vs without installed PVT system.

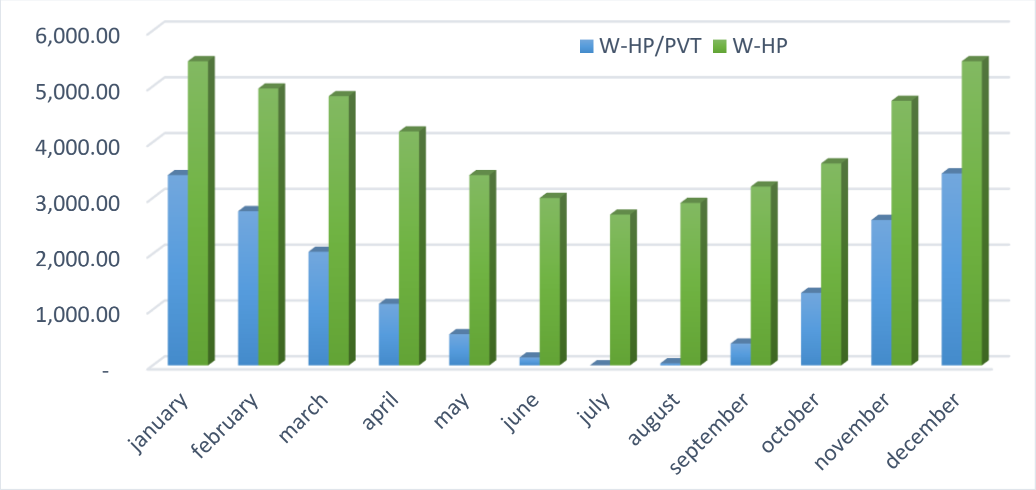


Figure 28 Heat Pump's electrical demands with vs without installed PVT system

Also exists another option in addition to that of PVT/heat pump, which is the conventional photovoltaic system, as a renewable system that also capable of converting solar energy into usable electrical energy. So, for its cheaper prices comparing with the PVT system, such a system has to be considered. For the aim of comparison technically and economically, a PV system that is performing in a similar way to the previously discussed PVT system has to be designed. So, a PV system that consists of 132 solar panels with an electrical peak power of 350 Wp, making the whole field reach 46.20 kWp is proposed.

Worth to be mentioned, the PVT system has size limitations that cannot surpass, as the maximum allowed solar contribution from the thermal part of the PVT modules is f=1, which can be seen for July in table (8) above. Moreover, it was indicated earlier, that the electrical energy demanded by the sports center can be less in the case of having a PVT solar system as for its thermal energy contribution to the system.

It can be noticed, the yearly electric production that the PVT can produce is indeed less than that of the PV system, even though, both systems are performing similarly, in the sense that the energy demand is different between both cases. Economics and savings comparison between these two systems will be carried out later on in the next chapter.

Table (10) shows monthly electrical energy requirements in both cases, and the ability to meet these requirements by each of the solar systems. Performance of both PV and PVT systems all over the year versus the electrical energy needed in both situations is depicted in the following figure (29).

Month	**Total Electrical Demand/PVT**	**Total Electrical Demand/PV**	**PVT**		**PV**	
			W_{PVT} KWh/m		W_{PV} KWh/m	
January	5,532.97	7,574.81	1,714.55	31%	2,954.302909	37%
February	5,625.64	7,824.87	1,858.82	33%	3,202.894659	39%
March	4,947.35	7,735.91	2,694.69	54%	4,643.156693	57%
April	3,483.90	6,573.34	3,213.99	92%	5,537.94801	79%
May	4,365.07	7,216.25	3,705.05	85%	6,384.082985	83%
June	4,257.88	7,116.64	3,990.63	94%	6,876.160787	91%
July	4,975.20	7,682.02	4,101.07	82%	7,066.450836	87%
August	4,369.19	7,243.98	3,782.00	87%	6,516.68236	85%
September	4,306.51	7,119.94	3,157.10	73%	5,439.933658	72%
October	3,897.83	6,217.21	2,597.59	67%	4,475.843349	68%
November	4,667.51	6,801.92	1,942.89	42%	3,347.743977	46%
December	6,023.15	8,033.81	1,648.88	27%	2,841.142714	33%
TOTAL	56,452.20	87,140.70	34,407.25	61%	59,286.34294	65%

Table 10 Monthly electrical energy requirements.

Another option also seems to be attractive, which can combine the PV systems for their simplicity and affordability on one hand, and the hybrid PVT systems for their high efficiency and capability of generating simultaneously both thermal and electrical energies on the other hand. A PVT+PV/Heat pump system can result to be a smart way to achieve energy balance and be economically more preferable.

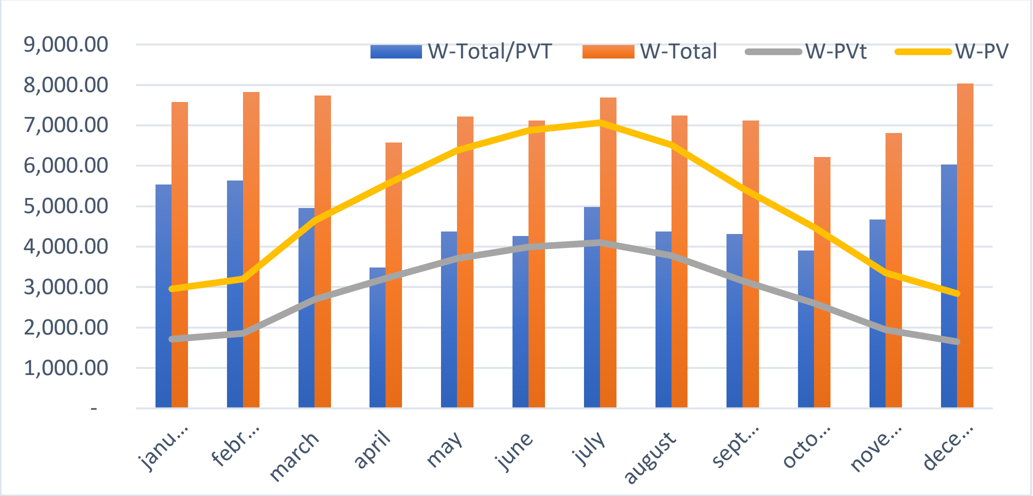


Figure 29 Monthly PV and PVT systems' performances versus electrical energy demanded in both cases

Considering just the thermal loads, a solar field that is composed of 45 PVT modules with both thermal QPVT and electrical outputs WPVT can meet the major part of them all, reaching an annual zero-net energy balance. Nevertheless, there are other electrical demands in the facility that need to be covered, for that, becomes installing a PV solar field that consist of 45 solar panels of 350 Wp each, and can operate side by side with the PVT solar field and sure compatible is of a gran interest.

This power plant can produce an annual thermal energy QPVT of 95,737.78 KWh/year, and an annual electrical energy WPVT/PV of 42,876 KWh/year. PVT and PV solar modules produce 23,820 KWh/year and 19,056 KWh/year of electrical power separately.

In July as a typical summer month, electricity produced by both PVT and PV, WPVT/PV can satisfy all of its electrical demands, as 57% is coming from WPVT, and 43% from WPV. PVT panels exclusively cover up to 84% of the month's thermal demands, and all the power needed for the heat pump WPVT-HP, reaching a 100% solar contribution. Taking January as a winter reference month, 35% of its electrical energy demands are covered by WPVT/PV. However, thermal demands in winter months are higher as the hot water consumption increases, moreover, solar irradiance is less for the periods of the year when thermal energy is needed the most. This makes the percentage of the PVT thermal output QPVT cover only 20% of the thermal requirements.

Table (11) below shows the thermal and electric contribution of this combined system to the whole energy demanded, and monthly coverage percentages gained through this combination.

Month	Q_{Total}	W_{Total}	Q_{PVT}/Q_{Total}	W_{PVT}/W_{Total}	W_{PV}/W_{Total}	$W_{PVT/PV}/W_{Total}$
	KWh/month	KWh/month				
January	24,533.13	6,061.68	20%	20%	16%	35%
February	22,332.92	6,199.63	25%	21%	17%	37%
March	21,712.12	5,654.80	37%	33%	26%	59%
April	18,865.54	4,193.75	52%	53%	42%	96%
May	15,346.12	4,957.32	62%	52%	41%	93%
June	13,502.88	4,744.74	77%	58%	47%	105%
July	12,163.58	4,980.00	84%	57%	46%	103%
August	13,103.92	4,850.50	80%	54%	43%	97%
September	14,422.22	4,886.09	66%	45%	36%	81%
October	16,286.46	4,468.10	43%	40%	32%	72%
November	21,334.16	5,235.99	26%	26%	21%	46%
December	24,533.13	6,539.07	19%	17%	14%	31%
TOTAL	218,136.16	62,771.68	44%	38%	30%	68%

Table 11 PVT thermal production and combined PVT/PV system's electric production.

Figure (30) shows total electricity produced by both PVT and PV modules, the electrical energy consumed monthly by the sports center, and of which, the power needed exclusively for the heat pump.

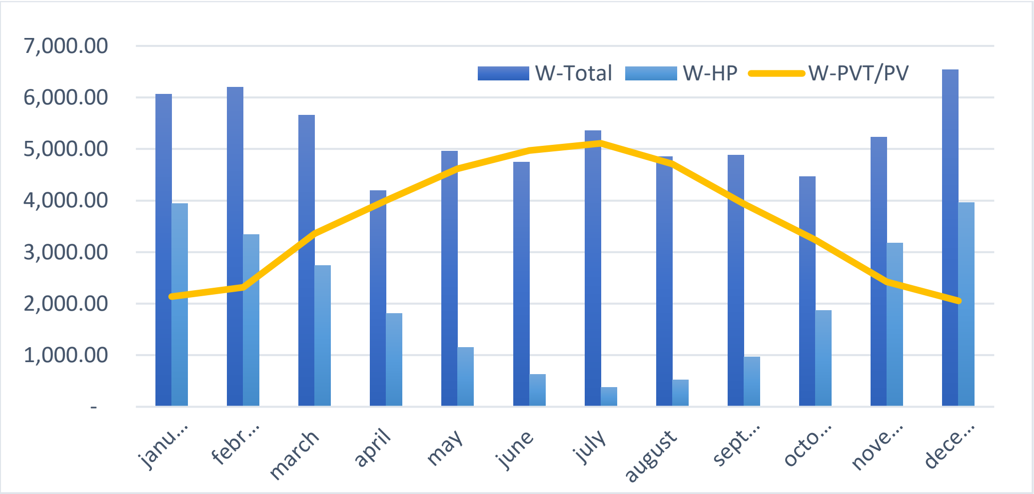


Figure 30 Total electrical energy produced by both PVT and PV modules.

Speaking of the thermal necessities, electrical and thermal energies produced by both PVT and PV solar fields are capable of covering all thermal energy demanded monthly by the whole facility; as the direct thermal output of the PVT panels QPVT is covering 44% of the total annual thermal demands represented by the swimming pool and the DHW, this percentage is defined by the solar fraction with a maximum value of about 84% for the month with less thermal needs and more available solar energy. So, the rest of the energy needed after the contribution of the PVT solar modules to the system which is 125,219.0 KWh/year, will be covered by the heat pump, which indeed requires electric power (WHP =22,360 kWh/year), the annual PVT electrical production WPVT in the majority of months meets it all. So, upon that, all thermal needs can be met by the PVT electrical and thermal outputs with the assistant of the heat pump for almost all the year, and in the months that thermal demands aren't met by the PVT/HP system, the PV system will be providing the electrical energy that heat pump needs to cover what remains of that demand. So, thermal energy balance formulas are to be presented as:

$$Q_{Total} = Q_{HP} + Q_{PVT}$$

$$W_{HP} = W_{PVT} + W_{PV}$$

In figure (31), the possibility for the thermal demands to be covered all along the year by the electrical productions WPVT & WPV is demonstrated. It was assumed that all the thermal requirements and also PVT thermal output are converted to an equivalent value of electrical energy for assessing the performances.

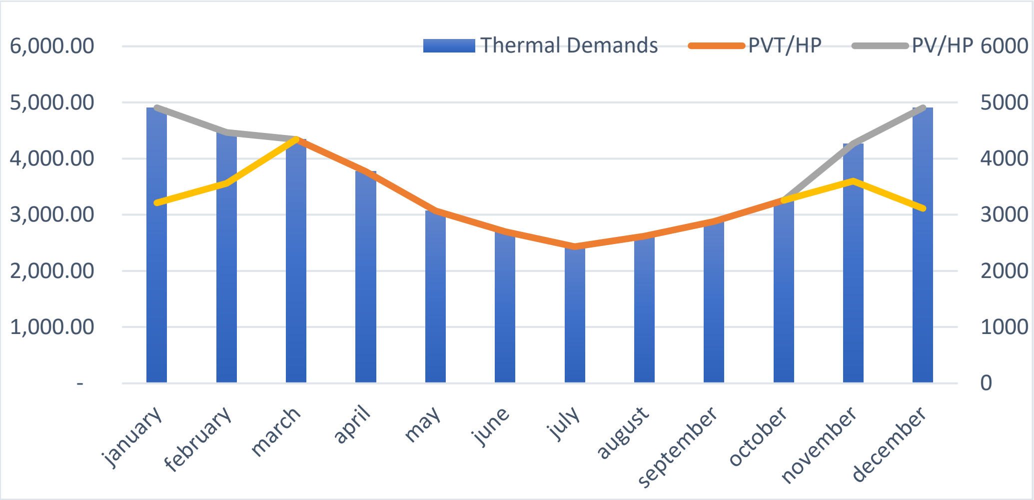


Figure 31 Electrical energy produced by PVT and PV modules and the thermal demands to be covered all along the year.

Thus, there exists three different configurations, with distinct thermal and electrical productivity for each, consequently the plants' sizes are different as the number of modules to be installed varies. Table (12) below lists the different sizes of the systems, the number of modules constitute each power plant, their thermal, electrical and total power outputs, and global fractional energy savings.

System	# Modules	Total Area m^2	Thermal		Electrical		Total
PVT-HP	65	122.2	129,205	59%	34,407	61%	77%
PVT/PV-HP	90	157.5	95,727	44%	42,876	68%	78%
PV-HP	132	213.84	-	0%	55,898	64%	64%

Table 12 The size and global fractional energy savings for each system.

4.2 Economic balance and savings

In the section above, it was described the configurations of three different systems; PVT/Heat pump, PV/Heat pump, and PVT-PV/Heat pump, and as can be seen thermal demands form the major part of the yearly energy consumption, which by this, the thermal portion that the PVT modules contribute to the system can lower down electrical consumptions significantly which leads to saving a huge amount of the center's monthly electricity bills. To calculate annual savings, the next formula was applied;

$$S = P_E . \sum_{t=1}^{T} [E_{Total} - E_{Solar}]$$

Where S is the total annual costs savings in euros €, P_E stands for the price of the purchased electricity in €/KWh, E_{Total} in (KWh/month) is the total energy consumption without solar system intervention, and E_{Solar} (KWh/month) is the total energy consumption after a solar system is installed, both energies are at time t.

For the PVT/HP system, as it greatly contributes thermal energy to the system, there exist significant thermal energy savings, by which, supposing the monthly electrical energy that meant to be consumed by the heat pump with the absence of any thermal supplement from a PVT solar field, versus electrical energy actually consumed after subtracting PVT's thermal output from the total thermal needs, a notable difference in the energy consumed between both cases can be detected.

Electricity consumed for heating purposes in the three different configurations PV and/or PVT- the heat pump is different, so obtainable thermal savings would also be distinct. Knowing that the retail electricity price in Palestine is 0.64₪/KWh, which converted to be in euros 0.17€/KWh with a conversion rate of [1:3.86].

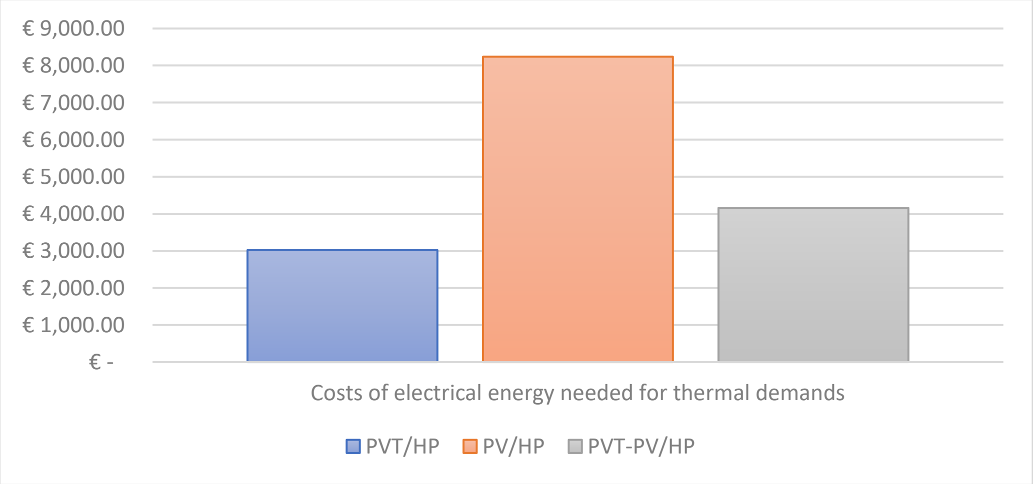


Figure 32 Annual costs for thermal demand for each design configuration.

Annual costs for thermal demand in each case can be seen in figure (32) above.

Furthermore, these systems are capable of generating electricity, so, this electrical energy produced by each system will add more costs savings. Figure (33) shows the total costs that are to be paid without the integration of any of these technologies, and how these costs are minimized by each of the systems.

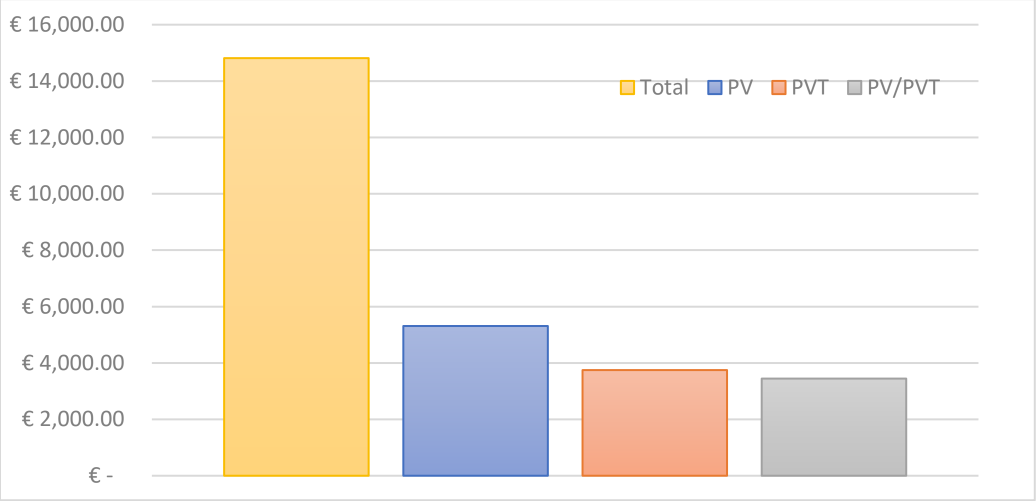


Figure 33 Total costs to be paid without any technology integration vs costs after the integration.

So, total annual savings acquired by each of the systems are listed in the table (13) below, noticing that for the case of a PV-heat pump, there are no thermal savings acquired.

System	Thermal savings	Electrical Savings	Total savings
PV	€0	€9,502.75	€9,502.75
PVT	€5,217.05	€5,849.23	€11,066.28
PV/PVT	€4,078.80	€7,298.04	€11,367.84

Table 13 Total annual savings acquired by each system.

As the aforementioned systems have different capital investment costs, previously calculated annual savings aren't the right baseline to correctly decide which of them should be the best solution. So, to be able to compare these systems, there exist different financial criteria for the aim of evaluation economically each of them, the factors that should be considered are; simple payback time (SPT), net present value (NPV), internal rate of return (IRR).

- simple payback time (SPT), is the number of years in which the money saved after the integrating of the solar system would repay the investment expenses. With the assumption that yearly savings will stay constant throughout the project duration, a simple payback period is determined as follows.

$$\mathrm{SPT} = \mathrm{I/S}$$

Where SPT stands for simple payback time in years, I is the investment costs in euros, S is the annual savings.

- Net present value (NPV), is one of the most significant parameters for measuring the financial efficiency of investments and is known as the difference between the current value of cash inflows (savings to be obtained in the case of a renewable energy solution) and the outflows (investments and maintenance costs) over a period of time. Normally NPV is used in capital budgeting and investment planning to determine the profitability of a proposed investment or project. The following is the method for calculating the NPV when all investments have been made at the start of the period.

$$\mathrm{NPV} = -\mathrm{CF}_0 + \sum_{t=1}^{T} \frac{\mathrm{CF}_t}{(1+\mathrm{i})^t}$$

where CF_0 is the present value of investments in €; CF_t is the net cash flow (the amount of cash inflow minus outflow) at time t, €; t is time of cash flow; and i is the discount rate, %. [103].

- IRR is the rate of discount that makes the value of future savings equal to the value of investments (the rate of discount that makes the NPV equal to zero). The following formula may be used to determine IRR: [103].

$$0 = -\mathrm{CF}_0 + \sum_{t=1}^{T} \frac{\mathrm{CF}_t}{(1+\mathrm{IRR})^t}$$

The capital cost of each of the systems are listed in the table below, where the investment costs of the PVT- heat pump system, and the PVT part of the PVT/PV-heat pump systems were obtained from a simulation tool that is proposed by the Spanish manufacturer (ABORA), the costs of the PV-heat pump system and the PV part of the PVT/PV-heat pump has been estimated according to the residential and commercial sector solar PV total installed costs by country (IRENA) [104]. Hence, the price of the heat pump isn't included, as the same heat pump can be employed for the three configurations, also, for our case study, the heat pump is already purchased and installed. The investment costs of each of the systems are listed in table (14) below.

System	Investment costs
PV	€60,000.00
PV/PVT	€75,000.00
PVT	€86,000.00

Table 14 The investment cost for each system.

So, having the investment costs of each system, and the annual savings, the three major economic parameters SPT, NPV, and IRR can be defined. Table (15) below lists the three major economic parameters for each system. Assuming that the lifetime period is 25 years, energy demands remain constant during the lifetime, the degradation rate of the photovoltaic cells was assumed to be 1%, retail electricity prices growth rate of 1%/year, and a discount rate of 3% were considered.

System	**SPT**	**NPV**	IRR
PV	6 years, 4 months	€177,281	15%
PV/PVT	6 years, 7 months	€208,954	15%
PVT	7years, 9months	€107,590	12%

Table 15 NPV, STP, and IRR values for each of the systems

5 Conclusions

Energy demands that are majorly represented by thermal and electrical necessities in the residential or multidisciplinary facilities can be totally fulfilled by renewable sources such as the solar energy, and for that purpose, there exist various technologies and solutions. This study has focused on the innovative solar technology PV/Thermal hybrid system, where the features of such a hybrid solar collector have been mentioned, the different types of the modules that are mainly categorized by the heat transfer fluid or concentration technology have also been listed, an overview of the market potential for the PVT system has been given, showing that such a system has the chance to compete with the already existed technologies for the same purpose.

It has been discussed that a heat pump, which is a pretty powerful technology used for the aim of heating and/or cooling, can be assisted by various solar systems that can supply electrical or thermal energies or even both in the case of PVT solar modules. By such a combination, the COP of the heat pump increases as the water enters its low temperature inlet is preheated by the solar modules, making the process of cooling down the modules more efficient, increasing by that the module’s efficiency, moreover, the compressor of the heat pump can be fed by the electrical energy output from the PVT modules, which by this, the overall performance of the system improves significantly.

Three systems have been proposed, a PVT that produce electrical and thermal energies simultaneously, a PV system that only produce electrical energy, and a system that is a combination between PVT and PV solar modules, in each case a heat pump is included. In the PVT/heat pump system, thermal output from the modules is capable of covering a huge part of thermal demands without the need of the heat pump, and when this thermal output isn’t enough, the electrical output of the hybrid modules can supply the compressor of the heat pump to fulfill the rest of the thermal demands, making by this, a solar fraction of 100% for the most of the months all along the year, it also can cover other electrical needs within the facility or it can be directed to the grid.

In the PV system, thermal needs are considered as an electrical energy needed by the heat pump, so the PV system was designed to cover electrical energy as it only produces electricity. In this case, it was noticed that the electrical energy needed for the whole facility is more than that needed in the case of PVT system, as the PVT system can contribute thermal energy to the system lowering by that the electrical needs of the heat pump, also the COP of the heat pump is less when there are no any helping factors that may increase it.

It has been found that a system that consists of PVT and PV solar modules would be a better solution economically, where the PVT solar field is assisting the heat pump reaching an annual zero-net thermal energy balance, and the PV solar field produces electrical energy that is supplied to the system.

It was found that a PVT solar system needs a field’s size of almost half of the area needed for a PV solar system to cover the same portion of energy demands, which means more energy production by square meter for the hybrid system.

6 Bibliography

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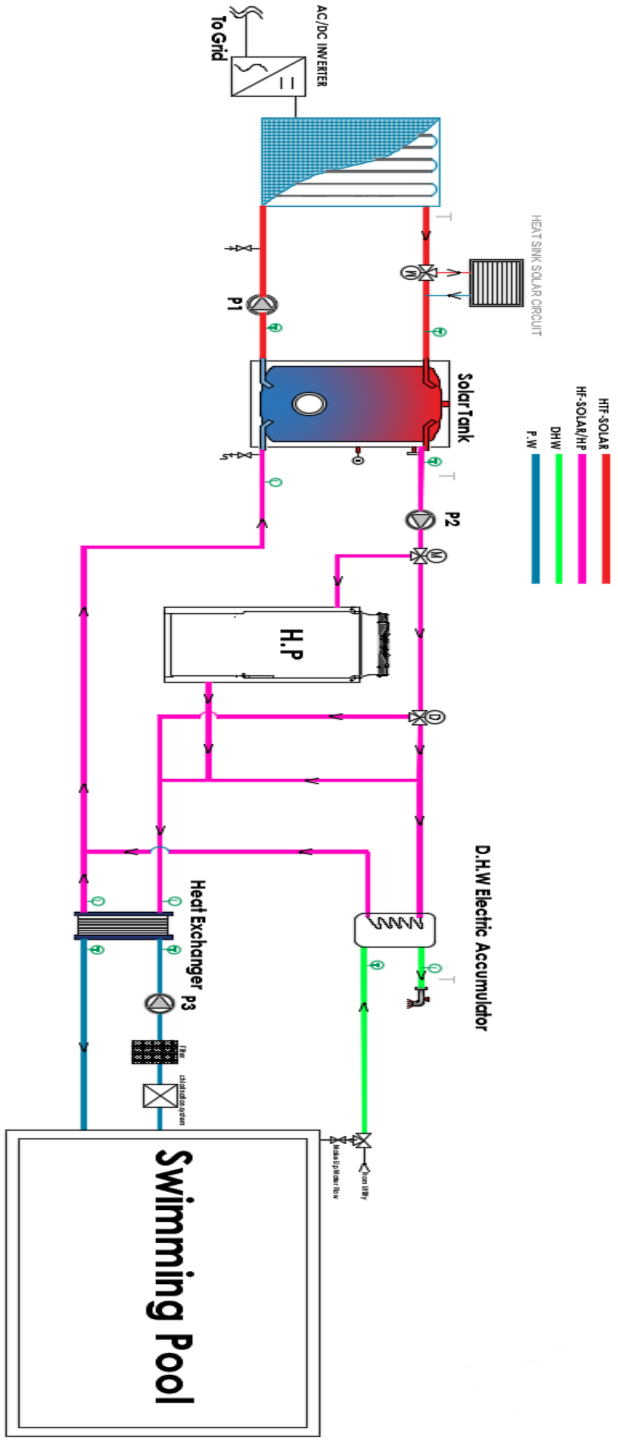
7 Annexes

7.1 Annex (1): System layout.



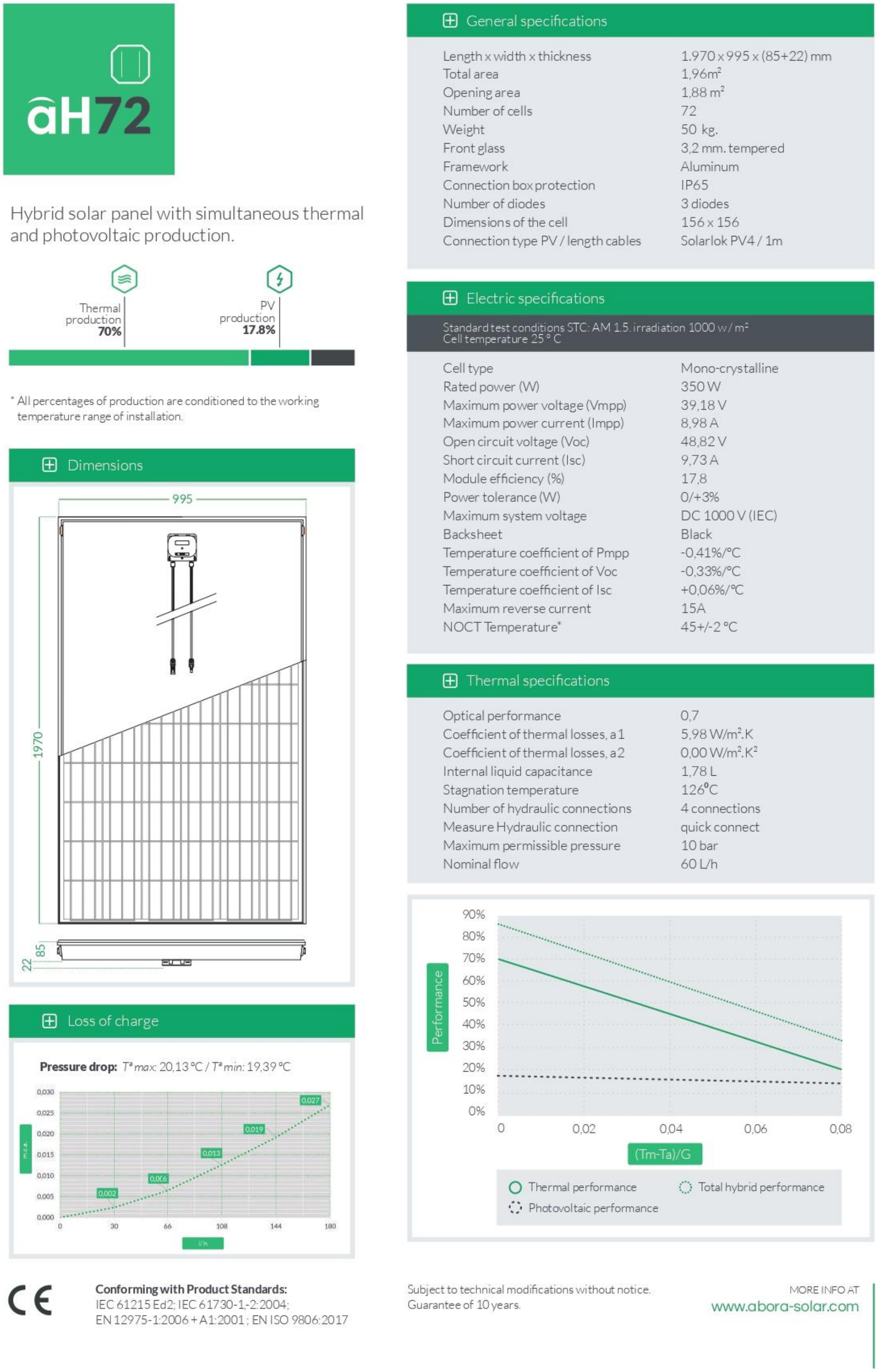
7.2 Annex (2): PVT manufacturers worldwide.

Manufacturer	Country	Heat Transfer Fluid	Brand
Triple Solar	Netherlands	Water- Glycole	PVT warmtepomppaneel
SYSTOVI	FRANCE	Air	R-VOLT ON TOP
Solvis	Germany	Water- Glycole	SolvisCala 254-AR
Solator	Austria	Water- Glycole	
PA-ID Process	Germany	Water- Glycole	HM 1305 Mono Black
PLAYSYSTEM srl	Italy	Water- Glycole	PSS
GSE INTEGRATION	FRANCE	Air	SOLUXTEC DAS MODULE MONO S.FR60, LONGiSOLAR LR6-60PB-300M, TRINA SOLAR TSM-265DD05A-05(II), LG 300N1C-G4
Hoval Aktiengesellschaft	Liechtenstein	Water- Glycole	UltraSol® 2-V
			UltraSol® 2-H
Gasokol GmbH	Austria	Water- Glycole	sunWin 24
			sunWin 27V
Consolar Solare Energiesysteme	Schweiz	Water- Glycole	KF500, SOLAERA HYBRIDKOLLEKTOR
3S Solar Plus AG	Switzerland	Water-Glycole	
Şimşek Güneş Kollektörleri	Türkiye	Water-Glycole	Orion-Series
Powertronic	Italy	Water-Glycole	300+1100
NIBE	Sweden	Air	
Canadian Solar EMEA GmbH	Canada	Air	BIHIKU7
SOLIMPEKS Solar	Turkey	Water-Glycole	VOLTHER POWERVOLT
Solarwall	Canada	Air	SOLARWALL
3S SWISS SOLAR SYSTEMS	Germany	Water-Glycole	SkySlate Hybrid
Crane	**Bulgaria**	Water-Glycole	
Brandoni	Italy	Water-Glycole	

7.3 Annex (3): aH72 PVT solar module specifications' sheet.

General specifications	
Length x width x thickness	1.970 x 995 x (85+22) mm
Total area	1,96m^2
Opening area	1,88 m^2
Number of cells	72
Weight	50 kg.
Front glass	3,2 mm. Tempered
Framework	Aluminum
Connection box protection	IP65
Number of diodes	3 diodes
Dimensions of the cell	156 x 156
Connection type PV / length cables	Solarlok PV4 / 1m
Electric specifications	
Standard test conditions STC	AM: 1.5. Irradiation:1000w/m2
Cell temperature	25 ° C
Cell type	Mono-crystalline
Rated power (W)	350 W
Maximum power voltage (Vmpp)	39,18 V
Maximum power current (Impp)	8,98 A
Open circuit voltage (Voc)	48,82 V
Short circuit current (Isc)	9,73 A
Module efficiency (%)	17,8
Power tolerance (W)	0/+3%
Maximum system voltage DC	1000 V (IEC)
Back sheet	Black
Temperature coefficient of Pmpp	-0,41%/ºC
Temperature coefficient of Voc	-0,33%/ºC
Temperature coefficient of Isc	+0,06%/ºC
Maximum reverse current	15A
NOCT Temperature*	45+/-2 ºC
Thermal specifications	
Optical performance	0,7
Coefficient of thermal losses, a1	5,98 W/m^2.K
Coefficient of thermal losses, a2	0,00 W/m^2.K^2
Internal liquid capacitance	1,78 L
Stagnation temperature	126C
Number of hydraulic connections	4 connections
Maximum permissible pressure	10 bar
Nominal flow	60 L/h

7.4 Annex (4): aH72 PVT solar module specifications' sheet.



aH72

Hybrid solar panel with simultaneous thermal and photovoltaic production.

* All percentages of production are conditioned to the working temperature range of installation.

Dimensions

Loss of charge

Pressure drop: *Tª max:* 20,13 ºC / *Tª min:* 19,39 ºC

General specifications

Length x width x thickness	1.970 x 995 x (85+22) mm
Total area	1,96m²
Opening area	1,88 m²
Number of cells	72
Weight	50 kg.
Front glass	3,2 mm. tempered
Framework	Aluminum
Connection box protection	IP65
Number of diodes	3 diodes
Dimensions of the cell	156 x 156
Connection type PV / length cables	Solarlok PV4 / 1m

Electric specifications

Standard test conditions STC: AM 1.5. irradiation 1000 w / m²
Cell temperature 25 ° C

Cell type	Mono-crystalline
Rated power (W)	350 W
Maximum power voltage (Vmpp)	39,18 V
Maximum power current (Impp)	8,98 A
Open circuit voltage (Voc)	48,82 V
Short circuit current (Isc)	9,73 A
Module efficiency (%)	17,8
Power tolerance (W)	0/+3%
Maximum system voltage	DC 1000 V (IEC)
Backsheet	Black
Temperature coefficient of Pmpp	-0,41%/°C
Temperature coefficient of Voc	-0,33%/°C
Temperature coefficient of Isc	+0,06%/°C
Maximum reverse current	15A
NOCT Temperature*	45+/-2 °C

Thermal specifications

Optical performance	0,7
Coefficient of thermal losses, a1	5,98 W/m².K
Coefficient of thermal losses, a2	0,00 W/m².K²
Internal liquid capacitance	1,78 L
Stagnation temperature	126ºC
Number of hydraulic connections	4 connections
Measure Hydraulic connection	quick connect
Maximum permissible pressure	10 bar
Nominal flow	60 L/h

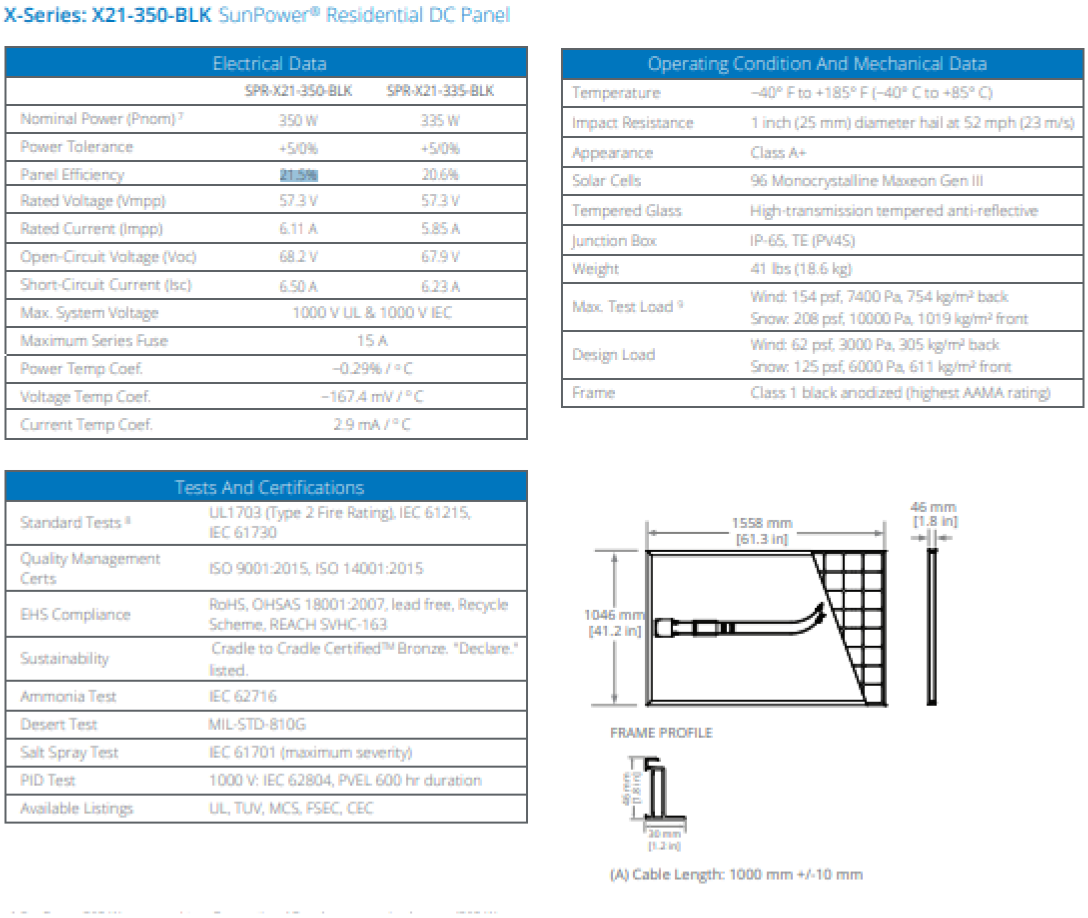
CE

Conforming with Product Standards:
IEC 61215 Ed2; IEC 61730-1,-2:2004;
EN 12975-1:2006 + A1:2001 ; EN ISO 9806:2017

Subject to technical modifications without notice.
Guarantee of 10 years.

MORE INFO AT
www.abora-solar.com

7.5 Annex (5): SunPower PV solar module specifications sheet.



X-Series: X21-350-BLK SunPower® Residential DC Panel

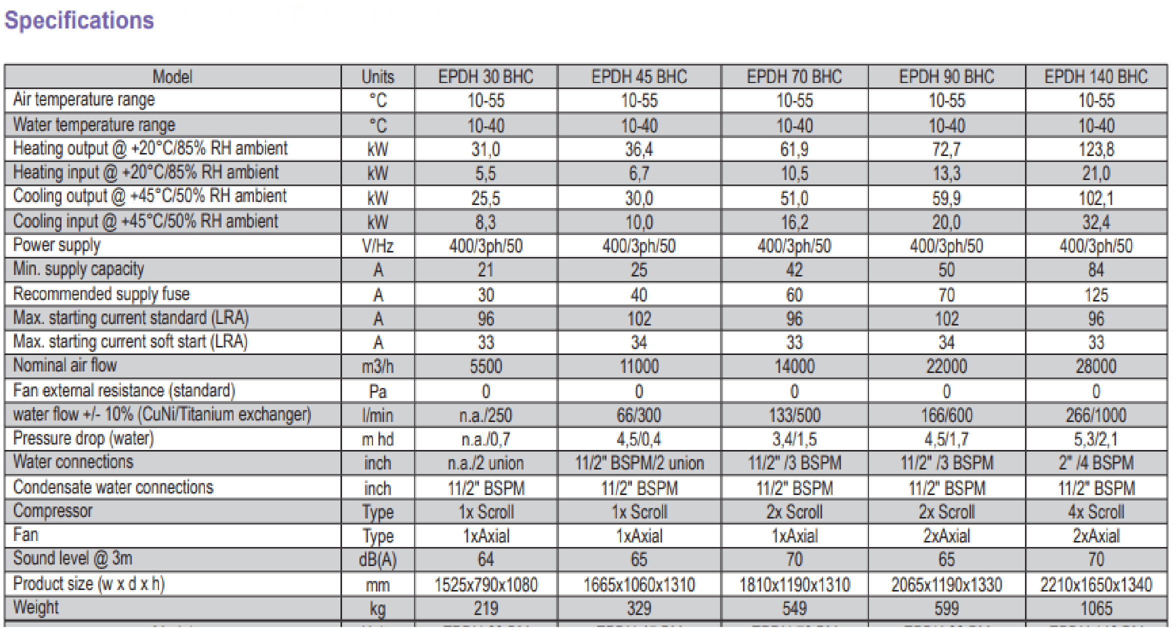
Electrical Data		
	SPR-X21-350-BLK	SPR-X21-335-BLK
Nominal Power (Pnom)[7]	350 W	335 W
Power Tolerance	+5/0%	+5/0%
Panel Efficiency	21.5%	20.6%
Rated Voltage (Vmpp)	57.3 V	57.3 V
Rated Current (Impp)	6.11 A	5.85 A
Open-Circuit Voltage (Voc)	68.2 V	67.9 V
Short-Circuit Current (Isc)	6.50 A	6.23 A
Max. System Voltage	1000 V UL & 1000 V IEC	
Maximum Series Fuse	15 A	
Power Temp Coef.	−0.29% / ° C	
Voltage Temp Coef.	−167.4 mV / ° C	
Current Temp Coef.	2.9 mA / ° C	

Operating Condition And Mechanical Data	
Temperature	−40° F to +185° F (−40° C to +85° C)
Impact Resistance	1 inch (25 mm) diameter hail at 52 mph (23 m/s)
Appearance	Class A+
Solar Cells	96 Monocrystalline Maxeon Gen III
Tempered Glass	High-transmission tempered anti-reflective
Junction Box	IP-65, TE (PV4S)
Weight	41 lbs (18.6 kg)
Max. Test Load[9]	Wind: 154 psf, 7400 Pa, 754 kg/m² back Snow: 208 psf, 10000 Pa, 1019 kg/m² front
Design Load	Wind: 62 psf, 3000 Pa, 305 kg/m² back Snow: 125 psf, 6000 Pa, 611 kg/m² front
Frame	Class 1 black anodized (highest AAMA rating)

Tests And Certifications	
Standard Tests[8]	UL1703 (Type 2 Fire Rating), IEC 61215, IEC 61730
Quality Management Certs	ISO 9001:2015, ISO 14001:2015
EHS Compliance	RoHS, OHSAS 18001:2007, lead free, Recycle Scheme, REACH SVHC-163
Sustainability	Cradle to Cradle Certified™ Bronze. "Declare." listed.
Ammonia Test	IEC 62716
Desert Test	MIL-STD-810G
Salt Spray Test	IEC 61701 (maximum severity)
PID Test	1000 V: IEC 62804, PVEL 600 hr duration
Available Listings	UL, TUV, MCS, FSEC, CEC

(A) Cable Length: 1000 mm +/-10 mm

7.6 Annex (6): Swimming pool heat pump specifications’ sheet.



Specifications

Model	Units	EPDH 30 BHC	EPDH 45 BHC	EPDH 70 BHC	EPDH 90 BHC	EPDH 140 BHC
Air temperature range	°C	10-55	10-55	10-55	10-55	10-55
Water temperature range	°C	10-40	10-40	10-40	10-40	10-40
Heating output @ +20°C/85% RH ambient	kW	31,0	36,4	61,9	72,7	123,8
Heating input @ +20°C/85% RH ambient	kW	5,5	6,7	10,5	13,3	21,0
Cooling output @ +45°C/50% RH ambient	kW	25,5	30,0	51,0	59,9	102,1
Cooling input @ +45°C/50% RH ambient	kW	8,3	10,0	16,2	20,0	32,4
Power supply	V/Hz	400/3ph/50	400/3ph/50	400/3ph/50	400/3ph/50	400/3ph/50
Min. supply capacity	A	21	25	42	50	84
Recommended supply fuse	A	30	40	60	70	125
Max. starting current standard (LRA)	A	96	102	96	102	96
Max. starting current soft start (LRA)	A	33	34	33	34	33
Nominal air flow	m3/h	5500	11000	14000	22000	28000
Fan external resistance (standard)	Pa	0	0	0	0	0
water flow +/- 10% (CuNi/Titanium exchanger)	l/min	n.a./250	66/300	133/500	166/600	266/1000
Pressure drop (water)	m hd	n.a./0,7	4,5/0,4	3,4/1,5	4,5/1,7	5,3/2,1
Water connections	inch	n.a./2 union	11/2" BSPM/2 union	11/2" /3 BSPM	11/2" /3 BSPM	2" /4 BSPM
Condensate water connections	inch	11/2" BSPM	11/2" BSPM	11/2" BSPM	11/2" BSPM	11/2" BSPM
Compressor	Type	1x Scroll	1x Scroll	2x Scroll	2x Scroll	4x Scroll
Fan	Type	1xAxial	1xAxial	1xAxial	2xAxial	2xAxial
Sound level @ 3m	dB(A)	64	65	70	65	70
Product size (w x d x h)	mm	1525x790x1080	1665x1060x1310	1810x1190x1310	2065x1190x1330	2210x1650x1340
Weight	kg	219	329	549	599	1065

UNIVERSIDAD DE ALMERÍA

Resumen/Abstract

Sun is an essential energy source for reducing fossil fuel usage and carbon emissions by substituting the conventional manner of producing energy with a renewable approach that can meet daily demands of thermal and electrical energies. This study was intended to give an overview of the photovoltaic-thermal/hybrid solar technology and its applications, by which, the combination between such technology and an air-water heat pump. That's to cover the thermal and electrical energy needs of a sports center with a swimming pool located in Nablus-Palestine (Mediterranean climate). Such a combination is then compared technically and economically with a PV/ heat pump and a PVT-PV/heat pump. It has been found that a combination between PVT and PV technologies with a heat pump PVT-PV/ HP, can be opted to cover all thermal and electrical energy necessities, and it can show a good performance all along the year, as it increases the COP of the heat pump, bringing more energy savings, and it needs a relatively smaller plant size. Economically, payback period, NPV, and IRR have been calculated and listed for the proposed systems

El sol es una fuente de energía esencial para poder reducir el uso de combustibles fósiles y las emisiones de carbono al ser capaz de sustituir las fuentes convencionales por una fuente de naturaleza renovable capaz de satisfacer las demandas diarias de energía térmica y eléctrica. Este estudio ha tenido como objetivo estudiar una aplicación de la tecnología solar fotovoltaica-térmica/ híbrida y la combinación entre dicha tecnología y una bomba de calor aire-agua para cubrir las necesidades de energía térmica y eléctrica de un centro deportivo con piscina ubicado en Nablus-Palestina (clima mediterráneo.) A tal fin se han estudiado técnica y económicamente dos propuestas de sistemas constituidos por una bomba de calor-PVT y una bomba de calor PVT-PV. Se ha comprobado cómo la opción híbrida puede cubrir todas las necesidades de energía térmica y eléctrica, y puede mostrar un buen desempeño a lo largo del año, ya que aumenta la COP de la bomba de calor, lo que genera más ahorros de energía y requiere un tamaño de planta relativamente más pequeño. Todos los indicadores económicos del proyecto analizado, el período de recuperación, el VPN y la TIR confirman la idoneidad de la propuesta realizada

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