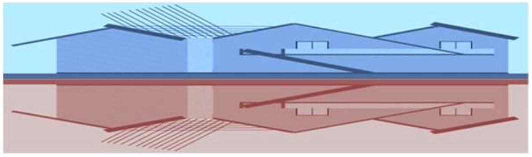
Hybrid Photovoltaic/Thermal Collectors



Prof. Yiannis Tripanagnostopoulos

Univ. of Patras, Patra, Greece

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Photovoltaics and temperature aspects

The conversion rate of solar radiation into electricity by photovoltaics depends on cell type and is between 5%-25%.

The greater part of the absorbed solar radiation by photovoltaics is converted into heat (at about 60%-70%), increasing cell temperature.

This effect reduces their electrical efficiency - mainly to silicon cells - and is an essential difference between solar thermal collectors and photovoltaics, for the required conditions for their effective operation.

The solar thermal collectors aim to achieve higher absorber temperature, in order to provide heat removal fluid efficiently and at higher temperature, while the PV cells operate in lower temperatures in order to achieve higher efficiency in electricity.

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Photovoltaics are mainly made from silicon semiconductors, based on monocrystalline silicon (c-Si) , polycrystalline silicon (pc-Si) and amorphous silicon (a-Si) modules.

In terrestrial applications, the pc-Si type PV modules are the most widely applied among silicon type photovoltaics, followed by cadmium telluride (CdTe) and copper indium gallium selenide CIGS, while new types of photovoltaics, as of dye-sensitized solar cells (DSSCs), have been investigated.

Silicon type photovoltaics are still the main cell types in applications because they have longer durability and higher efficiency than other photovoltaics.

The photovoltaics based on other than silicon materials (CdTe, CIGS, DSSCs, etc), would follow in applications next years and mainly in the built sector.

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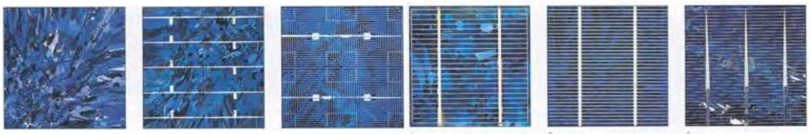
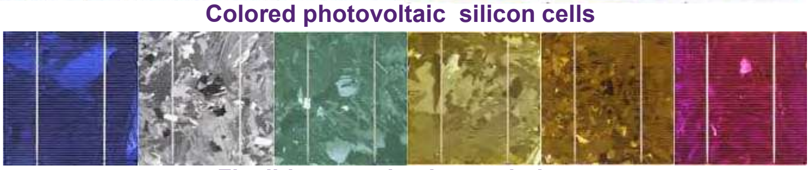
Photovoltaics

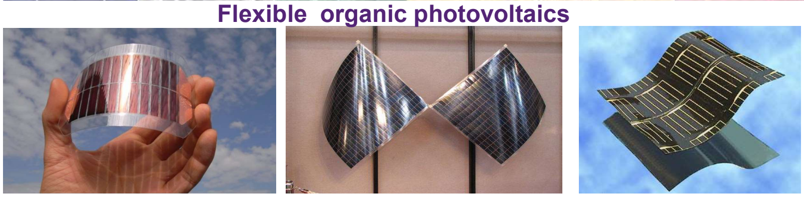
Typical silicon photovoltaic cells



Colored photovoltaic silicon cells



Flexible organic photovoltaics



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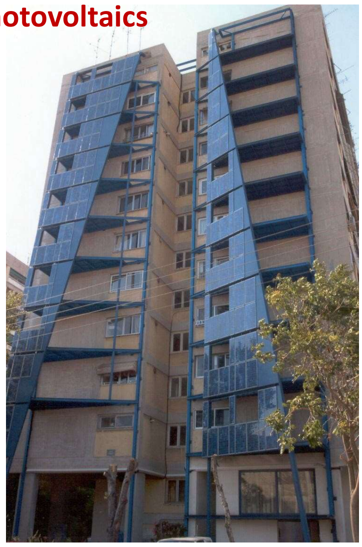
Photovoltaics



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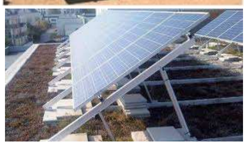

In case of PV modules that are installed in parallel rows on horizontal plane of ground or building roof, the exposure of both PV module surfaces to the ambient permits their natural cooling.

In façade or inclined roof installation on buildings the thermal losses are reduced due to the thermal protection of PV rear surface and PV modules operate at higher temperatures. This undesirable effect can be partially avoided by applying a suitable heat extraction with a fluid circulation, air or liquid (water), keeping the electrical efficiency at a satisfactory level.

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The hybrid Photovoltaic/Thermal (PV/T or PVT) collectors are the solar energy systems that consist of PV modules combined with thermal units and provide simultaneously electricity and heat. PV/T collectors are mainly of flat type in form and are distinguished in water cooled (PV/T-water) and air cooled (PV/T-air) collectors.

PV/T collectors can be applied to buildings, instead of separate solar thermal and photovoltaics

In addition, there have been developed concentrating PV/T collectors (CPV/T), using reflectors or lenses and a circulating fluid to avoid higher PV operating temperatures, due to the concentrated solar radiation on cells.

Hybrid PV/T systems can be used for the production of electricity and heat to residential and office buildings, hotels, hospitals, athletic centers, industries and to agricultural applications.

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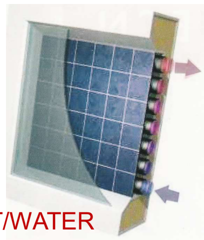
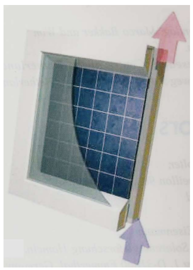
Hybrid Photovoltaic/Thermal Solar Energy Systems



PVT/WATER



PVT/AIR

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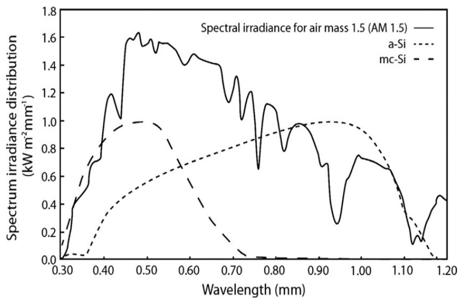
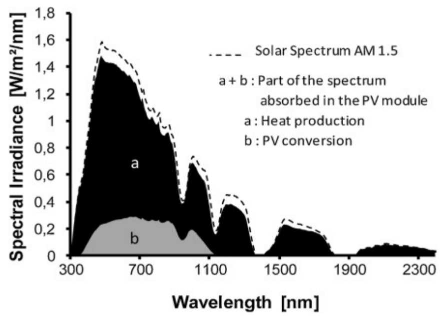


(from Aste et al, 2014)



(from Dupeyrat et al, 2014)

Spectral solar radiation absorption response of crystalline and amorphous silicon cells and the conversion rates for heat and electricity

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History of PV/T (1st period 1975-2000)

The first step on PV/T collectors is the works of Wolf (1976) and Kern and Russell (1978), for the design and performance of water and air cooled PV/T systems.

Following, are the studies of Hendrie (1979) , Florschuetz (1979) and Cox and Raghuraman (1985). PV/T collectors for building integration: Sopian et al (1996), Garg and Adhikari (1997), Brinkworth et al (1997), Moshfegh and Sandberg (1998), Schroer et al (1998), Brinkworth (2000).

Eicker et al (2000) give monitoring results from a BIPV/T system and Bazilian et al (2001) evaluate the practical use of several PV/T systems with air heat extraction in the built environment.

Applications of PV/T-air systems have been given by Chow (2003), Hegazy (2000), Ito with Miura (2003), Infield et al (2004), Charron and Athienitis (2006), Brinkworth and Sandberg (2006).

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History of PV/T (1st period 1975-2000)

Some of the most important first studies on PV/T-Water systems is the work of Bergene and Lovvik (1995) for detailed analysis on liquid type PVT systems, of Elazari (1998) for design, performance and economic aspects of commercial type PV/T water heater, Hausler and Rogash (2000) for a latent heat storage PVT system and of Kalogirou (2001), with TRNSYS study for PVT-Water systems.

Later, Huang et al (2001) presented a PV/T system with hot water storage and Sandness and Rekstad (2002) gave results for PVT collectors with polymer absorber.

Dynamic 3D and steady state 3D, 2D and 1D models for PV/T –Water have been studied and presented by Zondag et al (2002, 2003).

Experimental results on PV/T-Water and PV/T-Air systems, including the use of diffuse reflectors, were published by Tripanagnostpoulos et al (2002, 2007).

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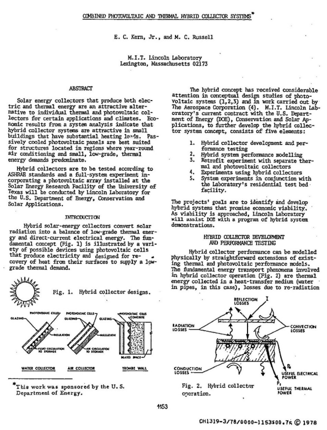

COMBINED PHOTOVOLTAIC AND THERMAL HYBRID COLLECTOR SYSTEMS*

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Lexington, Massachusetts 02173

ABSTRACT

Solar energy collectors that produce both electric and thermal energy are an attractive alternative to individual thermal and photovoltaic collectors for certain applications and climates. Economic results from a system analysis indicate that hybrid collector systems are attractive in small buildings that have substantial heating loads. Passively cooled photovoltaic panels are best suited for structures located in regions where year-round air conditioning and small, low-grade, thermal energy demands predominate.

Hybrid collectors are to be tested according to ASHRAE standards and a full-system experiment incorporating a photovoltaic array installed at the Solar Energy Research Facility of the University of Texas will be conducted by Lincoln Laboratory for the U.S. Department of Energy, Conservation and Solar Applications.

INTRODUCTION

Hybrid solar-energy collectors convert solar radiation into a balance of low-grade thermal energy and direct-current electrical energy. The fundamental concept (Fig. 1) is illustrated by a variety of possible devices using photovoltaic cells ...

The hybrid concept has received considerable attention in conceptual design studies of photovoltaic systems (1,2,3) and in work carried out by The Aerospace Corporation (4). M.I.T. Lincoln Laboratory's current contract with the U.S. Department of Energy (DOE), Conservation and Solar Applications, to further develop the hybrid collector system concept, consists of five elements:

1. Hybrid collector development and performance testing
2. Hybrid system performance modelling
3. Retrofit experiment with separate thermal and photovoltaic collectors
4. Experiments using hybrid collectors
5. System experiments in conjunction with the Laboratory's residential test bed facility.

The projects' goals are to identify and develop hybrid systems that promise economic viability. As viability is approached, Lincoln Laboratory will assist DOE with a program of hybrid system demonstrations.

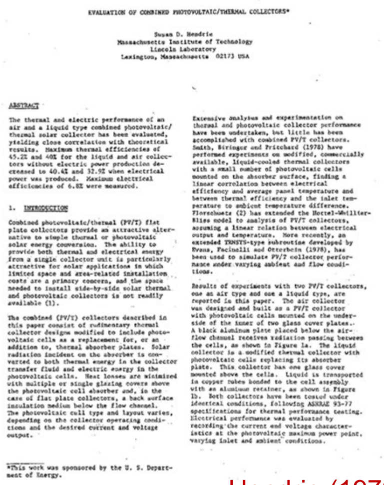
HYBRID COLLECTOR DEVELOPMENT AND PERFORMANCE TESTING

Hybrid collector performance can be modelled ...

Fig. 1. Hybrid collector designs.

Fig. 2. Hybrid collector operation.

*This work was sponsored by the U.S. Department of Energy.



EVALUATION OF COMBINED PHOTOVOLTAIC/THERMAL COLLECTORS*

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Massachusetts Institute of Technology
Lincoln Laboratory
Lexington, Massachusetts 02173 USA

ABSTRACT

The thermal and electric performance of an air and a liquid type combined photovoltaic/thermal solar collector has been evaluated, yielding close correlation with theoretical results. Maximum thermal efficiencies of 45.2% and 40% for the liquid and air collectors without electric power production decreased to 40.4% and 32.9% when electrical power was produced. Maximum electrical ...

Extensive analyses and experimentation on thermal and photovoltaic collector performance have been undertaken, but little has been accomplished with combined PV/T collectors. Smith, Biringer and Pritchard (1978) have performed experiments on modified, commercially available, liquid-cooled thermal collectors with a small number of photovoltaic cells mounted on the absorber surface, finding a ...

1. INTRODUCTION

*This work was sponsored by the U. S. Department of Energy.

Kern and Russell (1978)
13th IEEE Photovoltaic Specialists, Washington , 1978

Hendrie (1979)
ISES Conf., Atlanta, 1979

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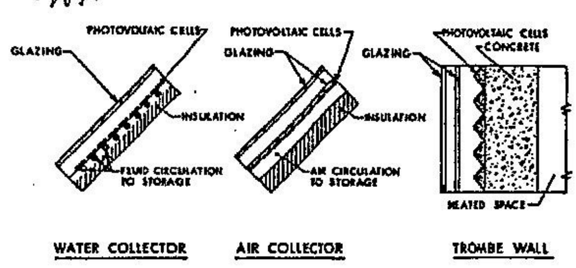
Fig. 1. Hybrid collector designs.



Kern and Russell (1978)
13th IEEE Photovoltaic Specialists, Washington , 1978

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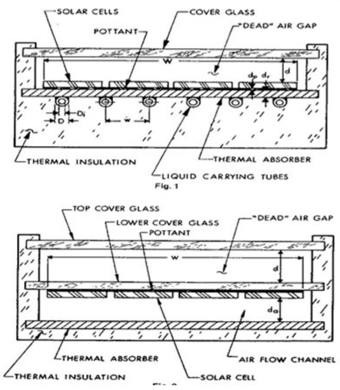
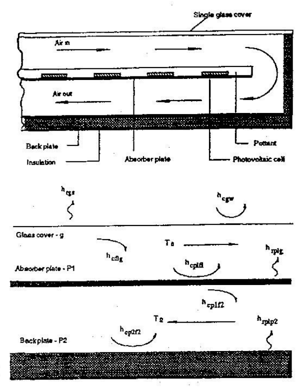


Bhargava et al (1991),



Sopian et al (1996)

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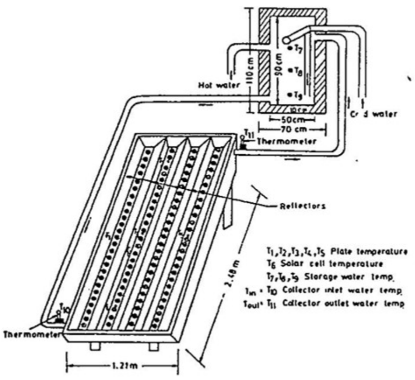
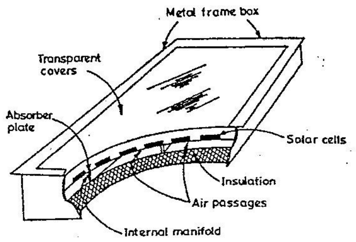


Garg and Agarwal (1995)

Garg and Adhikari (1997)



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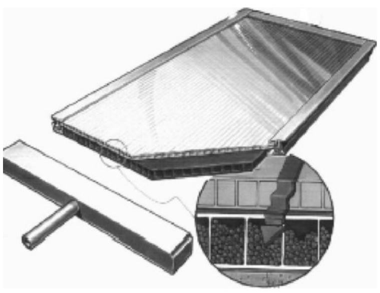
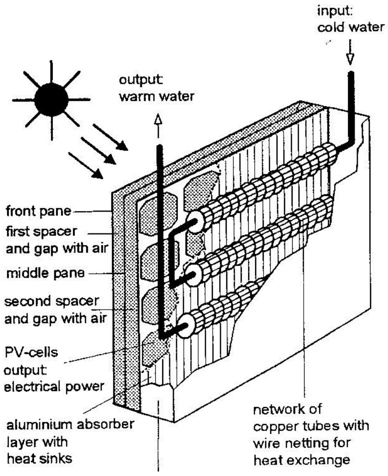
Sandness and Rekstad (2002)





Hausler and Rogash (2000)

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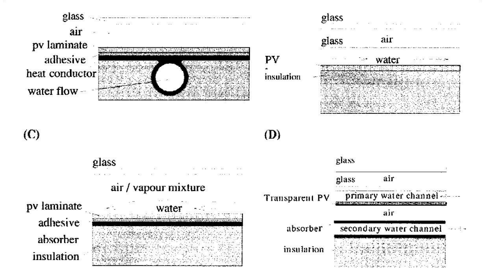
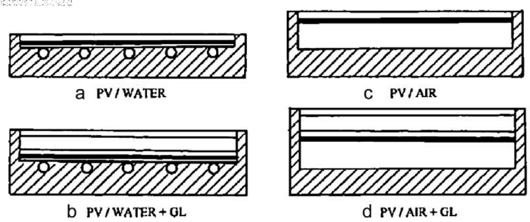


Zondag et al (2002)



Tripanagnostopoulos et al (2002)

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History of PV/T (2nd period 2000-2015)

Following, among other works are: PV/T modelling by Chow (2003), Ji et al (2003), Notton et al (2005), PV/T-water prototypes by Busato et al (2008), domestic PV/T systems by Coventry and Lovegrove (2003) and performance/cost results of a roof PV/T system by Bakker et al (2005).

In addition, there are: the theoretical approach for domestic heating and cooling with PV/T collectors by Vokas et al (2006), performance evaluation by Tiwari and Sodha (2006), floor heating by Fraisse et al (2007) and heat pump PV/T by Fang et al (2010).

Works on thermosiphonic PV/T systems have been performed by Kalogirou (2001), Chow and He (2006), Kalogirou & Tripanagnostopoulos (2006).

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History of PV/T (2nd period 2000-2015)

Works on ventilated building PV facades were also performed by Guiavarch and Peuportier (2006), Charron and Athienitis, (2006) and Brinkworth and Sandberg (2006). Some studies on improved PV/T-air collectors were published by Tonui and Tripanagnostopoulos (2007, 2008), a detailed study using CFD methodology for air cooled photovoltaics was presented by Gan (2009) and the performance of a building integrated PV/T collector was published by Anderson et al (2009).

The energy performance for three PV/T configurations for a house (Pantic et al, 2010) gives interesting information and the effective use of PV/T-air collectors for buildings with life cycle cost analysis (Agrawal and Tiwari, 2010), shows the difference in using c-Si and a-Si PV modules to buildings.

Last years, the works of Mazon et al (2011), Dupeyrat et al (2011, 2014), Ibrahim et al (2011), Ciulla et al (2012), J.H Kim and J.T. Kim (2012), Aste et al (2012, 2014), Helmers and Kramer (2013), Kramer and Helmers (2013), Fortuin et al (2014), Touafek et al (2014) and also Matuska (2014) could be referred.

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History of PV/T (concentrating PV/T)

PV modules should be kept at low temperatures to result satisfactory electrical efficiencies. This requirement limits PV/T effective operation to low temperatures, although temperatures up to 60 °C - 70 °C can be achieved.

To obtain effective fluid temperature at higher level, PV/T collectors with lower thermal losses for higher thermal efficiency or CPV/T collectors, could be used. CPV/T collectors are of flat, CPC, PTC and Fresnel type reflectors or lenses.

In CPV/T systems PV cooling is needed because the absorbed concentrated radiation results to higher cell temperatures. In that case the circulating heat removal fluid can be heated to a considerable temperature level for practical applications.

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History of PV/T (concentrating PV/T)

Regarding dielectric lens-type concentrators, optical results show that for 3D static acrylic lens concentrators, a reduction of 62% in cell surface is achieved (Yoshioka et al, 1997, Zacharopoulos et al., 2000, Shaw and Wenham, 2000).

In medium concentration photovoltaics, 2D concentrators have been applied, with most known being the Eucledes system (Luque et al, 1998), consisted of a parabolic trough reflector and flat type absorber of PV cell strips on focal line.

In the 3D CPV systems, the Fresnel lenses is the majority of the used concentrating optical media with less applied the concentrators of reflector type (Ries et al., 1997, Rumyantsev et al., 2000, Lorenzo and Sala, 1979, O'Neil et al., 2000, Bottenberg et al., 2000, Kritchman et al, 1979).

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History of PV/T (concentrating PV/T)

Concentrating photovoltaics are more sensitive than thermal collectors to the density of solar radiation on the absorber surface and a homogenous radiation distribution is necessary, to avoid reduction of the electrical output from the cells.

Flat or CPC type reflectors combined with PV/T collectors have been proposed by Garg and Adhikari (1999), Brogren et al (2000, 2002), Karlsson et al (2001), Tripanagnostopoulos et al (2002), Othman et al (2005), Mallick et al (2007), Nilsson et al (2007), Robles-Ocampo et al (2007) and Kostic et al (2010).

Works on CPV/T systems with linear parabolic reflectors are by Coventry (2005), linear Fresnel reflectors by Rossel et al (2005), compound reflectors by Tyukhov et al (2009), linear Fresnel lenses by Tripanagnostopoulos et al (2006), by Chemisana and Ibanez (2010) and point focus paraboloidal dish reflector by Helmers and Kramer (2013).

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History of PV/T (LCA and economic studies)

Economic aspects on PV/T systems are given by Leenders et al (2000), while the environmental impact of PV modules by using the Life Cycle Assessment (LCA) methodology has been extensively used at University of Rome "La Sapienza". Frankl et al (2002) presented LCA results on the comparison of PV/T systems with standard PV and thermal systems, confirming the environmental advantage of PV/T systems.

LCA results for PV/T collectors (Tripanagnostopoulos et al, 2005, 2006) are compared with standard PV modules for the positive environmental impact for low temperature heating of water or air PV/T collectors.

The application of PV/T systems in the industry is suggested as a viable solution for wider use of solar energy systems (Battisti and Tripanagnostopoulos, 2005).

History of PV/T (use in industry and agriculture)

Some other works on PV/T systems are referred to TRNSYS results (Kalogirou and Tripanagnostopoulos, 2007) and to the PV/T absorbers with linear Fresnel lenses, for integration on building atria or greenhouses, aiming to achieve solar control in illumination and temperature of the interior space, providing also electricity and heat (Tripanagnostopoulos et al, 2007).

New designs of PV/T devices were suggested for heating of water and air (Tripanagnostopoulos, 2007, Assoa et al, 2007), some others to be coupled with heat pumps (Jie et al, 2008), to achieve cost effective desiccant cooling (Beccali et al, 2009) and to agricultural applications (Garg et al, 1991, Sopian et al, 2000, Othman et al , 2006, Rocamora and Tripanagnostopoulos, 2006, Nayak and Tiwari, 2008 and Kumar and Tiwari, 2010).

History of PV/T (commercial models)

Commercial PV/T collectors are few and the market is still at the ground level. For concentrating PV/T collectors, some steps have been done for operation at higher temperatures and some commercial CPV/T collectors have been introduced in the market.

The first commercial PV/T model, which has been introduced in the market was the Multi Solar System (MSS) from Millenium Electric, which is a flat type PV/T collector for water and air heating.

Other commercial flat type PV/T collectors are Twinsolar (Grammer), Solar, SolarVenti (Aidt Miljo), TIS (Secco Sistemi), SolarDuct (SolarWall), PVTWIN, SES, Solimpeks, Solarhybrid, etc.

Concentrating PV/T collectors (CPVT), are products of Heliodynamics, Arontis (Absolicon), Power-Spar, ZenithSolar, Cogenra, Menova, etc.

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PVT/WATER collectors

Multi Solar System, MSS Millenium Electric, Israel

ΤΕΣ PV/T SOLAR WATER HEATING SYSTEM

CPC Hybrid PV/T – WATER solar collectors

RenOn : PV cells attached on thermal absorber

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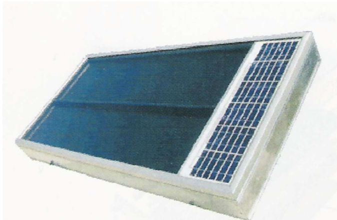
PVT/AIR collectors



Twinsolar (Grammer)

SolarWall

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Absolicon

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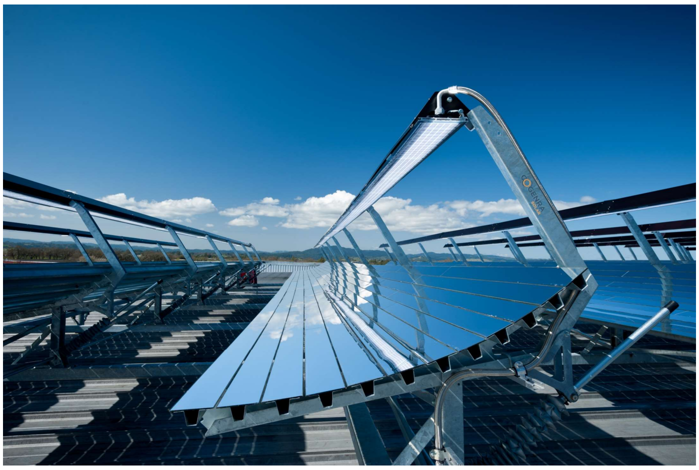

cogenra

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Design aspects of PV/T

In PV/T, the cost of the thermal unit is the same irrespective if the PV module is c-Si, pc-Si or a-Si. Thus the relative cost of the thermal unit per PV area cost is different and almost double for a-Si compared to c-Si or pc-Si PV modules.

The complete PV/T systems include the necessary additional components (BOS, for the electricity and the BOS for the heat) and therefore the final energy output is reduced due to the electrical and thermal losses from one part to the other.

Aiming to establish criteria for PV/T collector standards and certification, Kramer and Helmers (2013) have recently introduced basic aspects. In addition, the study of Dupeyrat et al (2014) gives interesting results for a new PV/T collector design.

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Design aspects of PV/T

PV/T collectors can adapt energy load with limitations in availability of external building surface, as for zero energy buildings. Aelenei and Goncalves (2014), give a figure of PV/T application to the achievement of zero energy buildings.

Regarding the thermal part of PV/T collectors, the active efficiency is less than that of the typical solar thermal collectors, because the suppression of thermal losses has limitations regarding the electrical part of the PV/T collector.

The PV/T systems that use typical PV modules and provide heat above 80° C have lamination problems, due to the high operating temperatures and need further development.

Some improvements in PV module encapsulation and construction, aiming to swift thermal insulation and suffer operating temperatures higher than 80° C, have been recently presented by Fortuin et al (2014).

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Design aspects of PV/T

The prediction of the operating temperature of PV module is complicated and several formulas have been suggested (Lasnier and Ang, 1990, Skoplaki et al 2008, Skoplaki and Palyvos, 2009, Tripanagnostopoulos et al, 2005, 2006).

An additional cover to PV modules increases PV/T thermal performance, but decreases electrical output, because of the absorbed and reflected away solar radiation and the electrical efficiency reduction due to higher temperature.

In façade/tilted roof mounted PV/T systems the thermal protection increases system thermal efficiency, but the lower thermal losses keep PV temperature at higher level, reducing electrical efficiency. For effective BIPV cooling of PVT collectors, passive cooling with PCM can be used (Aelenei et al, 2014).

Among PV/T review papers are the works of Charalambous et al (2007), Zondag (2008), Chow (2010), Tripanagnostopoulos (2012) and Ibrahim et al, 2011 and the material on PV/T collectors in the web-site of IEA-SHC/Task 35 (2005).

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Design aspects of PV/T

The flat type PV/T solar systems can be used in the domestic and in the industrial sectors, mainly for preheating water or air and to feed Heat Pumps with electricity and heat, to increase their COP.

In PV/T-air systems, ambient air is directly heated by PV panels, while in the PV/T-water systems, the thermal contact is through a heat exchanger.

PV/T solar collectors integrated on building roofs and facades can replace separate thermal collectors and photovoltaics.

These new solar devices can be used to residential buildings, hotels, hospitals and other buildings, to cover agricultural and industrial energy demand and also to provide simultaneously electricity and heat in several other sectors.

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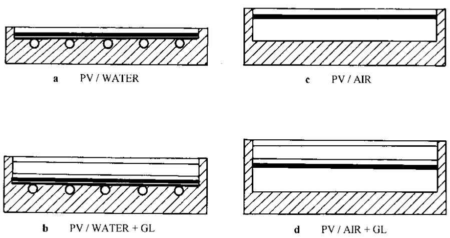
Design aspects of PV/T



(Tripanagnostopoulos et al, 2002)

To increase system operating temperature, an additional glazing is used, but it decreases the absorbed solar radiation and therefore PV module electrical output, because the incoming solar radiation is reduced due to absorption by the glazing and reflection from it, depending on the angle of incidence.

For water heat extraction, the water can circulate through pipes in contact with a flat sheet, placed in thermal contact with PV module rear surface.

In PV/T systems the thermal unit, the necessary fan or pump and the external ducts or pipes for fluid circulation constitute the complete system.

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Design aspects of PV/T

In most industrial processes, electricity for the operation of motors and other machines and heat for water, air or other fluid heating and for physical or chemical processes, are necessary.

This makes hybrid PV/T systems promising devices for an extended use adapting industrial applications (washing, cleaning, pasteurizing, sterilizing, drying, boiling, distillation, polymerization, etc).

In the agricultural sector, typical form or new designs of PV/T collectors can be used as transparent cover of greenhouses and applied for drying and desalination processes, providing the required heat and electricity.

Hybrid PV/T systems can be also applied to buildings combined with geothermal, biomass or wind energy. In combination with photovoltaics, small wind turbines can provide also electricity and cover effectively the load.

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Design aspects of PV/T

The combination of concentration devices with PV modules is a viable method to reduce system cost, replacing the expensive cells with a cheaper solar radiation concentrating system to achieve higher efficiencies at effective PV temperatures.

The concentrating PV/T systems (CPVT) use reflective (mirrors) and refractive (lenses) optical devices and are characterized by their concentration ratio C (or CR). Concentrating PV/T (CPVT) systems consist of tracking flat reflectors, parabolic trough reflectors, Fresnel lenses and dish type reflectors, combined with PV/T receivers.

CPVT systems with medium or high CR values require PV modules that suffer temperatures up to 150 °C or more, to produce steam, or to adapt processes in higher temperatures .

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Design aspects of PV/T

Life Cycle Assessment (LCA) methodology and cost analysis for typical PV and PV/T systems confirm their environmental advantage compared to standard PV modules (Tripanagnostopoulos et al, 2005, 2006).

TRNSYS methodology and other modeling methods can be used, to get a clear idea about practical aspects, including their cost effectiveness (Kalogirou, 2001).

PVT Roadmap (2006), the European guide for the development and market introduction of PV-Thermal technology, is a basic brochure that provides information for this solar technology.

Task 35 of the International Energy Agency (IEA-SHC/Task35) has performed studies on the technology and application of PV/T systems.

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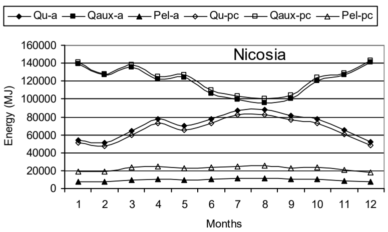
Design aspects of PV/T

A TRNSYS simulation for industrial process heat of 60° C and 80° C of PV/T collectors, is the work of Kalogirou and Tripanagnostopoulos (2007), applying pc-Si and a-Si PV panels.

The electrical production of pc-Si PV panels is more than a-Si PV panels, but the solar thermal contribution is lower.

A non-hybrid PV system produces about 25% more electrical energy but the present system covers also a large percentage of the thermal energy of the industry considered.

Although a-Si PV modules are much less efficient than pc-Si PV modules, they give better economic figures due to their lower initial cost, thus they have better cost/benefit ratio.



Monthly useful, auxiliary and electrical energy of the 80° C load temperature industrial process heat system for Nicosia. (Kalogirou and Tripanagnostopoulos, 2007)

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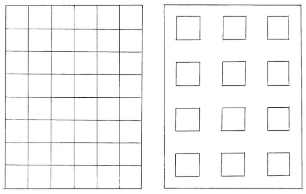
Design aspects of PV/T

Convectional PV/T solar collectors usually consist of two parts, the solar radiation absorbers and the heat extraction units.

The fraction of absorber plate area covered by PV cells is given in terms of cells packing factor, *PF*. The *PF* is defined as the fraction of the area occupied by the cells to the total module surface area.

In partially filled PV/T systems, the spaces between rows of cells allow incident solar radiation to pass through and get absorbed directly by the secondary absorber plate (Aste et al, 2003).



packing factor (PF) of pasted cells (100% left, 25% right).

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Design aspects of PV/T

The PF in PV/T systems is selected either for electrical load (electrical priority operation, EPO) or thermal load (thermal priority operations, TPO) (Fujisawa and Tani 1997).

The EPO has higher packing factor ($PF \geq 0.7$), hence the electrical power is optimized while the TPO has lower packing factor hence optimized for thermal production.

PV cells are of higher cost compared to other PV/T components and thus a priority is given to the electrical power.

TPO is affected by the direct absorption of solar radiation that passes through inter-cells spacing and increases the heat extraction from the back of cells. Thus, *PF* determines the ratio of electricity to heat and characterizes the practical use of PV/T modules.

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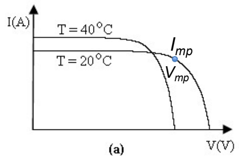
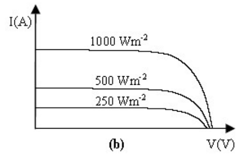
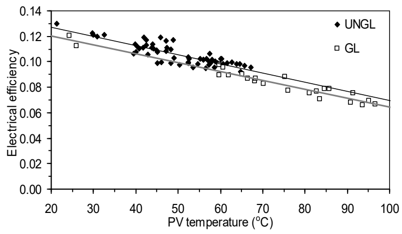
PV/T energy performance

V_{oc}, open circuit voltage
I_{sc}, short circuit current
V_{mp} maximum voltage
I_{mp} maximum current
MPP: maximum power: $P_{max} = I_{mp} * V_{mp}$
Incident solar radiation: $Pin = Ir * A\ a$
Fill factor, $FF= (I_{mp} * V_{mp})/ (I_{sc} * V_{mp})$
Electrical efficiency: $\eta el = P_{max}/ Pin$
Thermal efficiency: $\eta th = Q_u / Qin$
$Qu = mCp(To-Ti)$
$Qin= Ir*Aa$
electrical efficiency $n_{el} = P_{max} / Pin$
thermal efficiency $n_{th} = Qu/Qin$
total conversion efficiency
n_t: $n_t = n_{el} + n_{th}$







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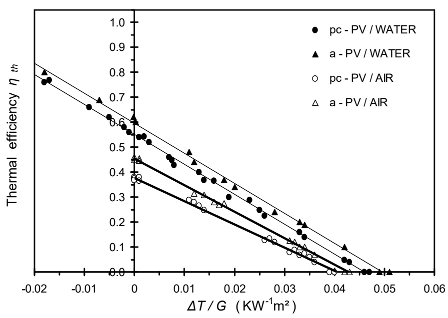
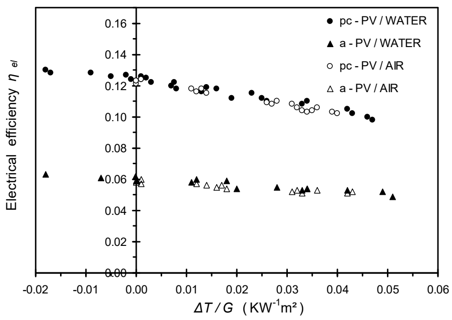
PV/T energy performance





(Tripanagnostopoulos et al, 2002)

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PV/T energy performance

Formula to calculate pc-Si and c-Si PV module temperature as function of ambient temperature T_a and solar radiation G (Lasnier and Ang, 1990):

T_{PV}**=30+0.0175(G-300)+1.14(**T_a**-25)**

Formula for a-Si PV modules, as their lower electrical efficiency results to slightly higher PV module temperature compared to pc-Si PV modules.

T_{PV}**=30+0.0175(G-150)+1.14(**T_a**-25)**

In PV/T systems PV temperature depends also on the system operating conditions and mainly on heat extraction fluid mean temperature. PV electrical efficiency η_{el} can be function of $(T_{PV})_{eff}$, which corresponds to the PV temperature for the operating conditions of PV/T systems.

$(T_{PV})_{eff}=T_{PV}+(T_{PV/T}-T_a)$

The operating temperature $T_{PV/T}$ of PV/T system corresponds to PV module and to thermal unit temperatures and can be determined approximately by the mean fluid temperature. This modified formula corresponds to the increase of PV operating temperature due to the reduced heat losses to the ambient.

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PV/T-WATER systems

$$Q_s = Q_u + Q_L + Q_{OL} + Q_{el}$$

$$Q_s = A_{pv} G$$

$$Q_u = n_{th} A_{pv} G$$

$$Q_{OL} = (1-(\tau\alpha))A_{pv} G$$

$$Q_{el} = n_{el} A_{pv} G$$

$$\eta_{th} = \dot{m} c_p (T_o - T_i) / A_\alpha G$$

$$\Delta T / G \qquad \Delta T = T_i - T_\alpha$$

$$\eta_{el} = I_m V_m / A_\alpha G$$

$$U_L = U_t + U_b + U_e$$

$$\overline{U}_L = U_L - \tau\alpha\eta_{ref}\beta_{ref} G$$

$$\eta_{el} = \eta_{ref}\left(1 - \beta_{ref}(T_{pv} - T_{ref})\right)$$

$$n_{th} = \frac{Q_u}{A_c G}$$

$$Q_u = A_c \left[S - U_L \left(T_{p,m} - T_a \right) \right]$$

$$Q_u = A_c F_R \left[S - U_L \left(T_i - T_a \right) \right]$$

The steady state efficiency modified by Florschuetz (1979) for PV/T collectors

$$n_{th} = \overline{F_R}\left[\tau\alpha\left(1 - n_{pv}\right) - \overline{U_L}\left(\frac{T_{wi} - T_a}{G}\right)\right] = \frac{mC_p\left(T_{wo} - T_{wi}\right)}{A_c G}$$

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PV/T –AIR systems

For the PV/T-air collector, efficiency factor F is calculated from the modified equation from Duffie and Beckman (1991):

$$\bar{F}' = \left[1 + \frac{\bar{U}_L (h_c + h_r)}{h_c^2 + 2h_c h_r}\right]^{-1}$$

where h_c and h_r are the convective and radiative heat transfer coefficients in the air duct. The relationship to determine heat removal efficiency F is given by Florschuetz (1979) as:

$$\bar{F}_R = \frac{\dot{m} C_p}{A_{pv} \bar{U}_L}\left[1 - \exp\left(-\frac{A_{pv} \bar{U}_L \bar{F}'}{\dot{m} C_p}\right)\right]$$

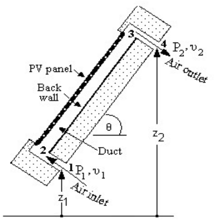
where $\boldsymbol{m}$ and $\boldsymbol{C_p}$ are air flow rate and specific heat capacity of air. The steady-state thermal efficiency of the PV/T-air collector is calculated from the measured data from:

$$\eta_{th} = \frac{\dot{m} C_p (T_{out} - T_{in})}{A_a G}$$

The forced convection heat transfer coefficient in the air channel is assumed constant for all channel walls . In case of short length PV/T modules (≈ 1 m), the correlation of Tan and Charters (1969) can be used (which includes the effect of thermal entrance length of the air duct) to compute Nusselt number hence forced convection heat-transfer coefficient. Reynolds number Re and hydraulic diameter are determined from their usual expressions and Prandtl number Pr is usually 0.7 for air.

PV/T –AIR systems

The pressure drop is derived by applying Bernoulli's law and energy equation (with assumptions of Esposito, 1998). For forced flow, the driving force is provided by the pump which does some work by pushing air through the pump head H_p.



(Tonui and Tripanagnostopoulos, 2007, 2008)

The opposing forces are represented by the total head loss H_L which includes major losses due to friction between channel walls and air stream represented by friction head H_f and the minor losses caused by any obstruction that hinders smooth flow of air from inlet to outlet, evaluated as the product of loss coefficient k_i and available velocity head. The head loss is then given as the sum of major and minor losses:

$$H_p = H_L = H_f + \sum_i k_i \frac{\upsilon^2}{2g}$$

The loss coefficients k_i for PV/T-air collector include the effect of entrance, exit and the two 90° turns inside the channels and loss coefficients at these four places give the total loss coefficient k (Young et al ,1997). The major head loss H_f is determined from the Darcy-Weisbach equation (Esposito, 1998):

$$f = 64\mathrm{Re}^{-1} \quad \text{Laminar flow}$$

$$f = 0.316\mathrm{Re}^{-0.25} \quad \text{Turbulent flow}$$

$$H_f = \frac{\upsilon^2}{2g} f\left(\frac{L}{D_H}\right)$$

The pressure drop ΔP is

$$\Delta P = g\rho H_P$$

The electrical power required also depends on the fan efficiency η_{fan} and the motor efficiency η_{motor} and the power required P is given by:

$$P = \frac{\dot{m}\Delta P}{\rho} = \frac{\dot{m}\Delta P}{\rho \eta_{fan} \eta_{motor}}$$

PV/T –AIR systems

The expression for the induced air flow rate by natural convection in steady-state analysis is based on Bernoulli's equation from inlet (location 1) to outlet (location 4) of the airflow channel

$$P_1 + \frac{\rho_1 \upsilon_1^2}{2} + \rho_1 g z_1 - \frac{fL}{D_H}\frac{\upsilon^2}{2} - k_1 \frac{\rho_1 \upsilon_1^2}{2} - (k_2 + k_3)\frac{\rho \upsilon^2}{2} = P_2 + \frac{\rho_2 \upsilon_2^2}{2} +$$

$$\rho_2 g z_2 + k_4 \frac{\rho_2 \upsilon_2^2}{2}$$

Considering simplifying assumptions both vents at inlet (1) and outlet (2) are open to the atmosphere hence $P_1 = P_2$ and inlet ambient air is considered as an infinite reservoir with negligible velocity, hence ≈ 0, (Esposito, 1998). Considering these assumptions, the above equation is reduced to:

$$\rho_1 g z_1 - \rho_2 g z_2 = \frac{\rho_2 \upsilon_2^2}{2} + \frac{fL}{D_H}\frac{\rho \upsilon^2}{2} + (k_2 + k_3)\frac{\rho \upsilon^2}{2} + k_4 \frac{\rho_2 \upsilon_2^2}{2}$$

The buoyancy term is derived for one-dimensional "fictitious loop analysis" for naturally ventilated buildings (Ibarahim et al, 1999, Brinkworth et al, 2000) and using the expression for buoyancy term from these references it becomes:

$$(\rho_1 - \rho_2) g L \sin\theta = \frac{\rho_2 \upsilon_2^2}{2} + \frac{fL}{D_H}\frac{\rho \upsilon^2}{2} + (k_2 + k_3)\frac{\rho \upsilon^2}{2} + k_4 \frac{\rho_2 \upsilon_2^2}{2}$$

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PV/T –AIR systems

The parameter D_H is the hydraulic diameter of the air duct and equals four times the cross-sectional area of the duct divided by the wetted perimeter. The continuity equation and the simplified relationship between temperature and density (Boussinesq approximation) are given respectively by:

$$\dot{m} = \rho A_{ch} \upsilon = \rho_2 A_2 \upsilon_2 \qquad \rho_T = \rho \beta T$$

where A_{ch} and A_2 are channel and exit vent areas respectively, is the density of air at any temperature T and $\beta = 1/T_f$, with $T_f = (T_{in} + T_{out})/2$.

$$\beta L g \sin\theta (T_{out} - T_{in}) = \frac{\upsilon^2}{2}\left[\frac{fL}{D_H} + \beta T_{out}(1 + k_4)\left(\frac{A_{ch}}{A_2}\right)^2 + (k_2 + k_3)\right]$$

$$\upsilon^2 = 2 g \beta L \sin\theta (T_{out} - T_{in})\left[2.2 + \frac{fL}{D_H} + 2\beta T_{out}\left(\frac{A_{ch}}{A_2}\right)^2\right]^{-1}$$

$$Q_u = \dot{m} C_p (T_{out} - T_{in}) = \eta_{th} A_{pv} G$$

$$\dot{m}^2 = 2 g \beta L \sin\theta (A_{ch}\rho)^2 (T_{out} - T_{in})\left[2.2 + \frac{fL}{D_H} + 2\beta T_{out}\left(\frac{A_{ch}}{A_2}\right)^2\right]^{-1}$$

$$Gr = \frac{L^3 \rho^2 g \beta \Delta T}{\mu}$$

$$f = 1.906(\mathrm{Gr}/\mathrm{Pr})^{1/12}$$

Laminar flow

$$\dot{m} = \left(\frac{2 g \beta (A_{ch}\rho)^2 A_{pv} \eta_{th} G L \sin\theta}{C_p\left[2.2 + fL/D_H + 2\beta T_{out}(A_{ch}/A_2)^2\right]}\right)^{\frac{1}{3}}$$

$$h_c = \frac{k}{D_H}\mathrm{Nu} \qquad \mathrm{Nu}_L = 1.2\, Ra^{1/3}$$

$$\mathrm{Nu}_L = 0.378\, Ra^{1/4}$$

$$f = 1.368(\mathrm{Gr}/\mathrm{Pr})^{1/11.9}$$

Turbulent flow

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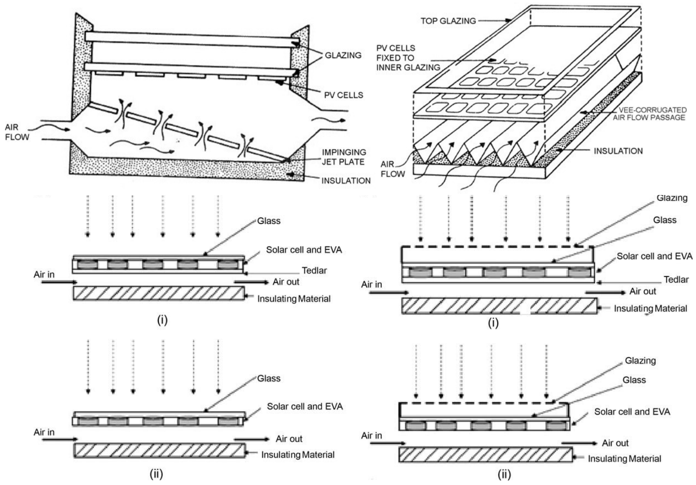
PV/T –AIR systems



(Tiwari and Sodha, 2006)

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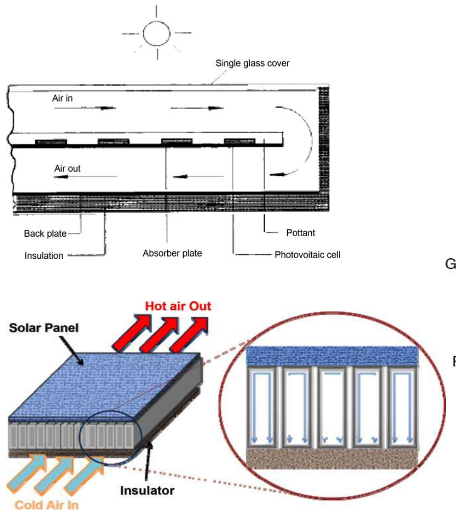

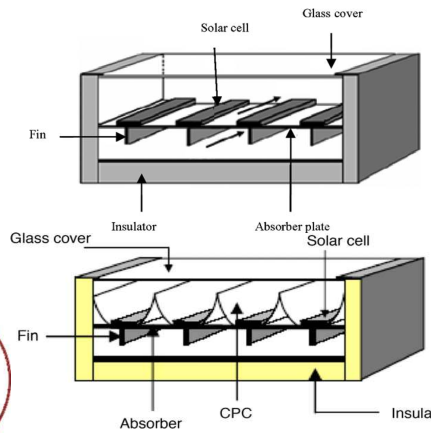

(Othman et al, 2005)

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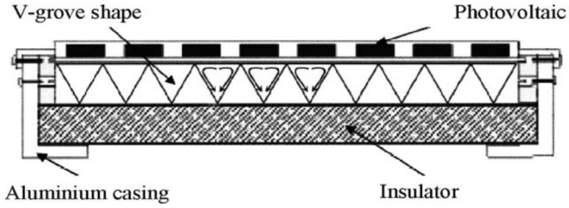

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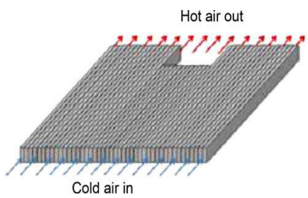

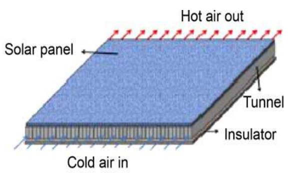

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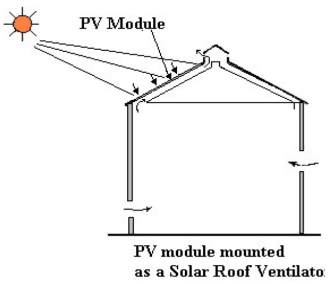

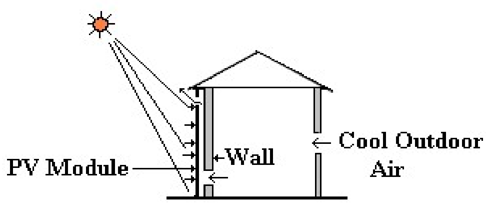

For PV module mounted on the roof, fresh air enters into building through open (or infiltration) windows and doors and achieves natural ventilation. PV modules integrated on the façade with air gap, contribute to effective heat flow of circulating air out of the building. PV/T system can be used as "ventilation driver" for natural ventilation of building creating substantial ventilation rate. TMS "shields'' the back wall from undesirable heat transmission.

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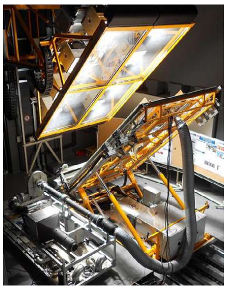
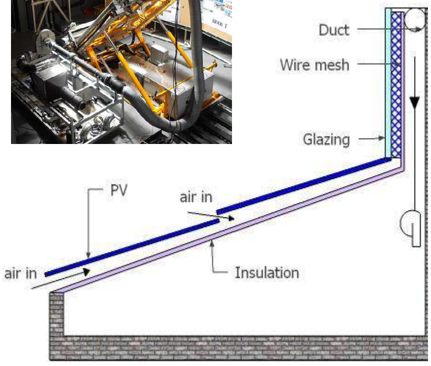
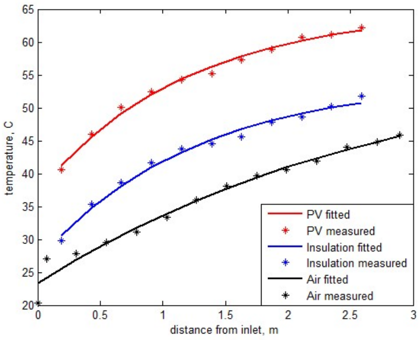
PV/T –AIR systems







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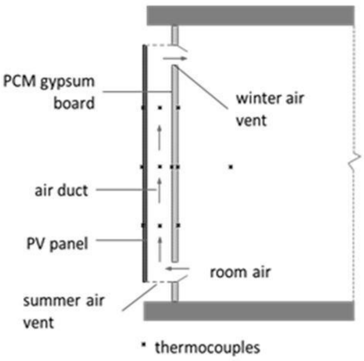

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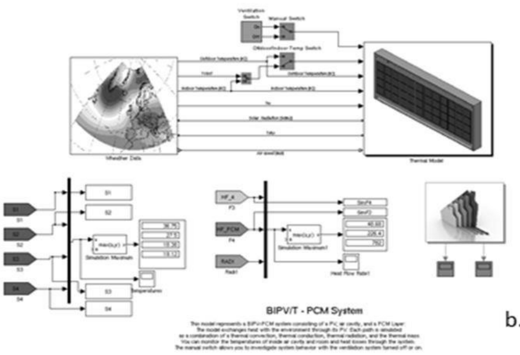

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(Aelenei et al, 2014)

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(Aelenei et al, 2014)



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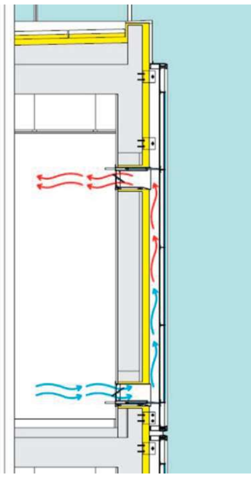
PV/T –AIR systems



(Aelenei et al, 2014)

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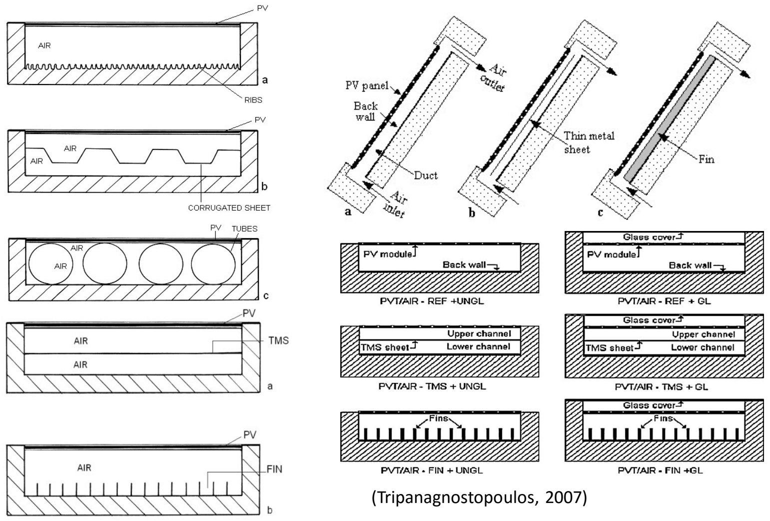
Modified PV/T systems



(Tripanagnostopoulos, 2007)

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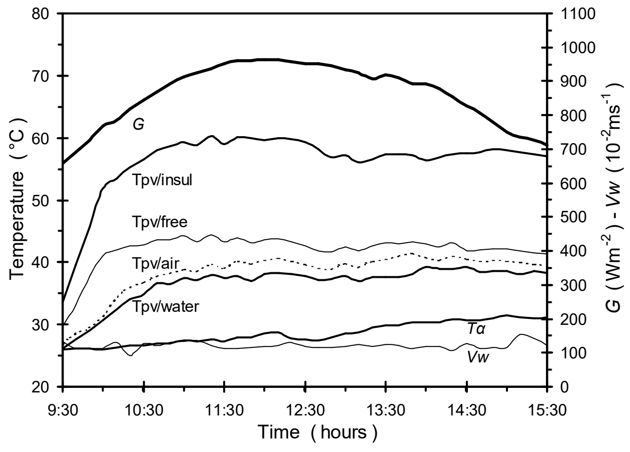
Daily test results of PV and PV/T systems



PVT/water: water cooled PV module

PVT/air: air cooled PV module

PV/free: thermal losses from both PV sides

PV/insul: thermally insulated PV rear side

(Tripanagnostopoulos et al, 2002)

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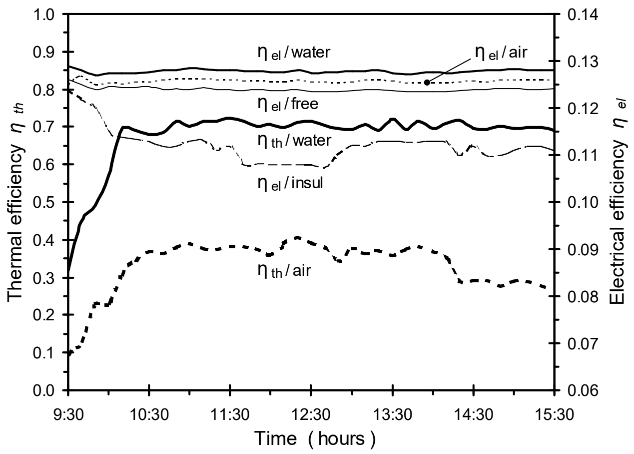

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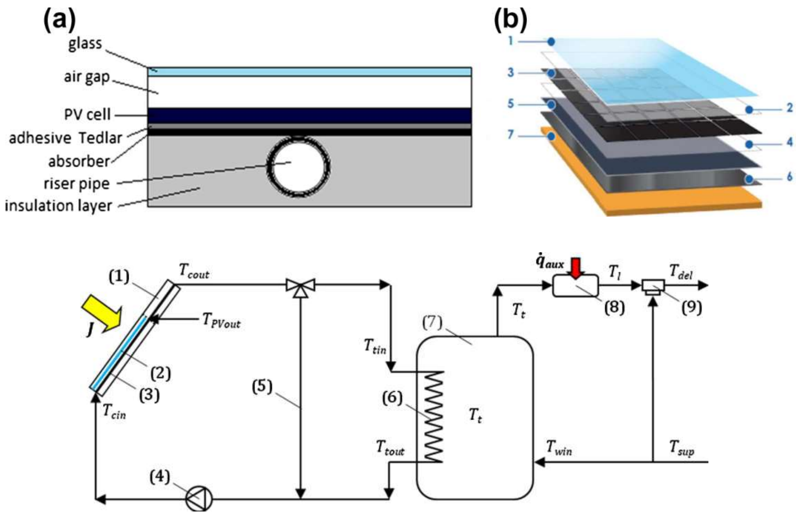
PV/T –WATER systems



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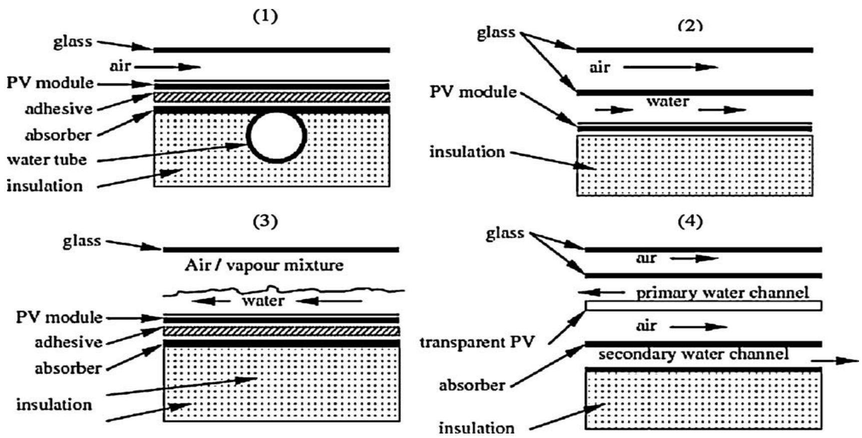
PV/T –WATER systems



(Zondag, 2008)

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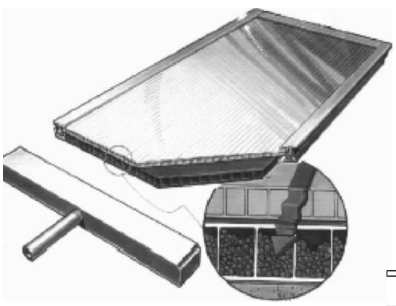
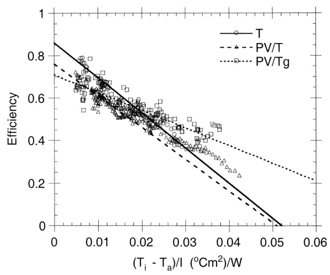
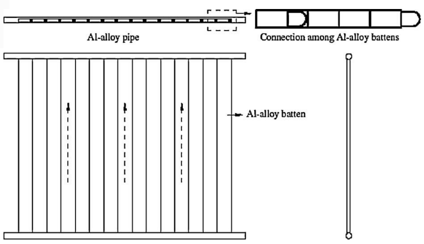
PV/T –WATER systems



(Sadnes and Rekstadt, 2002)





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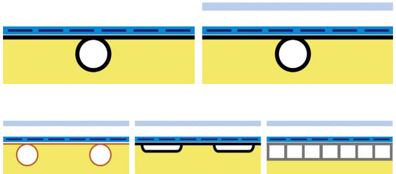
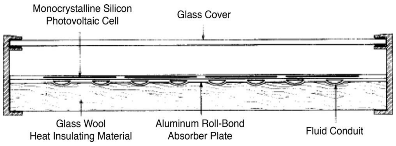


(Aste et al, 2014)



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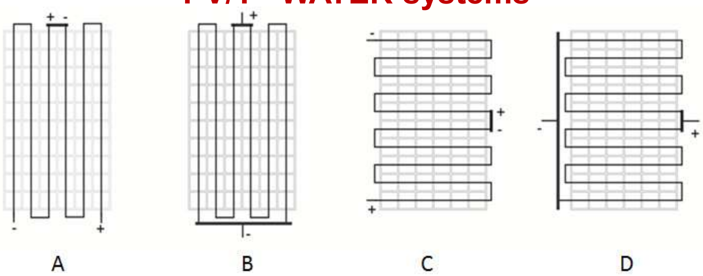
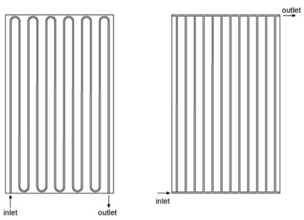
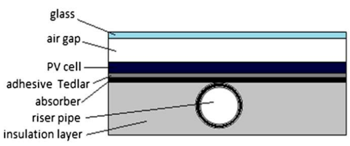
PV/T –WATER systems







(Aste et al, 2014)

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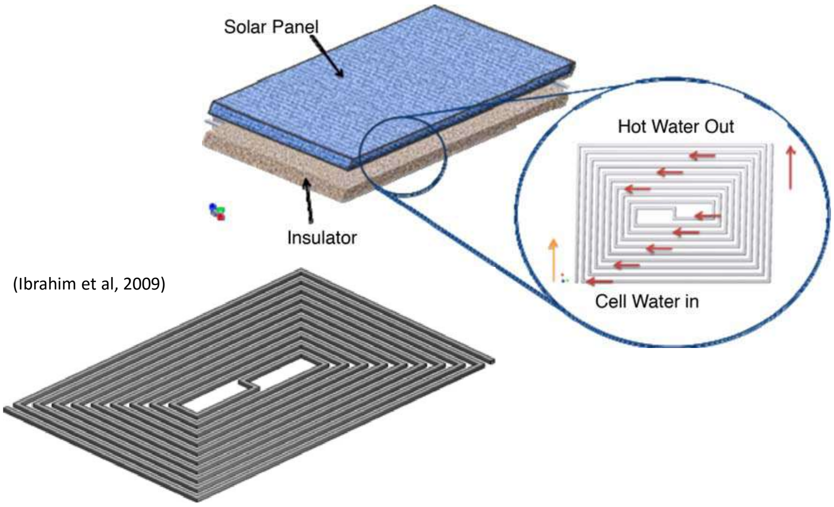
PV/T –WATER systems



(Ibrahim et al, 2009)

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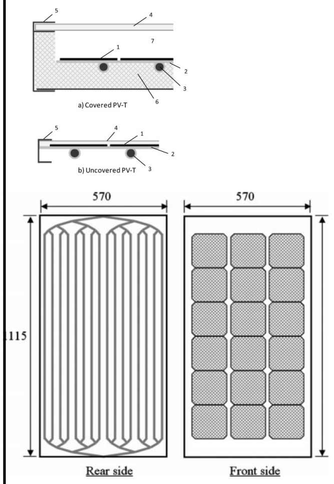
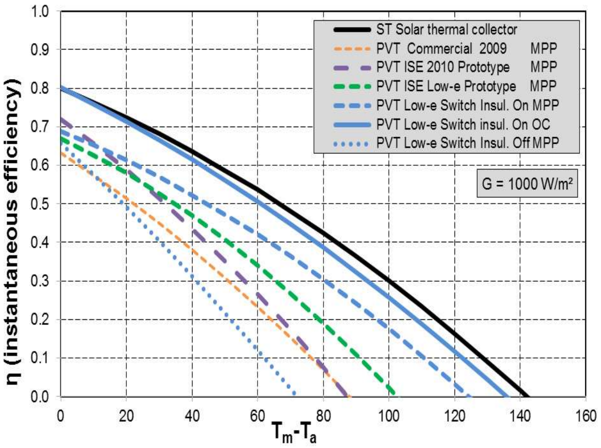
PV/T –WATER systems



(Dupeyrat, 2011, 2014)



(Fortuin et al, 2014)

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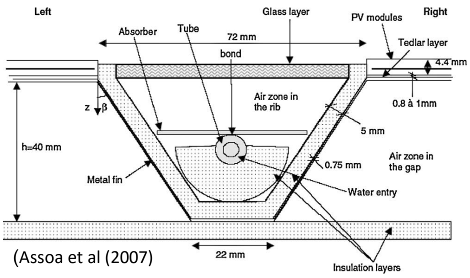
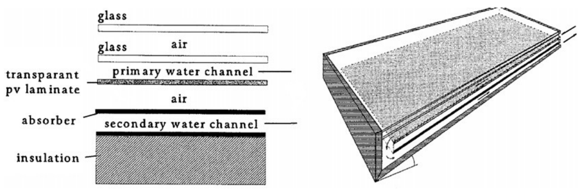
PV/T –WATER +AIR systems

One of the first commercial PV/T collectors (MSS, Millenium Electric) is based on the concept of PVT collector with heat and water heat extraction (Elazari, 1998).
Tripanagnostopoulos (2007) and Assoa et al (2007) suggest such PV/T collectors and give results from tested experimental models.



(Assoa et al (2007)



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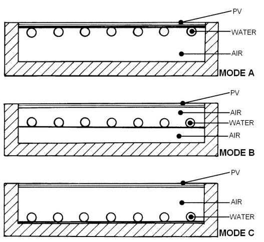
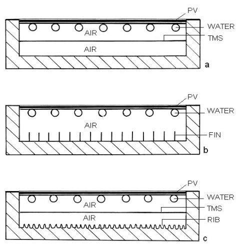
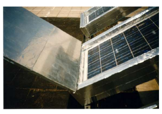
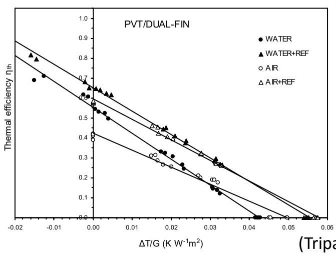
PV/T –WATER +AIR systems

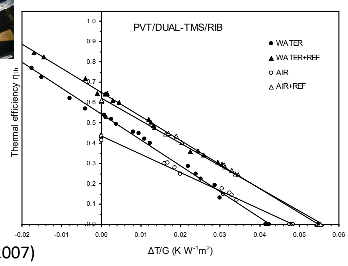


The suggested systems are based on the TMS, FIN and RIB modifications , for the air heat extraction improvements









(Tripanagnostopoulos, 2007)

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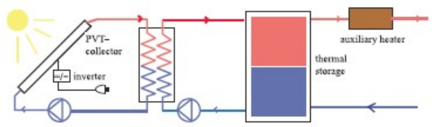
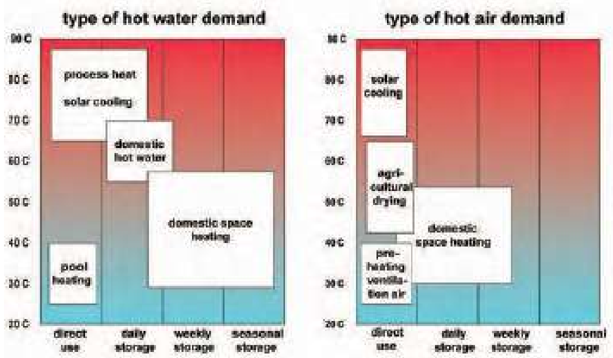
Solar energy system application chart





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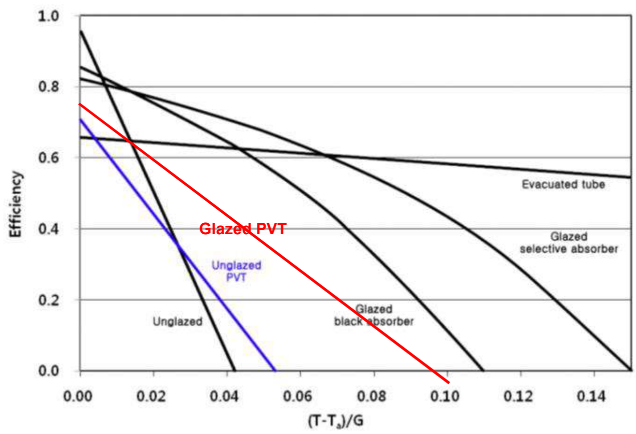
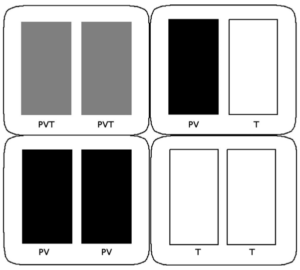
ST and PV/T system performance



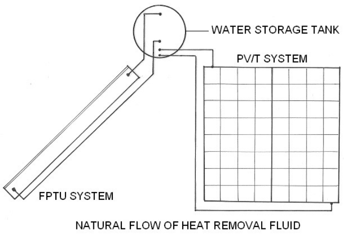
Comparison of thermal efficiency curves of solar thermal and PV/T collectors

PV/T +THERMAL systems

For the optimal use of building roof and façade to obtain heat and electricity from solar energy systems, an effective combination of thermal collectors, photovoltaics and PV/T systems should be applied.



An effective system is the thermal collectors with PV/T collectors connected with the same water storage tank. The PV/T collectors preheat the water and the thermal collector s work for the main heating.



(Tripanagnostopoulos, 2006)

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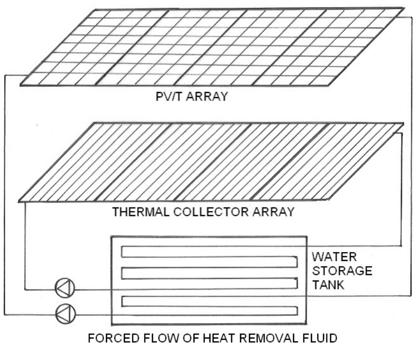
PV/T +THERMAL systems



(Tripanagnostopoulos, 2006)

The suggested PV/T+Thermal collector system can be applied to larger solar energy arrays. Both systems (PV/T and Thermal Collectors) can be connected with the same water storage tank.

In this system the heat from PV/T collectors is transmitted to water storage tank through Heat Exchanger . The HE is placed at the lower part of storage tank to have thermal contact with the cooler water in the tank .

The thermal collectors provide storage tank with heat of higher temperature than PV/T system, as they can operate efficiently at higher temperatures without the existing PV/T thermal limitations.

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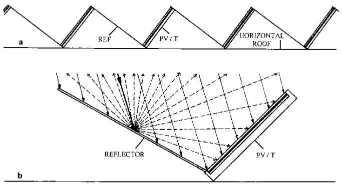
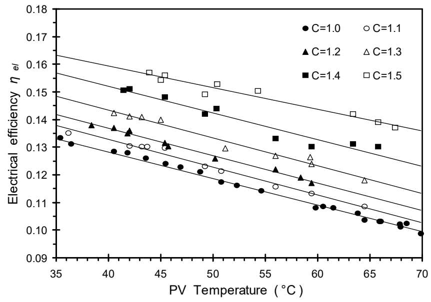
LOW CONCENTRATING PV/T systems



(Tripanagnostopoulos et al, 2002)



Effective use of diffuse booster reflectors to PV and PV/T systems to improve performance (Tripanagnostopoulos et al, 2005, 2006, 2007, Robles-Ocampo et al. 2007, Kostic et al, 2010)

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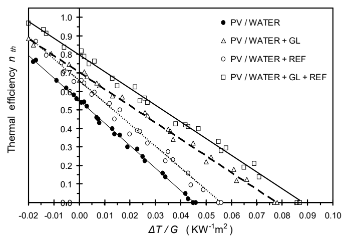
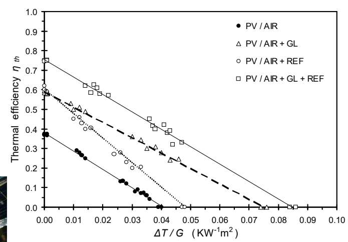
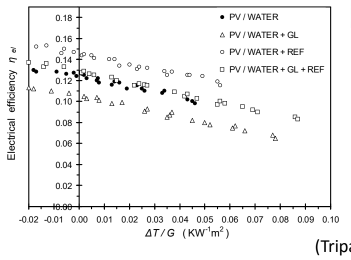
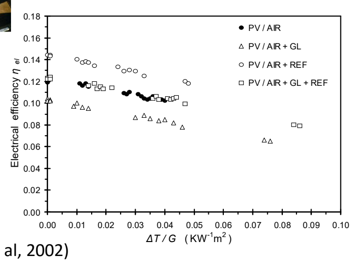
LOW CONCENTRATING PV/T systems









(Tripanagnostopoulos et al, 2002)

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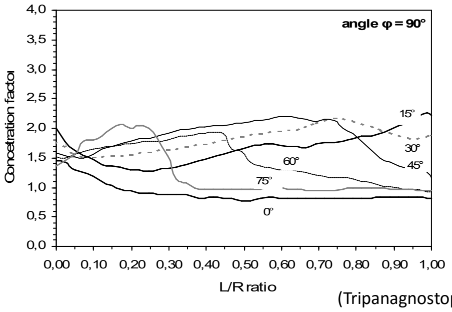
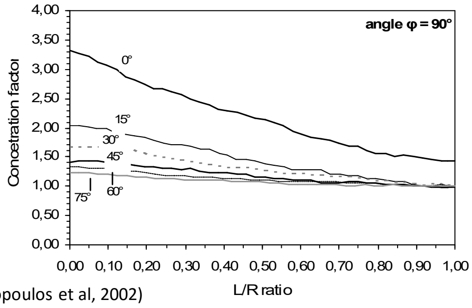
LOW CONCENTRATING PV/T systems

The system concentration ratio factor along PV module, for different reflectors: flat aluminum sheets (left) and white painted sheets (right), as low cost diffuse reflectors.





(Tripanagnostopoulos et al, 2002)

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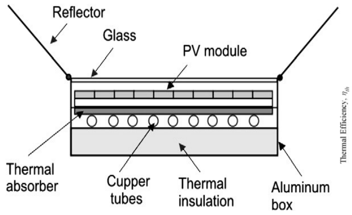
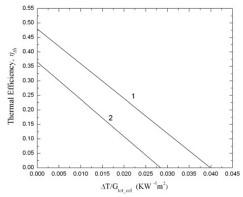
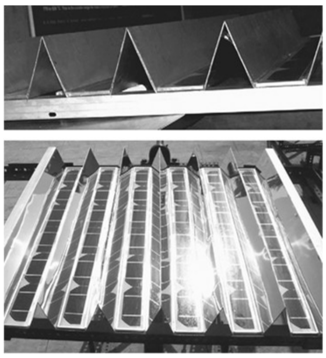
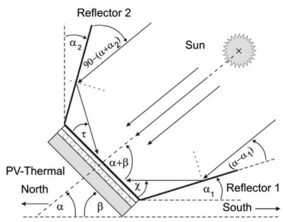
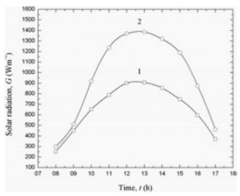


(Kostic et al, 2010)









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LOW CONCENTRATING PV/T systems

Low concentrating
trough CPVT collector

(Coventry, 2006)

High concentrating
dish CPVT collector

(Helmers and Kramer, 2013)

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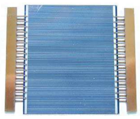
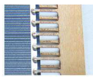
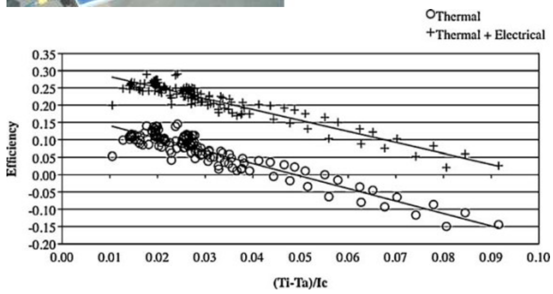
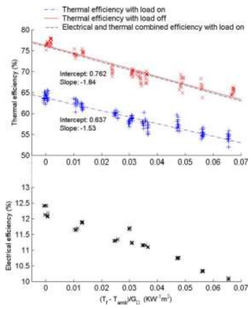
LOW CONCENTRATING PV/T systems





(Coventry, 2006)





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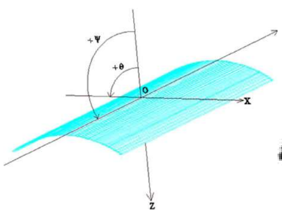

(Chemisana and Ibanez, 2010)

(Rossel et al, 2005)

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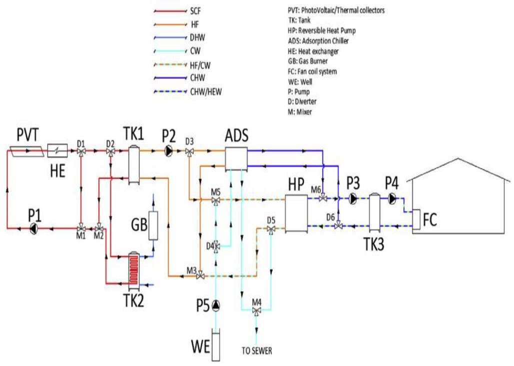
Example of application of PVT

PVT field area 20 [m2]
Reference temperature for PV efficiency 25 [C]
PVT slope 30˚
PVT azimuth 0 ˚
PVT set point temperature (when TK1 is supplied) 30/70 [C]
PVT set point temperature (when TK2 is supplied) 55 [C]
TK1 volume/PVT area 100 [l/m2]
TK1 set point temperature 25/65 [C]
TK2 volume/PVT area 50 [l/m2]
TK2 set point temperature 50 [C]
TK3 volume 1 [m3]
TK3 set point temperature winter 47 [C]
TK3 set point temperature summer 6 [C]
TK1, TK2, TK3 los coefficient 0.278 [W/(m2 C)]
P3 flow 2400 [kg/h]
P4 flow 1500 [kg/h]
P5 flow 3600 [kg/h]
HP rated heating capacity 8 [kW]
HP rated cooling capacity 7 [kW]
Space heating set point temperature 20 [C]
Space cooling set point temperature 26 [C]



From: A novel solar-assisted heat pump driven by photovoltaic/thermal collectors: Dynamic simulation and thermoeconomic optimization. Francesco Calise , Massimo Dentice d'Accadia , Rafal Damian Figaj , Laura Vanoli

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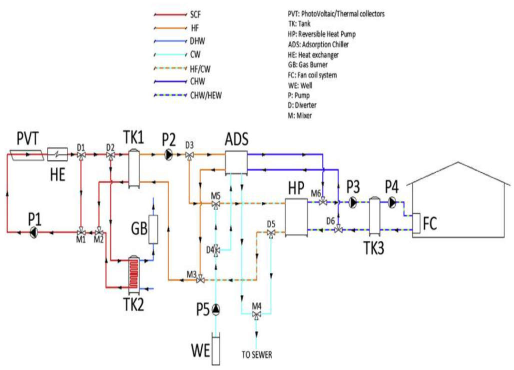
Example of application of PVT

Operation functioning

In winter time the PVT provides the heat to Tank 1(TK1) and Tank 2(TK2). TK1 provides the heat for the evaporator of the heat pump whereas from TK2 comes the heat for the DHW (Domestic hot Water). The heat Pump heats tank 3 (TK3) that feeds the Fan coil for the space heating.

In summer time the PVT provides the heat to Tank 1(TK1) and Tank 2(TK2). From TK1 comes the heat for the adsorpition chiller.
When the power of the adsorpition chiller is not enough we can use the heat pump like auxiliary.
All of this two system cool TK3 that feeds the Fan coil for the space cooling.



From: A novel solar-asisted heat pump driven by photovoltaic/thermal collectors: Dynamic simulation and thermoeconomic optimization.
Francesco Calise , Masimo Dentice d'Accadia , Rafal Damian Figaj , Laura Vanoli

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Study for PV/T and STC application

Suitable application for the use of PV/T systems is a Hotel. We are realizing a solution for an existing hotel in Patras (GR), that already uses the thermal panels for producing DHW.

Total surface of the roof [m2]: 431
Hotel 3* [l/day*person]: 60
Total liters for day of DOMESTIC HOT WATER: 6120
Heat Pump data middle cop= 5,00

PV data
average solar radiation [kWh/day]=5,69
B.O.P. factor balance of system=0,8
η PV=0,12
η th = 0,7
Optimum panel inclination: 33°

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Study for PV/T and STC application

Our idea is to cuple PVT with solar Thermal panels in order to cover all the DHW consumption and to provides a tiny amount of electrical energy to reduce the required from the net.

The balance point between PVT and Thermal panels

(1) to use a heat pump to provide the heat to DHW and to use, in the winter, the heat from the PVT to have an higher COP of the HP;

(2) to use the heat from the PVT for pre-heating the water and thus to use the solar thermal panels to achieve the higher temperatures

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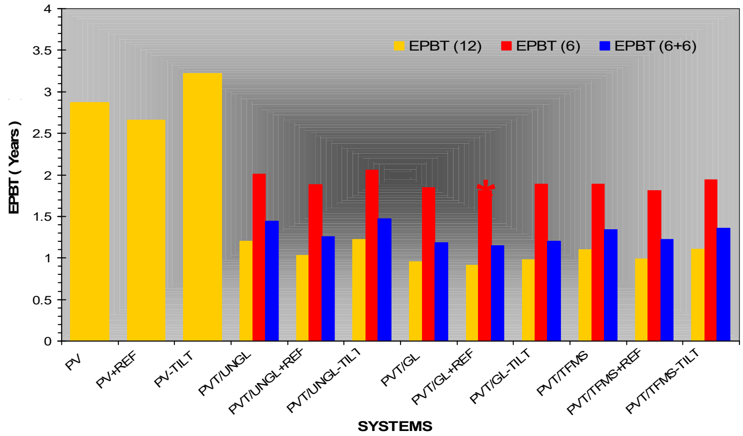
PV/T and PV Energy Pay Back Times



(Tripanagnosatopoulos et al, 2006)

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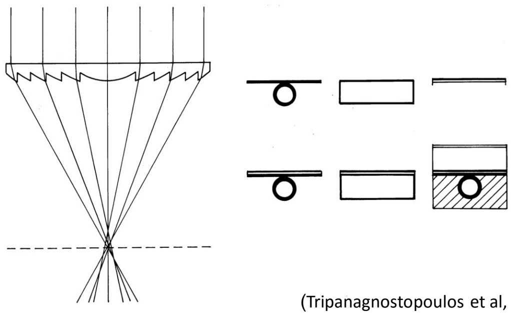
PV/T systems combined with Fresnel lenses

The direct incident solar radiation can be concentrated on an absorber strip, located at the focal position and can be taken away to achieve lower illumination level and also to avoid the overheating of the space.



In low intensity irradiance, the absorber can be out of focus leaving the light to come in the interior space and keep the illumination at an acceptable level.

(Tripanagnostopoulos et al, 2006)

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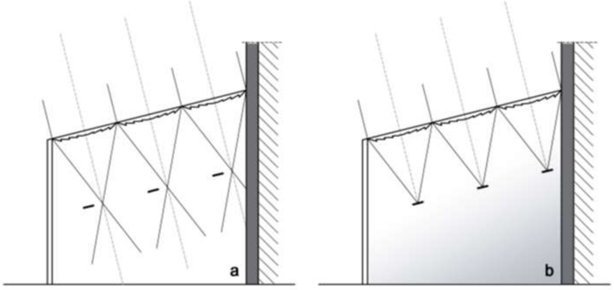
PV/T systems combined with Fresnel lenses



Absorbers out of focus   Absorbers at focus

The combination of Fresnel lenses with linear PV/T absorbers can control the illumination and the temperature of the transparently covered internal spaces of buildings (atria, sunspaces). (Tripanagnostopoulos et al, 2006)

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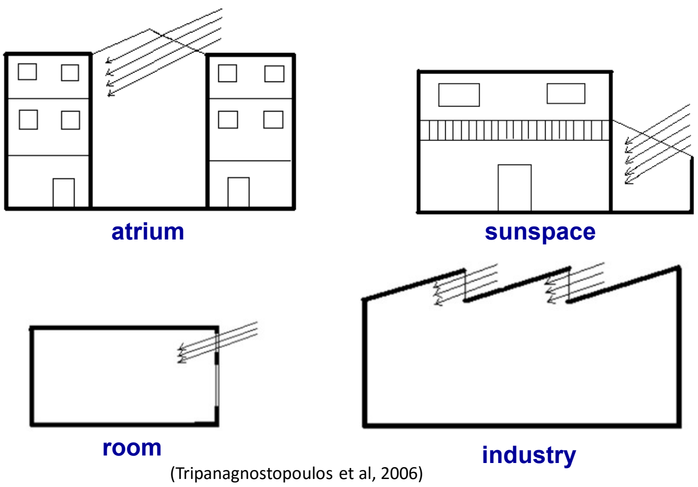
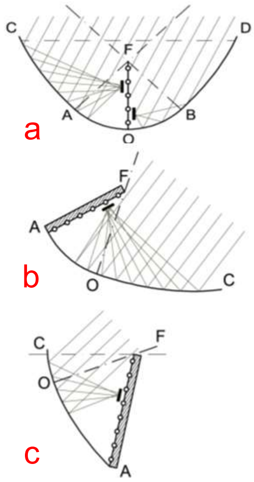
PV/T systems combined with Fresnel lenses



(Tripanagnostopoulos et al, 2006)

CPC reflectors combined with PVT absorbers



Stationary CPC reflectors with flat bifacial absorber is combined with PV strips that track the converged solar radiation and absorb the concentrated solar radiation.

The non-absorbed beam solar radiation and the diffuse solar radiation are absorbed by the secondary flat bifacial thermal absorber.

In asymmetric CPC reflector, the PV strip is moving in front of the thermal absorber, tracking the converged solar radiation.

The parabola axis is directed to: (b) the higher altitude of sun (summer) or to (c) the lower sun altitude (winter).

(Tripanagnostopoulos , 2008)

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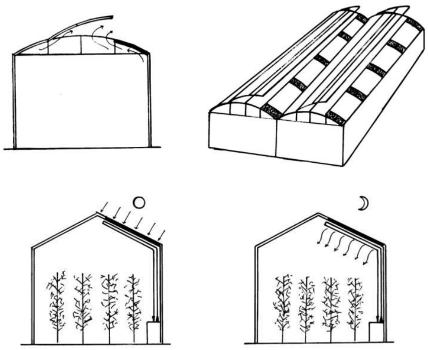
Greenhouse with PV and PVT systems

Greenhouse roof can be used to install PV modules and provide electricity.

PV modules should be arranged in a suitable way, to avoid permanent plant shading and to contribute to natural ventilation of greenhouse.

The PV modules can carry water heat exchangers at their rear surface and be combined with thermal storage to operate as cooling (during day)-heating (during night) system of the greenhouse.



(Rocamora and Tripanagnostopoulos, 2006)

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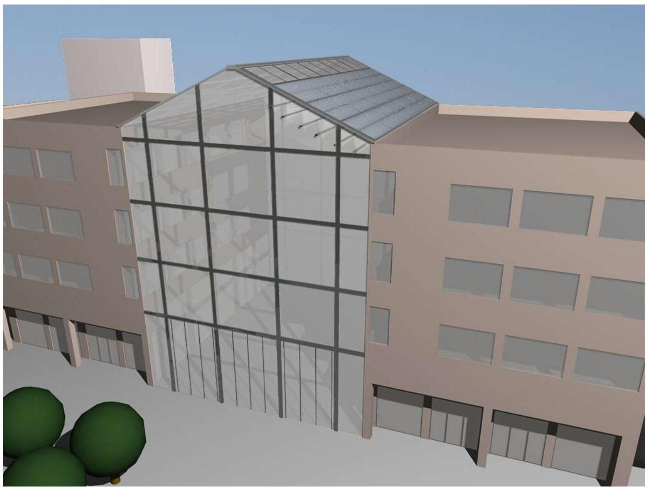
Suggested applications of improved PVT systems



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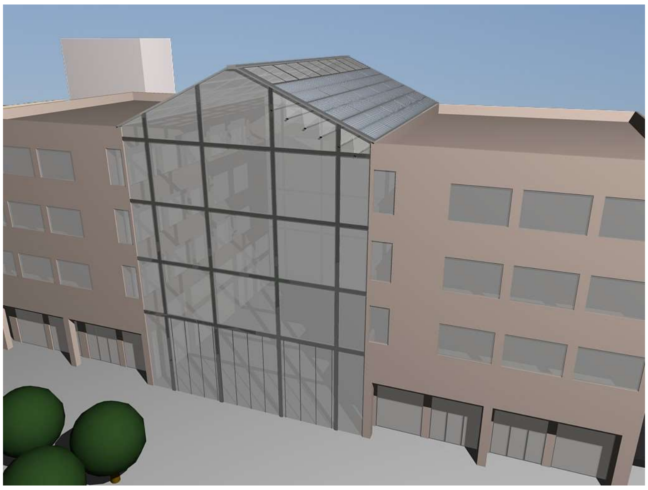
Suggested applications of improved PVT systems



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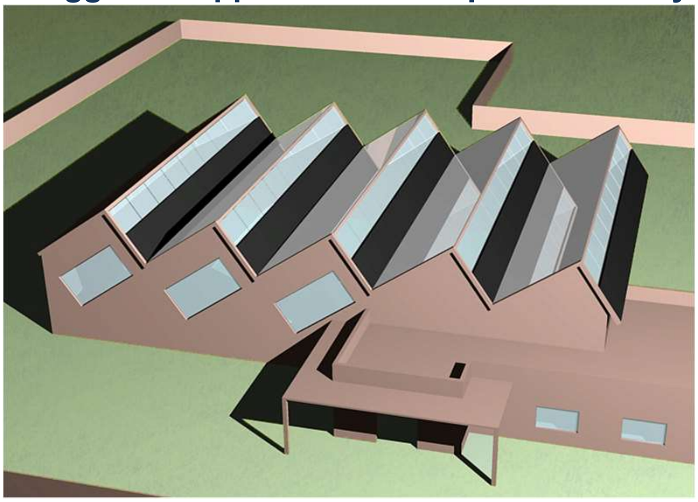
Suggested applications of improved PVT systems



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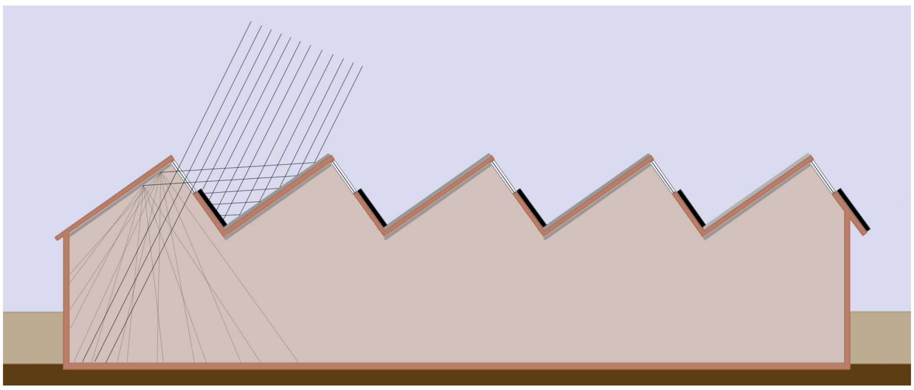
Suggested applications of improved PVT systems



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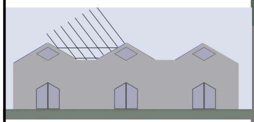
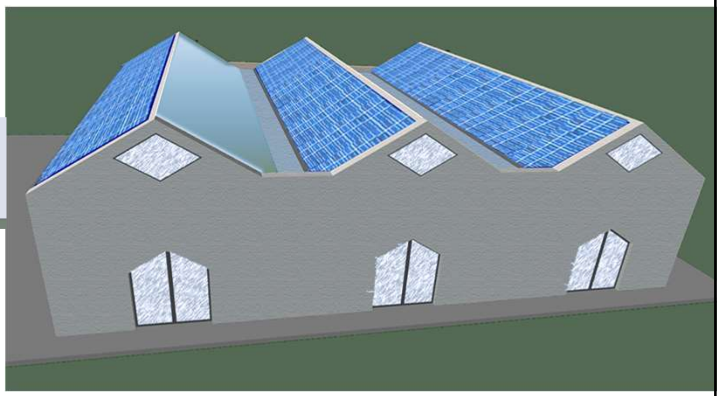
Suggested applications of improved PVT systems





Building roofs can be effectively used to install PV modules, filling the opposite roof surface with diffuse reflectors, to provide additional solar energy and increasing system's electrical output

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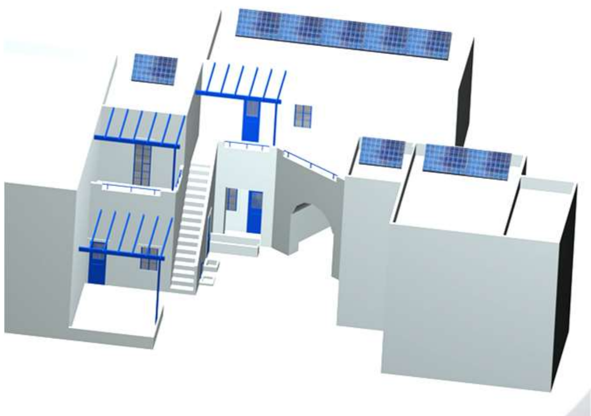
Suggested applications of improved PVT systems



HYBRID PV/T COLLECTORS ON CYCLADIC HOUSE ROOF

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Suggested applications of improved PVT systems

Example of aesthetic integration of solar and wind energy systems on a building of Cycladic islands, for effective operation of sun and wind

EPILOGE (1)

The hybrid Photovoltaic/Thermal (PV/T or PVT) collectors convert solar radiation simultaneously to electricity and heat, increasing the total energy output of PVs.

PV/T collectors are distinguished in PV/T-water and PV/T-air collectors, depending on the heating medium used. In PV/T-air collectors the contact of air with PV panels is direct, while in PV/T-water collectors the water heating is usually through a heat exchanger.

Apart from the use of the flat type PV/T collectors, there have been developed concentrating PV/T collectors (CPVT) using reflectors or lenses and concentrating type cells, aiming to cost effective conversion of solar energy.

The work on PV/T collectors has started before forty years and still they are not yet applied enough. New PV/T collector designs are promising for a wider application next years, mainly to adapt zero energy building requirements.

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EPILOGE (2)

Among the interesting suggested improvements to PV/T collectors for the achievement of higher performance and longer durability, there can be referred the following:

- The placement of TMS and FIN in the air duct of PV/T-AIR collectors
- The combination of PV/T collectors with booster diffuse reflectors
- The installation of both PV/T and Thermal collectors to building roofs and facades
- The use of temperature resistant PV modules to PV/T collectors
- The high performance attachment of PV modules and heat extraction units
- The thermal insulation switching to control PV/T system operating temperature
- The effective combination of concentrators with PV/T solar radiation receivers

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REFERENCES

Aelenei L. and Goncalves H. 2013. From solar building design to Net Zero Energy Buildings: performance insights of an office building. Energy Procedia 48, 1236-1243.
Aelenei L., Pereira R., Goncalves H., Athienitis A. 2014. Thermal performance of a hyrid BIPV-PCM: modelling, design and experimental investigation. Energy Procedia 48, 474-483.
Agrawal B., Tiwari G.N. 2010. Life cycle cost assessment of building integrated photovoltaic thermal (BIPVT) systems. Energy and Buildings 42, 1472-1481.
Anderson T.N., Duke M., Morrison G.L., Carson J.K. 2009. Performance of a building integrated photovoltaic/thermal (BIPVT) solar collector. Solar Energy 83, 445-455.
Assoa Y.B., Menezo C., Fraisse G., Yezou R., Brau J. 2007. Study of a new concept of photovoltaic-thermal hybrid collector. Solar Energy 81, 1132-1143.
Aste N., Beccali M., Solaini G. 2003. Experimental validation of a simulation model for a PV/T collector. ISES solar world congress, June 14-19, Goteborg, Sweden, CD-ROM.
Aste N., Del Pero C., Leonforte F., 2012. Thermal-electrical optimization of the configuration a liquid PVT collector. Energy Procedia 30, 1-7.
Aste N., Del Pero C., Leonforte F., 2014. Water flat plate PV-thermal collectors: A review. Solar Energy 102, 98-115.
Bakker M., Zondag H.A., Elswijk M.J., Strootman K.J., Jong M.J.M. 2005. Performance and costs of a roof-sized PV/thermal array combined with a ground coupled heat pump. Solar Energy 78, 331-339.
Battisti R. Tripanagnostopoulos Y. 2005. PV/Thermal systems for application in industry. In Proc. (CD-ROM) of 20th European Photovoltaic Solar Energy Conference, 6-10 June 2005, Barcelona, Spain, paper 6CV.2.3.
Bazilian M., Leeders F., van der Ree B.G.C. and Prasad D. 2001. Photovoltaic cogeneration in the built environment. Solar Energy 71, 57-69.
Beccali M., Finocchiaro P. Nocke B. 2009. Energy and economic assessment of desiccant cooling systems coupled with single glazed air and hybrid PV/thermal solar collectors for applications in hot and humid climate. Solar Energy 83, 1828-1846.
Bergene T. and Lovvik O.M. 1995. Model calculations on a flat-plate solar heat collector with integrated solar cells. Solar Energy 55, 453-462.
Bhargava A.K., Garg H.P. and Agarwal R.K. 1991. Study of a hybrid solar system – solar air heater combined with solar cells. Energy Convers. Mgmt. 31, 471-479.
Bottenberg W. R., N. Kaminar, T. Alexander, P. Carrie, K. Chen, D. Gilbert, P. Hobden, A. Kalaita, J. Zimmerman, Manufacturing technology improvements for the PVI SUNFOCUS™ concentrator. 16th European PV Solar Energy Conference 2000, 1–5 May, Glasgow, UK, 2233-2236.
Brinkworth B.J., Cross B.M., Marshall R.H. and Hongxing Yang. 1997. Thermal regulation of photovoltaic cladding. Solar Energy 61, 169-179.
Brinkworth B.J., Marshall R.H., Ibarahim Z. 2000. A validad model of naturally ventilated PV cladding. Solar Energy 69, 67-81.
Brinkworth B. J, 2000a. A procedure for routine calculation of laminar free and mixed convection in inclined ducts. Int. J. Heat Fluid Flow, 21, 456-255.
Brinkworth B.J. 2000b. Estimation of flow and heat transfer for the design of PV cooling ducts. Solar Energy 69, 413-320.
Brinkworth B.J., Sandberg M. 2006. Design procedure for cooling ducts to minimise efficiency loss due to temperature rise in PV arrays. Solar Energy 80, 89-103.
Brogren M., Ronnelid M., Karlsson B., Proc. 16th Europ. PV Solar Energy Conf. Vol. III, pp. 2121-2124, 1-5 May, Glasgow, U.K. (2000).
Brogren M., Nostell P. and Karlsson B. 2000. Optical efficiency of a PV-Thermal hybrid CPC module for high latitudes. Solar Energy 69, 173-185.
Brogren M., Karlsson B., Werner A. and Roos A. 2002. Design and evaluation of low-concentrating, stationary, parabolic reflectors for wall-integration of water-cooled photovoltaic-thermal hybrid modules. In Proc. Int. Conf. PV in Europe 7-11 Oct. Rome, 551-555.
Busato F., Lazzarin R., Noro M. 2008. Experimental analysis of photovoltaic cogeneration modules. International Journal of Low Carbon Technologies 3-4, 221-244.
Charalambous P.G., Maidment G.G., Kalogirou S.A., Yiakoumetti K. 2007. Photovoltaic thermal (PV/T) collectors: A review. Applied Thermal Engineering 27, 275-286.
Charron R., Athienitis A.K. 2006. Optimization of the performance of double-facades with integrated photovoltaic panels and motorized blinds. Solar Energy 80, 482-491.
Chemisana D., Ibanez M. 2010. Linear Fresnel concentrators for building integrated applications. Energy Conversion and Mngmnt. 51, 1476-1480.
Chow T.T. 2010. A review on photovoltaic/thermal hybrid solar technology. Applied Energy 87, 365-379.
Chow T.T. 2003. Performance analysis of photovoltaic-thermal collector by explicit dynamic model. Solar Energy 75, 143-152.
Chow T.T., He W., Ji J. 2006. Hybrid photovoltaic-thermosyphon water heating system for residential application. Solar Energy 80, 298-306.
Ciulla G., Lo Brano V., Cellura M., Franzitta V., Milone D. 2012.A finite difference model of a PV-PCM system. Energy Procedia 30, 198-206.

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REFERENCES

Coventry J.S., Lovegrove K. 2003. Development of an approach to compare the 'value' of electric and thermal output from a domestic PV/thermal system. Solar Energy 75, 63-72.

Coventry J. 2005. Performance of a concentrating photovoltaic/thermal solar collector. Solar Energy 78, 211-222.

Cox C.H. III and Raghuraman P. 1985. Design considerations for flat - plate- photovoltaic/thermal collectors. Solar Energy 35, 227-241.

Duffie J. A and W. A Beckman, 1991. Solar Engineering of Thermal Processes. John Wiley & Sons, Inc. New York.

Dupeyrat P., Menezo Ch., Rommel M., Henning H.M. 2011. Efficient single glazed flat plate photovoltaic-thermalhybrid collector for domestic hot water system. Solar Energy 85, 1457-1468.

Dupeyrat P., Menezo Ch., Fortuin S. 2014. Study of the thermal and electrical performances of PVT solar hot water system. Energy and Buildings 68, 751-755.

Eicker U., Fux V., Infield D. and Mei Li. 2000. Heating and cooling of combined PV-solar air collectors facades. In Proc. Int. Conf. 16th Europ. PV solar energy. 1-5 May Glasgow, UK, 1836-1839.

Elazari A. 1998. Multi Solar System – Solar multimodule for electrical and hot water supply for residentially building. In Proc. 2nd World Conf. On Photovoltaic Solar Energy Conversion , 6-10 July, Vienna, Austria, 2430-2433.

Esposito A, 1998. Fluid Mechanics with Applications. *Prentice-Hall, INC*. New Jersey.

Fang G., Hu H., Liu X. 2010. Experimental investigation on the photovoltaic-thermal solar heat pump air-conditioning system on water-heating mode. Experimental Thermal and Fluid Science 34, 736-743.

Florschuetz L.W. 1979. Extention of the Hottel -Whillier model to the analysis of combined photovoltaic / thermal flat plate collectors. Solar Energy 22, 361-366.

Fortuin S., Hermann M., Stryi-Hipp G., Nitz P., Platzer W. 2014. Hybrid PV-Thermal collector development: conceps, experiences, results and research needs. Energy Procedia 48, 37-47.

Fraisse G., Menezo C., Johannes K. 2007. Energy performance of water hybrid PV/T collectors applied to combisystems of Direct Solar Floor type. Solar Energy 81, 1426-1438.

Frankl P. "Analisi del ciclo di vita di sistemi fotovoltaici" (LCA of Photovoltaic Systems), Ph.D. dissertation thesis, Università di Roma "La Sapienza", Roma, May 1996 - available at the Dipartimento di Meccanica e Aeronautica, Università di Roma "La Sapienza", Roma, or at the Biblioteca Nazionale, Roma, 1996.

Frankl P. Life cycle assessment (LCA) of PV systems–Overview and future outlook. In Proc. Int. Conf. PV in Europe, 7-11 Oct., Rome, Italy, 2002; 588-592.

Fujisawa T., Tani T. 1997. Annual exergy evaluation on photovoltaiv-thermal hybrid collector. Solar Energy Materials and Solar Cells 47, 135-148.

Garg H.P., P.K. Agarwal and A.K. Bhargava. 1991a. The effect of plane booster reflectors on the performance of a solar air heater with solar cells suitable for a solar dryer. Energy Convers. Mgmt. 32, 543-554.

G. Gan, "Effect of air gap on the performance of building-integrated photovoltaics," Energy, vol. 34, no. 7, pp. 913–921, 2009

Garg H.P. and Agarwal P.K. 1995. Some aspects of a PV/T collector/forced circulation flat plate solar water heater with solar cells. Energy Conv. Mgmt. 36, 87-99, 1995.

Garg H.P., and Adhikari R. S. 1997. Conventional hybrid photovoltaic / thermal (PV/T) air heating collectors: steady – state simulation. Renewable Energy 11, 363-385.

Garg H.P.,and Adhikari R.S. 1999. Performance analysis of a hybrid photovoltaic/thermal (PV/T) collector with integrated CPC troughs. Int. J. Energy Res. 23, 1295-1304.

Guiavarch A., Peuportier B. 2006. Photovoltaic collectors efficiency according to their integration in buildings. Solar Energy 80, 65-77.

Hausler T. and Rogash H. 2000. Latent heat storage of photovoltaics. In Proc. 16th Europ. PV Solar Energy Conf., 1-5 May, Glasgow, U.K. Vol III, 265-2267.

Hegazy A.A. 2000. Comparative study of the performances of four photovoltaic/thermal solar air collectors. Energy Convers. Mgmt 41, 861-881.

Helmers H., Kramer K. 2013. Multi-linear performance model for hybrid (C)PVT solar collectors. Solar Energy 92, 313-322.

Hendrie S.D. 1979. Evaluation of combined Photovoltaic/Thermal collectors. Proc. of Int. Conf. ISES, Atlanta, Georgia, USA, May 28 – June 1, Vol.3, 1865- 1869.

Hernandez M., R. Mohedano, F. Munoz, A. Sanz, P. Benitez and J. C. Minano. 16th European Photovoltaic Solar Energy Conference, 1–5 May, Glasgow, UK, 2394-2397, (2000).

Huang B.J. Lin T.H. Hung W.C. and Sun F.S. 2001. Performance evaluation of solar photovoltaic/thermal systems. Solar Energy 70, 443-448.

IEA-SHC/Task 35/PV/Thermal systems.2005. www.iea-shc.org/task35.

Ibarahim Z, Marshall R.H and Brinkworth B.J, 1999. Simplified loop analysis for naturally ventilated channel heated from one side by PV elements. Proc. UKISES Silver Jubilee Conf. Brighton, May 1999, pp. 69-74.

Ibrahim A., Othman M.Y., Ruslan M. H., Mat S., Sopian K. 2011. Recent advances in flat plate photovoltaic/thermal (PV/T) solar collectors. 2011. Renewable and Sustainable Energy Reviews 15, 352-365.

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REFERENCES

Infield D., Mei Li., Eicker U. 2004. Thermal performance estimation for ventilated PV facades. Solar Energy 76, 93-98.

Ito S. and Miura N. 2003. Usage of a DC fan together with photovoltaic modules in a solar air heating system. In Proc (CD-ROM) ISES World Congress Goteborg, Sweden, 14-19 June.

Jie J., Keliang L., Chow T.T., Gang P., Wei H., Hanfeng H. 2008. Performance analysis of a photovoltaic heat pump. Applied Energy 85, 680-693.

Kalogirou S.A. 2001. Use of TRNSYS for modelling and simulation of a hybrid PV-Thermal solar system for Cyprus. Renewable Energy 23, 247-260.

Kalogirou S.A. and Tripanagnostopoulos Y. 2006. Hybrid PV/T solar systems for domestic hot water and electricity production. 2006. Energy Conversion and Management 47, 3368-3382.

Kalogirou S. A. and Tripanagnostopoulos Y. Industrial application of PV/T solar energy systems. Applied Thermal Engineering 27 (8-9), pp. 1259-1270, (2007).

Karlsson B., Brogren M., Larsson S., Svensson L., Hellstrom B., Sarif Y. 2001. A large bifacial photovoltaic-thermal low-concentrating module. In Proc. 17th PV Solar Energy Conference 22-26 Oct Munich, Germany, 808-811.

Kern E.C. Jr and Russel M.C. 1978. Combined photovoltaic and thermal hybrid collector systems. Proc. of 13th IEEE Photovoltaic Specialists, Washington DC, USA, 1153 – 1157.

Kim J.H., Kim J.T. 2012. The experimental performance of an unglazed PV-thermal collector with a fully wetted absorber. Energy Procedia 30, 144-151.

Kostic Lj., Pavlovic T.M., Pavlovic Z.T. 2010. Optimal design of orientation of PV/T collector with reflectors. Applied Energy 87, 3023-3029.

Kramer K., Helmers H. 2013. The interaction of standards and innovation: Hybrid photovoltaic-thermal collectors. Solar Energy 98, 434-439.

Kritchman E.M., Friesem A.A., Yekutieli G. 1979. Efficient Fresnel lens for solar concentration. Solar Energy 1979, 22, 119-123.

Kumar S., Tiwari A. 2010. Design, fabrication and performance of a hybrid photovoltaic/thermal (PV/T) active solar still. Energy Conversion and Mngment 51, 1219-1229.

Lasnier F. and Ang T.G. 1990. *Photovoltaic Engineering Handbook.* Adam Higler, p. 258.

Leenders F. Shaap A.B, van der Helden B.G.C. 2000. Technology review on PV/Thermal concepts. In Proc. 16th European PV Solar Energy Conference, 1-5 May, Glasgow, U.K., 1976-1980.

Lorenzo E and Sala G. Hybrid silicon-glass fresnel lens as concentrator for photovoltaic applications. ISES Conf. Silver Jublilee Congress 1979, Atlanta, 536-539.

Luque A., Sala G., Arboiro J.C., Bruton T., Cunningham D., Mason N., 1998. Some results of the Eucledes photovoltaic concentrator prototype. Progress in Photovoltaics. Research and Applications 5, 195-212.

Mallick T.K., Eames P.C., Norton B. 2007. Using air flow to alleviate temperature elevation in solar cells within asymmetric compound parabolic concentrators. Solar Energy 81, 173-184.

Matuska T. 2014. Performance and economic analysis of hybrid PVT collectors in solar DHW system. Energy Procedia 48, 150-156.

Mazon R., Kaiser A.S., Zamora B., Garcia J.R., Vera F.2011. Analytical model and experimental validation of the heat transfer and the induced flow in a PV cooling duct in environmental conditions. WREC 2011, Linkoping, Sweden 8-13 May 2011, 2907-2915

Moshfegh B and Sandberg M. 1998. Flow and heat transfer in the air gap behind photovoltaic panels. Renewable & Sustainable Energy Reviews 2, 287-301.

Nayak S., Tiwari G.N. 2008. Energy and Exergy analysis of photovoltaic/thermal integrated with a solar greenhouse. Energy and Buildings 40, 2015-2021.

Nilsson J., Hakansson H., Karlsson B. 2007. Electrical and thermal characterization of a PV-CPC hybrid. Solar Energy 81, 917-928.

O'Neil M.J., Walters R.R., Perry J.L., McDanal A.J. Jackson M.C., Hess W.J. Fabrication, installation and initial operation of the 2000 sq. m. linear fresnel lens photovoltaic concentrator system at 3M/Austin (Texas). 21th IEEE PV Specialists Conference 1990, Florida, 1147 – 1152.

Notton G., Cristofari C., Mattei M., Poggi P. 2005. Modelling of a double-glass photovoltaic module using finite differences. Applied Thermal Engineering 25, 2854-2877.

Othman M.Y.H., Yatim B., Sopian K., Bakar M.N.A. 2005. Performance analysis of a double-pass photovoltaic/thermal (PV/T) solar collector with CPC and fins. Renewable Energy 30, 2005-2017.

Pantic S., Candanedo L., Athienitis A.K. 2010. Modeling of energy performance of a house with three configurations of building-integrated photovoltaic/thermal systems. Energy and Buildings 42, 1779-1789.

PVT ROADMAP, 2006. A European guide for the development and market introduction of PV-Thermal technology. www.pvtforum.org

Ries H., Gordon J.M. and Lasken M. High-flux photovoltaic solar concentrators with kaleidoscope-based optical designs. Solar Energy 1997, 60, 11-16.

Robles-Ocampo B., Ruiz-Vasquez E., Canseco_Sanchez H., Cornejo-Meza R.C., Trapaga-Martinez G., Garcia-Rodriguez F.J., Gonzalez-Hernandez J., Vorobiev Yu.Y. 2007. Photovoltaic/thermal solar hybrid system with bifacial PV module and transparent plane collector. Solar Energy Materials and Solar Cells 91, 1966-1971.

Rocamora M. C., Tripanagnostopoulos Y. 2006. Aspects of PV/T solar system application for ventilation needs in greenhouses. Acta Horticulturae 719, 239-245.

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REFERENCES

Rosell J.I., Vallverdu X., Lechon M.A. and Ibanez M. 2005. Design and simulation of a low concentrating photovoltaic/thermal system. Energy Conversion and Management 46, 3034-3046.

Rumyantsev V.D., Heim M., Andreev V.M., Bett A.W., Dimroth F., Lange G., Letay G., Shvarts M.Z., Sulima O.V. Concentrator array based on GaAs cells and fresnel lens concentrators. 16th European PV Solar Energy Conf. 2000, 1–5 May, Glasgow, UK, 2312-2315.

Sandness B., Rekstad J. 2002. A photovoltaic/thermal (PV/T) collector with a polymer absorber plate-experimental study and analytical model. Solar Energy 72, 63-73.

Shaw N. C. and S. R. Wenham. 16th European Photovoltaic Solar Energy Conference, 1–5 May, Glasgow, UK, 2342-2345, (2000).

Skoplaki E. Palyvos J.A. 2009. Operating temperature of photovoltaic modules:A survey of pertinent correlations. Renewable Energy 34, 23-29.

Sopian K, Liu H.T., Yigit K.S., Kakac S. and Veziroglu T.N. 1996.Perfromance analysis of photovoltaic thermal air heaters. Energy Convers. Mgmt 37(11), 1657-1670.

Souliotis M., Tripanagnostopoulos Y., Kavga A.. 2006. The use of Fresnel Lenses to reduce the ventilation needs of greenhouses. Acta Horticulturae 719, 107–113.

Tiwari A. and Sodha M.S. 2006. Performance evaluation of solar PV/T system: An experimental validation. Solar Energy 89, 751-759.

Tonui J.K and Tripanagnostopoulos Y, 2007a. Improved PV/T solar collectors with heat extraction by natural or forced air circulation. Renewable Energy 32, 623-637.

Tonui J.K and Tripanagnostopoulos Y, 2007b. Air-cooled PV/T solar collectors with low cost performance improvement. Solar Energy 81 (4), pp. 498-511

Tonui J. K. and Tripanagnostopoulos Y. Performance Improvement of PV/T solar collectors with natural air flow operation. Solar Energy 82, pp.1-12, (2008).

Touafek K., Khelifa A., Adouane M. 2014. Theoretical and experimental study of sheet and tubes hybrid PVT collector. 2014, Energy Conversion and Management 80, 71-77.

Tripanagnostopoulos Y., Nousia Th., Souliotis M. and Yianoulis P. 2002a. Hybrid Photovoltaic/Thermal solar systems. Solar Energy 72, 217-234.

Tripanagnostopoulos Y. and Souliotis M., Battisti R. and Corrado A. 2005. Energy, cost and LCA results of PV and hybrid PV/T solar systems. Progress in Photovoltaics: Research and applications 13, 235-250.

Tripanagnostopoulos Y. and Souliotis M., Battisti R. and Corrado A. 2006a. Performance, cost and Life-cycle assessment study of hybrid PVT/AIR solar systems. Progress in Photovoltaics: Research and applications 14, 65-76.

Tripanagnostopoulos Y., Siabekou Ch. and Tonui J.K. 2006b. The Fresnel lens concept for solar control of buildings. Solar Energy 81 (5), pp. 661-675, (2007).

Tripanagnostopoulos Y. Aspects and improvements of hybrid photovoltaic/thermal solar energy systems. Solar Energy 81 (9), pp. 1117-1131, (2007).

Tripanagnostopoulos Y. 2006. Cost effective designs for building integrated PV/T solar systems. Presented in 21st European PV Solar Energy Conf. Dresden, Germany 4-6 Sep 2006.

Tripanagnostopoulos. 2008. Building Integrated Concentrating PV and PV/T Systems. Proc Int Conf Eurosun, 7-10 Oct 2008, Lisbon, Portugal.

Tripanagnostopoulos Y. and Iliopoulou A. 2007. Improved designs for low concentration photovoltaics. Int Conf. 22nd PVSEC, Milan, Italy, 3-7 Sep 2007.

Tripanagnostopoulos Y., Souliotis M., Makris Th., Chemisana D. 2010. Effective Combination of Solar and Wind Energy Systems. Proc. Int Conf. Hybrid-PV and Mini Grid, Tarragona, Spain, April 2010.

Tripanagnostopoulos. Y, 2012, Photovoltaic/Thermal Solar Collectors. Comprehensive Renewable Energy, Volume 3, Chapter 8, 255–300. Oxford: Elsevier.© 2012 Elsevier Ltd).

Tyukhov I., Simakin V., Smirnov A., Poulek V. 2009. Combined PV/T system based on concentrator with vertical p-n junctions solar cells. In website proceedings of Int Workshop on Concentrating Photovoltaic Optics and Power, Darmstadt 9-10 March 2009.

Vokas G., Christandonis N., Skittides F. 2006. Hybrid photovoltaic-thermal systems for domestic heating and cooling-A theoretical approach. Solar Energy 80, 607-615.

Wolf M. 1976. Performance analyses of combined heating and photovoltaic power systems for residences. Energy Conversion, 16, 79-90.

Yoshioka K., S. Goma, S. Hayakawa and T. Saitoh, Progress in Photovoltaics: Research and Applications, Vol. 5, pp. 139 – 145, (1997).

Young F. D, Munson B. R and Okiishi T. H, 1997. A brief introduction to fluid mechanics. John Wiley & Sons, Inc. New York.

Zacharopoulos A., P. C. Eames, D. McLarnon and B. Norton, Solar Energy, Vol. 68, pp. 439 – 452, (2000).

Zondag H.A. 2008. Flat-plate PV-Thermal collectors and systems:A review. Renewable and Sustainable Energy Reviews, 12, 891-959.

Zondag, H. A., De Vries D.W., Van Helden W.G.J., Van Zolingen R.J.C. and Van Steenhoven A.A. 2002. The thermal and electrical yield of a PV-Thermal collector. Solar Energy 72, 113-128.

Zondag, H. A., De Vries D.W., Van Helden W.G.J., Van Zolingen R.J.C. and Van Steenhoven A.A. 2003. The yield of different combined PV-thermal collector designs. Solar Energy 74, 253-269.

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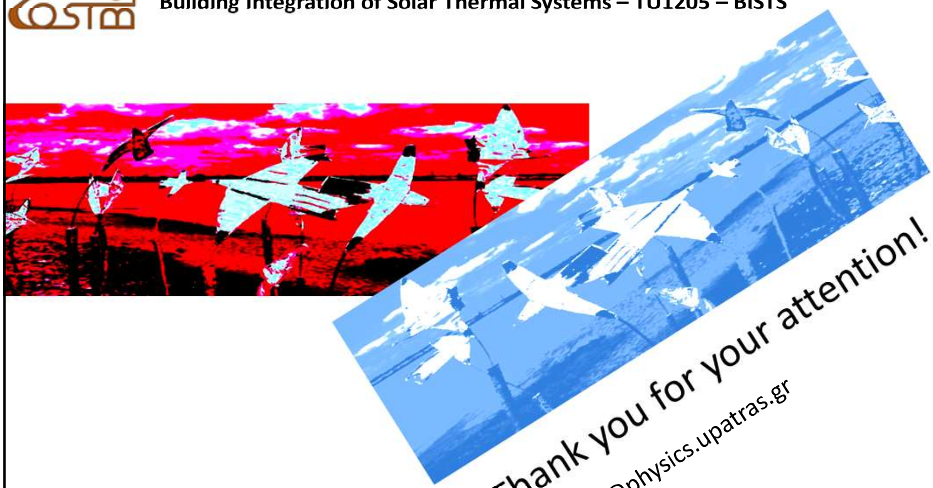

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