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A Systematic Literature Review of Photovoltaic Thermal Systems: Investigating Demand-Side Determinants of PV/T Performance.

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Abstract
This study reveals a gap in the system-centric literature on PV/T technology and analyses the published information from a demand-side perspective in order to identify generalisable PV/T performance principles for building applications. The seasonal variability and comparative relation of thermal and electrical demand profiles are examined as possible determinants of system efficiency. Conclusions are drawn that can assist in decision making and designing PV/T applications.

Keywords: Photovoltaic Thermal System, Demand, Performance

1 Introduction
Photovoltaic Thermal is a combination of a PV and a solar thermal collector simultaneously producing both electricity and heat. The PV cells are cooled by the motion of the fluid that absorbs and transfers heat as part of the solar thermal component of the system. This results to an improved PV efficiency and to an overall system efficiency higher than that of a separate PV panel or a thermal collector occupying the same area, ranging from 60% to 80%.

The R&D efforts in PV/T started in the 1970s with a strongly rising interest. Most published research studies on PV/T types and configurations aim at the optimization of the overall system performance, by achieving the highest sum of produced electricity and heat. The focus is on improving the efficiency on absolute numbers, usually omitting what this could mean in terms of supplied energy or on how this energy could be used for covering the specific thermal and electrical needs of a building (Chow 2010).

2 Aim and Methodology
Analysing the PV/T system performance from a demand-side perspective is important for actual building applications. The actual heating and electricity demand profiles in buildings vary according to the usage of spaces and the climatic context. The broad research issues investigated in existing research studies are the electrical and/or thermal efficiency and the opportunities for improving the performance of specific PV/T types. There is little, if any, reference to the actual building needs that these systems are asked to meet or to contribute to.

The present research constitutes of a Systematic Literature Review on PV/T systems. The principal aim is to systematically review and analyse - from a demand-side perspective - the research findings that have already been published for different types of PV/T systems, in order to identify generalisable PV/T performance characteristics as well as R&D gaps or shortcomings. It differs from other PV/T review papers in that the literature considered is systematically selected or excluded and classified according to specific criteria relevant to the

research aims. This study maps the published research data by identifying similarities in types and configurations tested in different research studies, by comparing and combining all findings. A decision making diagram, that aims to help designers to make an informed choice for each application, is presented and its applicability and limitations are discussed. Finally, the research gap is identified and detailed suggestions about future studies are made.

3.1 Process description

Special attention is given to the selection of papers in order to satisfy quality criteria and cover the development of the research performed throughout the last twenty years. In total 62 papers are selected for the systematic review dating from the 90s to today, when the interest in PV/T research was peaked due to the global environmental depletion (Chow 2010). They are categorized into two main groups: the first one including 8 papers focused only on reviewing the existing literature and the second including 54 papers, each presenting a research study about PV/T technology developments.

The potential contribution of different PV/T types and configurations for a building application is analysed from a demand-side perspective, by estimating the effect of each system design modification on heating and electric energy contribution separately. The methodologies, input data and contexts considered (climate and application) as well as the key findings and conclusions of these studies are analysed and critically evaluated.

3.2 PV/T Types

The literature reveals the following variations in PV/T systems:

-Air or water type according to the fluid used;
-Stand alone or building integrated into building roofs or facades;
-Uncovered - single / double covered (front glass covers);
-Thermal collector either fully or partially covered by the PV module;
-Flow pattern above or below the absorber;
-Natural or forced flow of the fluid, (and variations on the mass flow rate);
-Different types of PVs (monocrystalline or amorphous silicon a-Si) or different types of solar thermal collectors (flat plate or concentrator type) integrated into the PV/T systems;
-Different types of thermal collector absorbers (galvanized iron, copolymer or aluminium);
-Solar radiation reflectors integrated into the PV/T system;
-Other configurations such as adding ribs, placing a corrugated sheet, pipes, a thin metallic sheet, fins in single or double pass, using V groove or rectangular tunnel absorber or placing stationary flat booster diffuse reflectors;

3.3 Performance Evaluation of each PV/T Type

The analysis concludes that numerical results quoted refer only to the system tested under the specific climatic conditions and for specific assumptions made. The basis of the following comparisons and generalized conclusions is mostly qualitative and in some occasions relate to comparisons developed within the same paper or research context.

Air PV/T systems are found to be about 2% less efficient than the liquid ones (Charalambous et al. 2007), but the actual suitability of each system is mostly related with the region and the building application. Air type systems are usually considered to be more effective at high latitudes, especially when the building application requires a constant fresh air demand (Bosanac et al. 2003). At the same time, water types are considered to be suitable for low latitudes and especially when there is a need for hot water supply, as for example for any a residential application (Tripanagnostopoulos 2007). In this context there is no need of overcoming freezing problems. A combination of both PV/T water and air types is seen as a

good choice for medium latitudes (Tripanagnostopoulos 2007), in order to supply hot air during the cold season and contribute for hot water supply during the summer season.

The **building integrated PV/T system** allows for heat to be transferred from the building element to the indoor space (Bazilian et al. 2002). This can be an advantage for high latitudes especially during the cold season, but a disadvantage for low latitudes, requiring appropriate design and control for avoidance of overheating.

Increasing the **number of glass covers** reduces heat losses and improves the thermal efficiency, although it deteriorates the electrical one, due to the reflections caused from each cover (Zondag et al. 2003).

The temperature of the fluid inside the thermal collector gradually increases from the inlet to the outlet leading to a low PV efficiency at the edge close to the output (Zakharchenko et al. 2004), while the existence of the PV reduces the heat income of the thermal collector (Zakharchenko et al. 2004). As a result, a PV/T design with **a PV area smaller than the overall area of the thermal absorber** and placed on the top of the fluid inlet leads into a better thermal and overall efficiency, by optimizing the advantage of the PV and thermal collector combination (Zakharchenko et al. 2004).

Superimposing the layer of **fluid above the thermal absorber** results into higher thermal performance, but the liquid should be chosen carefully for allowing absorption of the infrared radiation and yet leaving the visible part of the spectrum unaffected (Rosa-Clot et al. 2011). At the same time, applying the fluid both **above and below the absorber in a double-pass** design results into a better electrical and thermal efficiency, as the PV cells are cooled more effectively while more heat is produced (Sopian et al. 1996).

Forced circulation is proven to be thermally more efficient than the natural one, due to increased convective and conductive heat transfer (Chow 2010), while the net electrical efficiency is decreased (Hegazy 2000). Moreover, **increasing the mass flow rate** up to a certain extent, results into a lower cell temperature as well as better electrical and thermal efficiency (Garg and Adhikari 1999; Chow 2010; Rosa-Clot et al. 2011).

Different types of PVs integrated into a PV/T system may perform differently and influence the thermal efficiency in various ways as well. For example the **transparent** systems lead to higher thermal efficiency than opaque ones (Zondag et al. 2003), the **monocrystalline silicon** to the best electrical daily performance (Mishra and Tiwari 2013), but low thermal (Daghigh et al. 2011), while **amorphous silicon** cells have the highest thermal absorption and a poor electrical performance (Daghigh et al. 2011). At the same time, **different types of solar thermal collectors** have been tested. The **concentrator** thermal collectors have a better thermal performance than the **flat plate** ones as the thermal losses are not radically increased when the fluid temperature increases because of the reduced surface area (Coventry 2005)

Different types of thermal collector absorbers such as galvanized iron, copolymer or aluminium not only improve the thermal and electrical performance, but also reduce the manufacturing cost and time, especially when compared with copper (Cristofari et al. 2009; Daghigh et al. 2011; Touafek et al. 2013).

A combination of bottom and upper position **solar radiation reflectors** integrated into a PV/T are significantly increasing the amount of thermal and electrical energy produced by the system (Kostic et al. 2010). Finally, it is proven that the heating outcome can be improved by various other configurations (Tripanagnostopoulos 2007; Othman et al. 2013). For

example, the pipes are heated by heat trapped at the back of the PV and contribute to the air heat extraction (Tripanagnostopoulos 2007).

4 Design Guidance for PV/T

The diagram shown in Figure 1 summarises the findings of the systematic literature review that are relevant to the application and design of PV/T systems in real projects. Through this review it is observed that, at present, PV/T related research efforts are fragmented and lack of coordination. For example, PV/T systems with different types of PVs have not been tested for both glazed and unglazed systems. Therefore this diagram does not provide detailed support or complete design guidance, as it suffers from shortcomings in established knowledge and experience on PV/T technologies. In addition to the diagram, 3 supplementary tables are also created, summarising methods of optimising the thermal or electrical system output.

The first stage of the diagram is about selecting between an air or a water type. The second is about choosing between a building-integrated or stand-alone PV/T system, according mostly to criteria irrelevant to the building demand, such as whether the project is going to be about a new building or a refurbishment or the opportunities for integration in a real scheme. The third stage is about whether priority will be given to the electrical or thermal performance at the design process. From the analysed research studies, it became obvious that whether the system is going to be glazed or unglazed has the greatest effect on the PV/T electrical and thermal performance (Zondag et al. 2003).

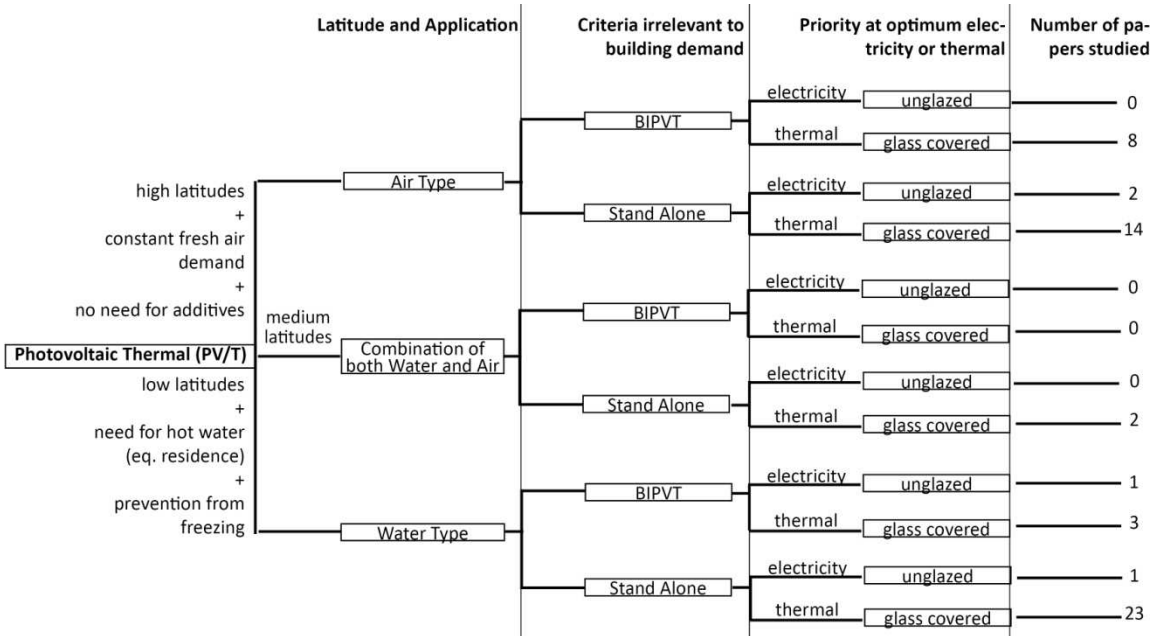

Figure 1. Design Guidelines.

The next stage includes studying ways of improving the thermal, electrical or combined performance. Some of the variations have been on air and others on water PV/T systems only, but the conclusions assume similar effects irrespective of the heat transfer fluid used. More than one improvements of those listed can be applied to a single system.

Table 1. PV/T modification improving Electrical Performance.

Type	Description	Performance - Comment	Efficiency
Water	Uncovered	reflection losses are foregone	-
	Monocrystalline silicon (c-Si) PV	better electrical efficiency	-

Table 2. PV/T modification improving Thermal Performance.

Type	Description	Performance - Comment	Efficiency
Air	Double Pass	effective cooling	-
	Roughening the channel with RIBS	the heat exchanger area is increased leading to higher heat extraction	-
	Adding a corrugated sheet in the channel		-
	Placing pipes in the air channel		-
	Placing a thin flat metallic sheet in the middle of the air channel		-
	Roughening the channel with FINS		-
	Double Pass with Fins	heat transfer to the air is greater	-
	Rectangular Tunnel Absorber		-
	Single Pass with V-groove Absorber		-
Air and Water	water heat exchanger at the back of the PV + placing a thin metallic sheet	heat exchanger area is increased	water heat extraction about 70% and air 55%
	water heat exchanger at the back of the PV + roughening the channel with FINS		
	water heat exchanger at the back of the PV + roughening the channel with RIBS		
Water	Increasing the number of glass covers	the heat losses are decreased	-
	Opaque PV	more radiation passing through the PV	-
	Fluid applied at the front of the PV	more radiation is absorbed from the fluid	-
	Double pass		-
	PV area smaller than the thermal collector	increasing solar absorption	-
	Amorphous silicon (a-Si) PV	higher thermal absorption	-

Table 3. PV/T modification improving both Thermal and Electrical Performance.

Type	Description	Performance-Comment	Efficiency
Air	Forced flow with 1 or 2 fans	increasing the flow rate	-
	Flat booster diffuse reflectors	increasing the solar input	-
	Double Pass with Fins and CPC	increasing the solar input + the heat exchanger area	-
Water	Parabolic concentrating collector	achieving constant optics	th: 58%+ el: 11%
	Multi-crystalline silicon PV	improving performance	th: 55% + el:12%
	Reflectors	increasing solar radiation	gain:20%-35%
	Thermal absorber made of galvanised iron	improving performance	thermal 48%

It becomes apparent that comparing the results of different studies is not possible, as technical characteristics and design vary significantly, as do climatic conditions and testing methods. It would have been useful if the same configurations had been tested for both water and air type PV/T systems, building-integrated or stand-alone ones, under different climatic conditions. This would provide us with a better indication of the factors influencing efficiency. Moreover, the most important factors affecting the choice of the PV/T system, such as the actual building application or whether the system is going to cover the electrical or thermal needs entirely or partially, are almost in all cases ignored by the researchers. It is often overlooked that hot air supply is not the only solution for heating, as low grade radiant systems can be very effective in residential building applications. Another point worth mentioning is that the potential of the dual PV/T systems for covering entirely the needs of a building application, by providing either hot air or water throughout the whole year, seems to be neglected as these systems are only rarely tested. Finally, the advantages of building-

integrated PV/T systems, especially when the available surface area is limited, have not being fully investigated.

5 Conclusions

This paper presents a systematic literature review of existing research studies on PV/T systems. The various types and configurations that have been tested are collected and divided into categories. The testing conditions and context, as well as the results about each PV/T type performance are analysed from a demand-side perspective, and their credibility is critically evaluated. Conclusions are drawn that can assist in choosing the most suitable PV/T system for each building application. Gaps and inconsistencies in current research are also identified.

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