Solar hybrid PV-thermal combined cooling, heating and power systems

Kai Wang and Christos N. Markides*

* E-mail: c.markides@imperial.ac.uk

Clean Energy Processes (CEP) Laboratory, Department of Chemical Engineering, Imperial College London, South Kensington Campus, London SW7 2AZ, United Kingdom

Summary:
We review hybrid photovoltaic-thermal (PV-T) technology for the combined provision of heating, cooling and power, present the state-of-the-art and outline recent progress, including by researchers at the Clean Energy Processes (CEP) Laboratory, on aspects from component innovation to system integration, operational strategies and assessments in key applications. Technologies appropriate for integration with PV-T collectors include thermal (hot and cold) and electrical storage, heat-driven heating/cooling (e.g., absorption, adsorption) and/or electrically-driven heating/cooling (e.g., heat pump, air-conditioning) systems. Thermoeconomic assessments of PV-T collectors integrated within wider solar-energy systems with such technologies in representative applications have been conducted, including for energy provision to residential, commercial and public buildings, and industrial process heating applications. Studies have shown that PV-T technology has an excellent decarbonisation potential and can cover a significant amount of the energy demand of end-users given reasonable areas. Further efforts relating to technology innovation and, primarily, cost reduction are required to improve its economic competitiveness over conventional fossil-fuel and other alternative solutions. Advanced heat-loss suppression techniques and spectral beam splitting concepts have emerged as promising directions for ground-breaking innovation in this area.

Keywords: cooling, distributed, heating, photovoltaic-thermal, PV-T, solar energy, spectral splitting

Introduction
Solar energy can play a central role in decarbonising key sectors through displacing current primary (fossil fuel) energy consumption. Both solar thermal and photovoltaic (PV) technologies have experienced immense growth in the past decade (13% for solar thermal [1] and 24% for PV [2] per year over the past 5-15 years) and reached total installed capacities of 472 GWth and 402 GWel respectively by 2017 [3], corresponding to savings of 150 million tons of CO2 [1]. However, these two technologies deliver inherently different energy outputs, and occupy additional space if both heat and power are required, and are met by non-integrated (side-by-side) installations. In order to deliver cost-effective solar-energy utilisation, it is necessary not only for the cost of energy generation to be lower, but also for the total energy outputs generated per unit area of roof coverage to be maximised. This requirement can be met by hybrid PT-thermal (PV-T) collectors [4], which generate both electricity and useful thermal energy from the same aperture area and can be integrated within wider energy-provision systems with other technologies (conversion, storage, etc.). These systems can provide renewable heating and/or cooling and power, which are necessary components of meeting the ambitious decarbonisation targets that have already been set. Heat, for example, accounts for 60-90% of the total energy demand in buildings in cold climates (and 30-40% even in warmer climates).

PV-T technology is considered superior in terms of energy density (by 15-20%), and can reduce emissions by 30-40%, space by 20-30%, and investment costs by 10-20% compared to equivalent side-by-side PV and solar-thermal systems delivering the same energy outputs. In the sections below, we consider component innovation, system integration, operation and thermoeconomic assessments of solar combined cooling, heating and power systems (S-CCHP) based on hybrid PV-T collectors in various applications. Future trends are finally presented.

Hybrid PV-T solar combined heating, cooling and power systems
Hybrid PV-T systems are highly-suitable solutions for meeting the complete energy needs of urban as well as off-grid environments, as they generate both electrical and thermal outputs from the same area with a higher total efficiency than separate, standalone systems, and can be readily integrated with other technologies (e.g. for cooling, clean water or storage) within wider, holistic energy systems [5]. One possible layout of an integrated solar-energy system based on PV-T collectors is illustrated in Figure 1. The thermal and electrical outputs of the collectors are first
regulated via relevant control systems (valves, pumps and their control components for the thermal output; DC/AC inverters, power meters and charge controllers, etc., for the electrical output) before downstream transmission/distribution and usage. In order to suppress the inherent variability of solar radiation, energy can be stored in thermal-energy stores and used directly for heating or indirectly for cooling via heat-driven cooling units (e.g., based on absorption or adsorption chillers). Electricity from the PV-T collectors can be used to cover the onsite electrical demands and any surplus can be stored in electrical storage devices and/or exported to the grid. Electrically-driven heating/cooling (H/C) units may be used in place of thermal alternatives. Cold stores can be integrated to ensure a stable supply of cooling, depending on the specific requirements, characteristics and energy demands of the building or end-user. Great flexibility and many options for system integration are therefore available in such distributed energy systems.

Figure 1. Solar energy systems based on PV-T collectors for distributed heating, cooling and power provision.

**Thermoeconomic assessments of PV-T systems for different applications**

Depending on the application, heat may be required at different temperatures, most of which are compatible with available collector technologies, as shown in Figure 2. Conventional stationary non-concentrating PV-T collector designs can achieve outlet fluid temperatures up to ~100 °C. Higher temperatures can be achieved with concentrated PV-T (CPV-T) collectors. Most domestic and commercial applications fall in the low-to-medium temperature range (e.g., domestic hot water is typically required at 60 °C, hot water for pool heating is typically below 60 °C), making solar-energy systems based on non-concentrating PV-T collectors a suitable option.

Figure 2. Typical temperature ranges associated with solar-thermal systems and relevant applications [5].
Dynamic coupled thermal-and-electrical models have been developed for sheet-and-tube hybrid PV-T collectors [6-9]. These models have allowed an understanding of the role key design parameters on the operation and performance of these collectors, and of how they can be used to optimise system performance in real, varying conditions. Based on these modelling methodologies, a UK-based assessment of hybrid PV-T systems for domestic heating and power provision was been conducted [7,10], which showed that up to 51% of the annual electrical and 36% of the annual hot-water demands can be covered based on average roof-space availability, with an expected emission saving of up to 16.0 tCO\(_2\) (35% higher than PV-only system) over a lifetime of 20 years.

Further studies on PV-T S-CCHP systems based on the integration of PV-T technology with heat pumps or air-conditioning units have been performed to assess their technoeconomic potential in the domestic sector in ten representative European locations [11]. The results indicate that there is strong evidence that such PV-T systems with appropriate component and system design and operation can cover more than 60% of the combined heating demand, i.e., including that for space heating and hot water, more than 50% of the cooling needs, and around 30-100% of electrical consumption of households given access to reasonable installation areas.

PV-T systems also appear to be promising energy solutions in commercial and public-building applications, which have multi-vector energy demands, such as university campuses and sports centres. Technoeconomic assessments and comparisons of various hybrid vs. conventional solar-energy systems including: 1) a solar combined heat and power (S-CHP) system based on hybrid PV-T collectors, 2) a solar-power system based on PV panels, 3) a solar-thermal system based on evacuated tube collectors (ETCs), and 4) a S-CHP system based on a combination of side-by-side PV panels and ETCs (PV-ETC), have been conducted [12]. A case study involving the University Sports Centre of Bari (in Italy) showed that the PV-T S-CHP system can outperform the other aforementioned systems in terms of total energy output, with annual electrical and thermal energy yields reaching 82% and 51% of the Centre’s demands, respectively. At 438 tCO\(_2\)/year, the CO\(_2\) emission reduction potential of the PV-T system is also considerably higher than those of the other systems (253-310 tCO\(_2\)/year). In summer when the thermal demand is low, the temperature in the thermal store often increases to 80-90 °C, and this excess thermal energy can be converted to additional electricity with secondary power cycles, e.g., ORC engines [13-17], or to provide cooling with absorption chillers [18,19].

The temperature requirements of solar industrial process heat applications range from 50-60 °C to 250-300 °C [20]. Conventional non-concentrated PV-T systems such as those used in domestic applications can be employed in industrial applications where only low-temperature process heat (<100 °C) is required. For industries requiring high-temperature heat (>100 °C), CPV-T collectors would be more suitable. For example, in dairy factories, the required temperatures range from 50-60 °C to ~200 °C for different heat-treatment processes, such as pasteurisation, sterilisation, spray drying, etc. [20]. A thermoeconomic assessment of a S-CHP system based on spectral-splitting CPV-T collectors for the provision of electricity, steam and hot water in such a dairy-factory application has shown that 80% of the thermal demand for steam generation, and 60% of the hot water demand can be satisfied by the solar system, along with a net electrical output amounting to 60% of the onsite demand [21]. Economic analyses have indicated payback times of around 15 years, which can be further reduced if more cost-effective collector technologies can be developed.

**Next-generation PV-T collectors**

Previous research has suggested that solar-energy systems based on PV-T collectors have an excellent decarbonisation potential and that further efforts should be directed towards more efficient collector designs with a cost that would make these systems more economically competitive [22-26].

A roadmap of technological advances that are required for hybrid PV-T collectors to realise their full potential for combined energy provision [27] showed that insulating cavities, low-emissivity coatings and PV cells with low temperature coefficients would be promising avenues for achieving high electrical and thermal efficiencies at high temperatures, as shown in Figure 3(a). Towards this end, a transparent low-emissivity Indium Tin Oxide (ITO) coating was applied directly over conventional PV cells, and was effective in reducing the emissivity at mid-infrared wavelengths [28,29], as shown in Figure 3(b) and 3(c). The most advanced PV-T collector along the roadmap employs an evacuated glazing cavity combined with a low-emissivity coating, and is projected to have double the thermal efficiency compared to present commercial PV-T collectors, and to provide 1.5 and 2 times the revenue or carbon savings of PV modules and ST collectors, respectively.

Conventional PV-T systems are typically operated below 100 °C, which limits their application when higher temperature heat is required. A promising solution to overcome this limitation is to split
the incoming sunlight into two bands and to direct these separately to PV and solar-thermal sections, as shown in Figure 4. Spectral splitting can be realised in practice by either surface interference (e.g., optical mirrors) or volumetric fluid-based filters (e.g., nanofluids) [21]. This decoupling of the thermal and electrical elements of a collector reduces the PV cell temperatures, thus allowing higher electrical conversion efficiencies, while at the same time allowing the collector to supply a thermal output at temperatures considerably higher than the PV operation temperature. Next-generation PV-T collectors are being developed by many groups, including by the CEP Laboratory at Imperial College London in collaboration with Solar Flow (www.solar-flow.co.uk), by synergistically integrating the above heat-loss suppression techniques and spectral splitting concepts through innovative engineering designs.

Figure 3. Heat-loss suppression via evacuation and emissivity control for high-performance PV-T collectors.

Figure 4. Spectral beam-split PV-T collectors based on: (a) interference filters; and (b) fluid filters.

Conclusions
An overview of recent research progress and trends in solar-energy systems based on hybrid PV-T collectors for the provision of combined heating, cooling and power has been presented. In particular, research efforts at the Clean Energy Processes (CEP) Laboratory of Imperial College London have been outlined. Related studies have shown that the dual-generation of electrical and thermal energy from a single collector area enables a wide range of possible system configurations in which the PV-T collectors can be integrated with many other technologies to provide diverse energy vectors to end-users, thus opening up a wide range of applications. Thermoeconomic assessments of such solar-energy systems have suggested and they can cover a significant amount of the energy demand of end-users given access to reasonable areas, and highlighted their excellent decarbonisation potential. Employing advanced heat-loss suppression techniques and spectral splitting concepts into next-generation PV-T collector designs emerge as key routes toward promoting and establishing this technology as an economically viable solution.
Acknowledgments
This work was supported by the UK Engineering and Physical Sciences Research Council (EPSRC) [grant number EP/M025012/1]. The authors would also like to thank company Solar Flow (www.solarflow.co.uk). Data supporting this publication can be obtained on request from cep-lab@imperial.ac.uk.

References