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Modeling of Photovoltaic-Thermal District Heating with Dual Thermal Modes

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Abstract. Solar photovoltaic thermal (PVT) collectors could be a competitive addition to district heating systems, particularly in areas with high energy density since they simultaneously produce electricity and heat whilst increasing the PV efficiency through cooling. This study presents a new Modelica PVT model, which is used together with EnergyPlus in a co-simulation setup to assess the technical feasibility of solar PVT district heating in new builds. The model has been applied to a block of 12 2-bedroom terraced houses with a 184m^2 PVT array on the south facing side of the roof. It was identified that well-designed seasonal PVT heating configurations and control schemes are required to maximise PVT outputs. PVT dual thermal modes occur when the PV is either connected to a load or producing at close to the maximum power point. Integrating the dual modes into a control system could be more economical if heat tariffs were higher than electrical ones when heat demand is greater than the PVT thermal output.

1. Introduction

Advances in building energy systems and improvement of existing/new infrastructure will play a pivotal role towards the target to reduce global emissions and avert increasing of the mean temperature over 1.5°C above pre-industrial levels [1], which would have pernicious consequences.

District Heating (DH) systems can improve energy efficiency whilst reducing emissions and running costs [2]. In these systems, a centralised heat source is used to meet building heating demands within an area, removing the need for individual heating systems in each property. A communal heating system is of an additional benefit to urban dwellings, constituting 81.5% of the UK building stock [3], where space is at a premium. DH offers an opportunity to utilise renewable energy sources which can support global decarbonisation strategies and efforts. Densely packed urban dwellings may individually not have available space or optimum locations for such systems, such as south-facing rooftops for Solar Thermal heating, large enough garden areas for Ground Source Heat Pumps or space far enough away from sleeping areas for the installation of noisy Air Source Heat Pumps. Installing a renewable energy communal heating system would allow these types of dwellings to benefit from additional space from neighbouring dwellings or communal shared areas, which otherwise would not have been feasible to install.

A competitive renewable technology used for DH in densely populated urban areas is the Photovoltaic Thermal (PVT) collector that could potentially be used stand-alone or in conjunction with another heating source such as heat pumps. The main benefit of this technology is that it simultaneously produces electricity and heat whilst increasing the PV cell's efficiency through cooling. This could be particularly useful when investigating communal heating systems with limited available space.

According to the International Energy Agency (IEA), as of 2019, there were only 20 PVT DH systems installed in the world [4]. Although there is technically great potential for the use of PVT in DH, the high initial costs and uncertainties caused by poor knowledge of the technology was found to be limiting market penetration and installation growth [5]. However, in recent years an international consortium working on IEA Task 60 have been developing best practice guidance to accelerate the market acceptance and increase awareness of PVT technology [6].

Reflecting the small uptake in practice, only a few academic studies have investigated the use of PVT for DH applications [7–10]. It is interesting to note that there is a difference in thermal behaviour of a PVT to a conventional solar collector since PVT has two thermal efficiency curves dependent on the mode of operation. When connected in an Open Circuit (OC) mode where there is no electrical load, the thermal efficiency will be higher since there is more energy available for thermal conversion when compared to electrical power generation being close to maximum power point (MPP) mode. A study by Guarracino [11] found that thermal efficiency was about 11% higher in OC mode. The opportunity of using dual PVT modes to optimise performance has not been studied. It can be economically beneficial to convert any excess power produced to heat, if the electricity market price is below that of the DH heat tariff and providing that the heat demand is higher than the solar heat generated [8]. Therefore, this paper presents a dual mode PVT model as a tool to investigate the potential for implementing dual PVT modes as part of a PVT DH control system. It was hypothesised that integrating PVT dual modes as part of a control scheme could maximise the overall system performance and efficiency.

There have been many PVT models developed with different levels of detail using a range of modelling tools such as mathematical modelling, TRNSYS, finite-element or Modelica. Previous models have not implemented thermal mode switching that occurs within the PVT system in OC and MPP modes. This could be an important consideration when modelling this technology as it could impact the performance of the technology, especially when part of a DH system. Additionally, previous models did not investigate co-simulation with EnergyPlus, which would enhance the simulation. Since different tools have their own expertise, a hybrid system using co-simulation can better represent certain scenarios. It can be particularly useful when integrating models with multiple aspects such as building geometry, demand models and technological systems [12], which can be provided by the specialist software EnergyPlus.

For these reasons, this study presents a developed PVT model with dual thermal mode switching using Modelica. To assess the applicability of PVT DH in urban scenarios, the Modelica PVT model is used with EnergyPlus in a co-simulation setup. Modelica was chosen as it allows transparent modelling with great flexibility, being able to modify low-level components and systems. Additionally it opens up the possibilities of modelling PVT DH in a truly multi-disciplinary engineering environment, whilst utilising the broad range of Modelica libraries. It could also help to further the understanding of the complex synergies and interactions that arise from a technology producing both thermal and electrical energy.

2. Methodology

2.1. Modelling and Co-simulation

EnergyPlus (EP) is the gold standard for whole-building simulation, and is used extensively in research and practice [13]. EP allows coupled dynamical thermal simulation of passive and active systems. Both Modelica and EP support data exchange with other tools using standardised Functional Mockup Interfaces (FMI). A Functional Mock-up Unit (FMU) allows model encapsulation in containers; FMUs can be coupled and exchange information through FMIs [14]. In our study, the building envelope was modelled in EnergyPlus, and an FMU was exported; this FMU, was linked to the HVAC model developed in Modelica.

2.2. Zone Creation
This study investigates Ultra-Low Temperature District Heating (ULTDH) since they are the most suitable DH type for PVT integration. Due to a lower panel temperature, the system produces the largest amounts of electricity and heat compared to the other DH types, achieving a higher efficiency [10]. Since this study investigates ULTDH, new build homes were modelled as well-insulated homes are able to implement low temperature heating efficiently. A new build housing development was selected in the south-east coast of England. UK Ordnance Survey data for a block of 12 2-bedroom terraced houses was input into EnergyPlus. The building fabric materials were selected according to the Building Regulations Part L1a (2013 edition), which defines the target U-values for walls, floor, roof, windows and air tightness [15]. Insulation manufacturers and best practice recommend lower design U-value starting points than what is implemented in the regulations, therefore the best starting point U-values were taken from the Kingspan guide to the 2013 building regulations [16].

Each of the 24 zones had hot water heating equipment controlled by a heating schedule containing the sum of convective and radiative heat transferred from the radiator component within the Modelica PVT heating model zones. Each zone in EnergyPlus sent the zone mean temperature to the corresponding dwelling in Modelica, whilst hysteresis control turned on the pump to the radiator as required to maintain the zone temperature setpoint.

2.3. PVT and storage system
The Modelica system comprised of 5 main sub-components. These included the hot water tanks, electric auxiliary heater to maintain the tank set point, PVT collector and dwellings. Figure 1 shows a high level representation of the PVT system configuration for providing space heating and hot water. A solar pump control only turned on the pump to the PVT when useful thermal heat could be added to the buffer tank. A heat exchanger was placed on the return line of the DH loop to pre-heat the DHW. Such cascade systems used to pre-heat DHW with the DH return are commonly used in Sweden [17], and were beneficial to PVT systems where a lower DH return temperature was desirable to maximise cooling of the PV.

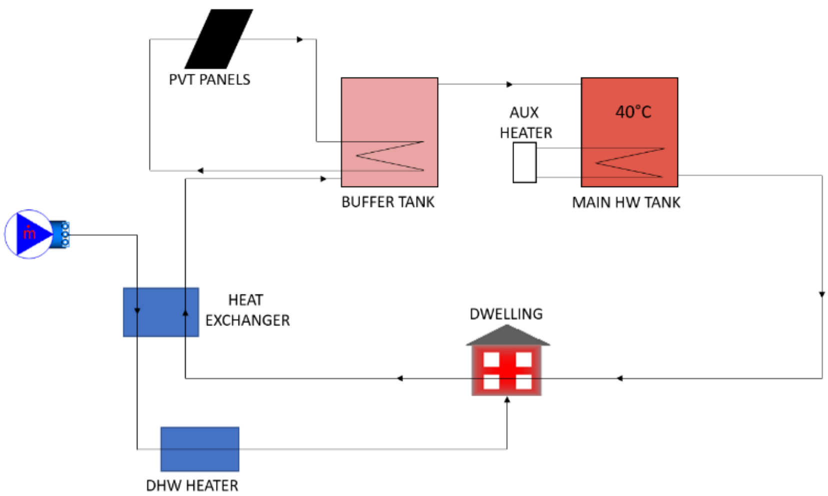

Figure 1: High level schematic diagram of PVT heating system.

2.3.1. PVT Collector Thermal Modelling
Tests modelled 184m^2 of PVT mounted on the available south facing area of the roof at a tilt angle of 39°, the annual average optimum angle for the building location [18]. The PVT model

was based on a commercial PVT collector and calibrated against EN19275-2 test data from Eurofins [19]. Thermal modelling of the PVT collector was based on the Modelica Buildings Library EN19275 Solar Collector model, where solar heat gains ($Q_{flow,i}$) and losses ($Q_{loss,i}$) were calculated by equations 1 and 2. The Modelica PVT model was tested under the same test conditions as in the Eurofins lab testing and matched closely with the measured leaving water collector temperature. The collector was modified so that operation could switch between OC and MPP modes, controlled by an input signal. MPP mode coefficients were taken from the test data report [19] and OC mode values were derived from the study by Guarracino [11]. Performance coefficients, η_0, C_1 and C_2 were different for both OC and MPP modes.

$$\mathrm{Q}_{loss,i} = \frac{\mathrm{A}_c}{\mathrm{n}_{seg} \times (\mathrm{T}_{env} - \mathrm{T}_{flu,i})(\mathrm{C}_1 - \mathrm{C}_2(\mathrm{T}_{env} - \mathrm{T}_{flu,i}))} \tag{1}$$

$$\mathrm{Q}_{flow,i} = \frac{\mathrm{A}_c}{\mathrm{n}_{seg} \times \eta_0(\mathrm{K}_{\tau\alpha}\mathrm{G}_{Beam}(1 - \mathrm{ShaCoe}) + \mathrm{K}_{Diff} \times \mathrm{G}_{Diff})} \tag{2}$$

where A_c was array area (m^2), n_{seg} - number of segments, T_{env} - ambient temp (°C), $T_{flu,i}$ - inlet temp (°C), C_1 - heat loss coefficient (W/m^{2}K), C_2 - temp dependence of heat loss (W/m^{2}K^2), η_0 - zero-loss efficiency, $K_{\tau\alpha}$ - beam IAM, G_{Beam} - beam radiation (W/m^2), $ShaCoe$ - shading coefficient, K_{Diff} - diffuse IAM, and G_{Diff} - diffuse radiation (W/m^2).

2.3.2. PVT Collector Electrical Modelling
Above 25°C, PV cells efficiency was reduced by the temperature derating co-efficient, λ (%/K). To compare PVT and conventional PV electrical performance the cell temperature of both technologies was calculated. The temperature of the conventional PV cell (without cooling) was calculated using the equation [20]:

$$\mathrm{T_c} = \mathrm{T_a} + 0.035 \times \mathrm{TSI}, \tag{3}$$

where T_c was the PV Cell Temperature (°C), T_a was the Ambient Air Temperature (°C), and TSI the Total Solar Irradiance (W/m^2). The PVT cell temperature was calculated by [21]:

$$\mathrm{T}_{cell,PVT} = \mathrm{T}_{mean} + \frac{\dot{\mathrm{q}}_{flow}}{\mathrm{U}_{AbsFluid}}, \tag{4}$$

where T_{mean} was the PVT fluid mean temperature (°C), $\dot{q}_{flow}$ was the useful thermal output (W/m^2) and $U_{AbsFluid}$ was the internal heat transfer coefficient between cell and fluid (W/m^{2}K). $U_{AbsFluid}$ was variable and dependent on the flow rate and fluid temperatures of the PVT.

3. Results and Discussion
PVT thermal outputs were sensitive to the flow rate through each PVT panel, where higher flow rates increased the amount of useful heat added to the buffer tank. Lower flow rates through the radiator in each zone reduced the DH return temperature. Figure 2 shows how DH return temperatures ranged from about 24 to 19°C for flow rates between 0.04 to 0.01 kg/s. With a radiator flow rate of 0.01 kg/s and a counterflow heat exchanger implemented on the DH return to pre-heat the DHW, the DH return temperature was further reduced and fluctuated between about 11 and 18°C. Lower DH returns were achieved during higher solar irradiance hours when less space heating (SH) was required and consequently lower flow rates through the DHW heat exchanger. These sensitivities demonstrated how variable flow rates can play a key role in fourth generation DH together with PVT and well-designed control. The dual thermal mode switching of the PVT could also be controlled by parameters such as the buffer tank temperature or a function of ambient temperature/solar irradiance. From January to March, the PVT thermal

output covered only about 18% of SH demands, with SH demands higher than the PVT thermal output, it could be more economical to switch the PVT to OC mode, especially if the DH heat tariff is higher than the electricity tariff. In summer, when DHW demands were lower than the thermal output at times, the system could operate in an open loop MPP mode configuration, where the cooling effect mazimised the PVT electrical output and was greater than conventional PV output. Overheating protection control could also be implemented in summer to priotise electrical performance [21].

During winter in a temperate oceanic climate such as London, the benefit of PVT cooling was almost negligent in comparison to conventional PV. With ambient temperatures being generally low with less solar irradiance, conventional PV was not significantly affected by temperature derating. In summer months, the PVT electrical output was higher compared to conventional PV since the PVT cooling effect was heightened with lower inlet temperatures. Also conventional PV cell temperatures were higher due to greater ambient temperatures and irradiance.

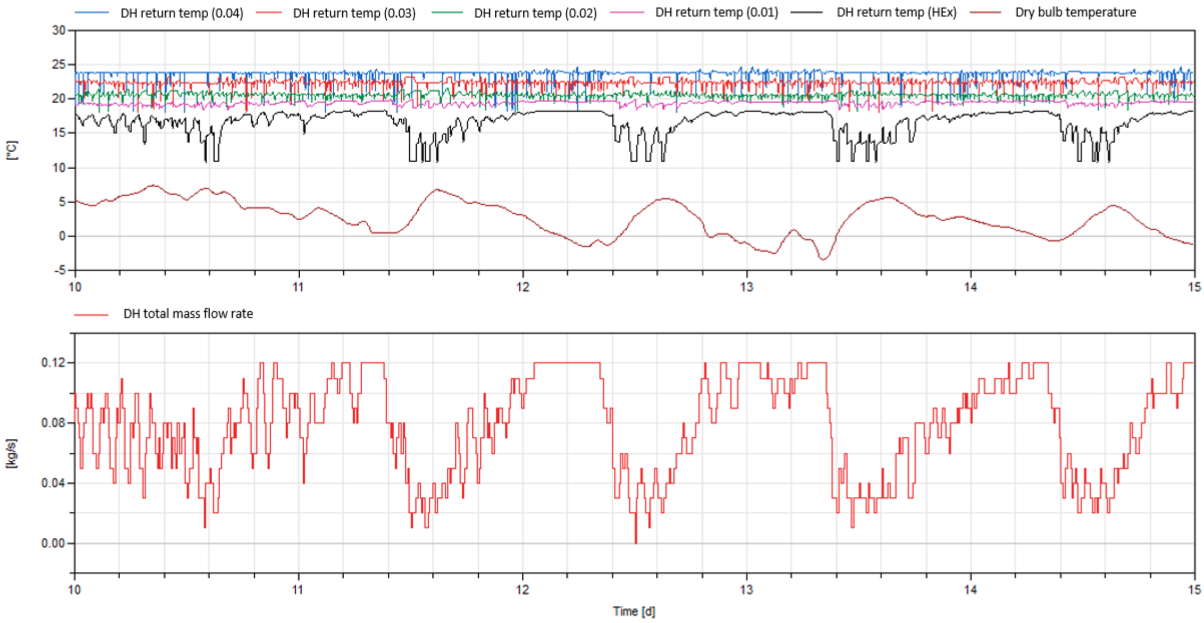

Figure 2: DH return temperature for various radiator flow rates and a DHW heat exchanger.

4. Conclusion

Since the PVT cell temperature was dependent on the collector mean fluid temperature, it was important for PVT DH systems to have a low DH return temperature. PVT DH configurations can include a separate low-temperature buffer tank and heat exchanger on the DH return to pre-heat DHW to reduce DH returns temperatures and maximise the PVT utilisation. Winter months could implement PVT dual thermal modes as part of the control strategy since it could be more economical to boost the thermal output if the heat tariff costs more than electricity. The PVT cooling effect was most beneficial in summer when conventional PV output would be lower due to a higher level of temperature degradation, and almost negligent in winter. Therefore, seasonal configurations and control schemes were required for maximising PVT output in DH configurations, where variable flow rates, dual mode switching and overheating protection could be implemented as part of well designed control strategies for fourth generation DH. The new Modelica PVT model and co-simulation methods described in this paper are important tools to progress the development of such work. Findings could contribute to the knowledge of relatively new PVT technology and aid market acceleration. Clean energy technologies will play a crucial role in the drive to reduce emissions, therefore the exploration of the potential for such systems could aid policy makers and industry to make informed decisions.

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