SOLAR HEAT AND POWER WITH THERMAL ENERGY STORAGE IN THE UK

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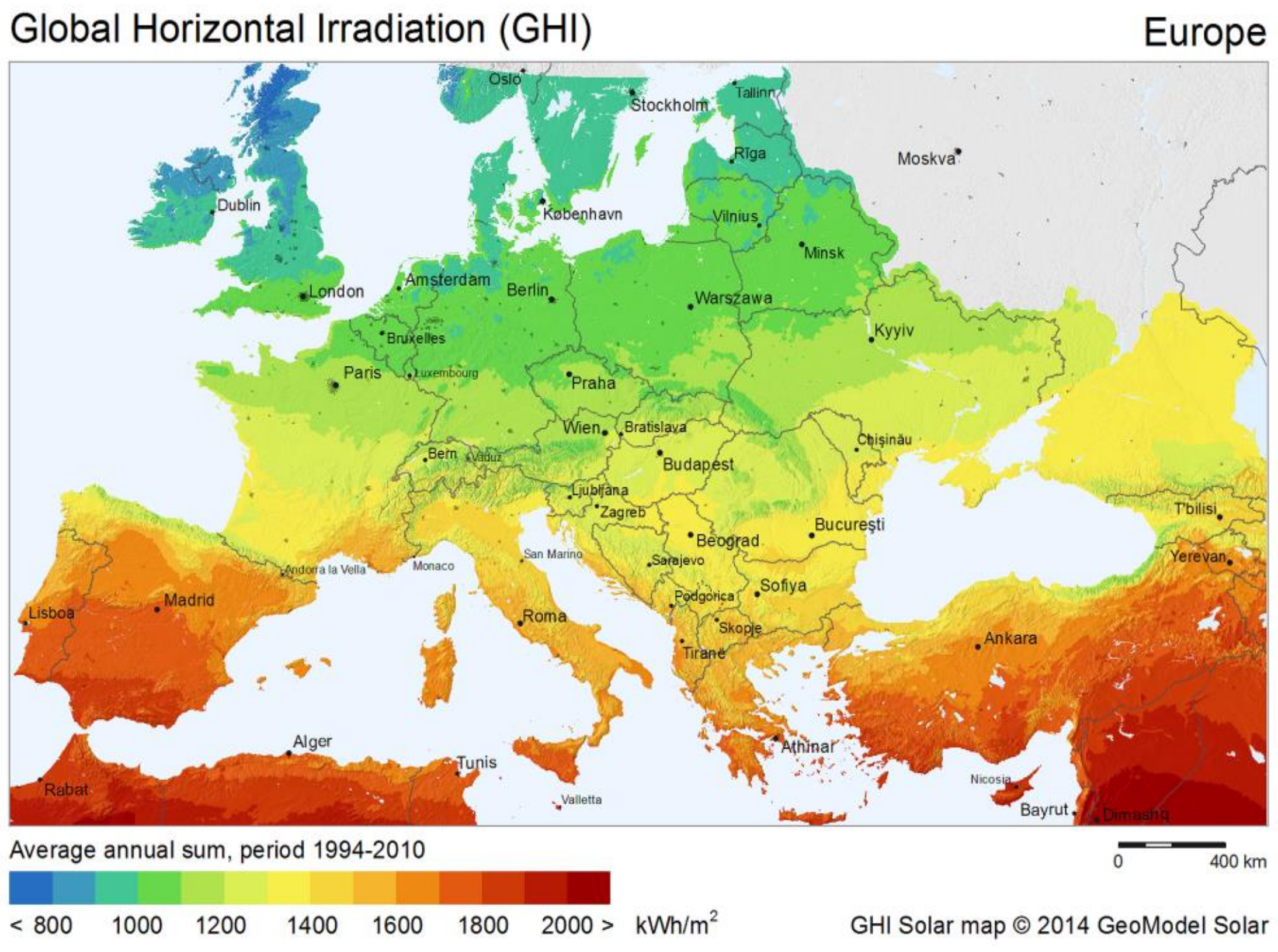


Figure 1: Total solar irradiation available on the surface

Solar energy has the potential to cover a high fraction of the demand for heat and electricity in residential buildings. Fig. 1 shows the variation in incident solar irradiation received across Europe.

In London the annual solar irradiation is ~1100 kWh/m^2 per year, while the typical domestic energy consumption per household is ~12000 kWh/year for heating and ~4000 kWh/year for electricity. Thus the solar energy received on a rooftop of ~15 m^2 is enough potentially enough to provide the entire annual demand for domestic energy.

Our research focuses on various aspects of two solar technologies for the combined provision of heating and power (CHP): solar organic Rankine cycle systems with low-to-medium temperature solar-thermal collectors (Figs. 2-3) and hybrid photovoltaic/thermal (PVT) systems. (Fig.4).

Figure 2: Vacuum-tube collectors

Figure 3: Thermal collectors

Figure 4 (a-b): Photovoltaic/thermal modules

SOLAR ORGANIC RANKINE CYCLE (ORC)

SYSTEM CONFIGURATION, ENERGY AND COST ANALYSIS

In a solar combined heat and power (S-CHP) system based on an ORC engine, the thermal energy needed to evaporate the working fluid is provided by solar thermal collectors. The heat rejected during de-superheating and condensation may also be used for useful downstream processes such as water heating (Fig. 5).

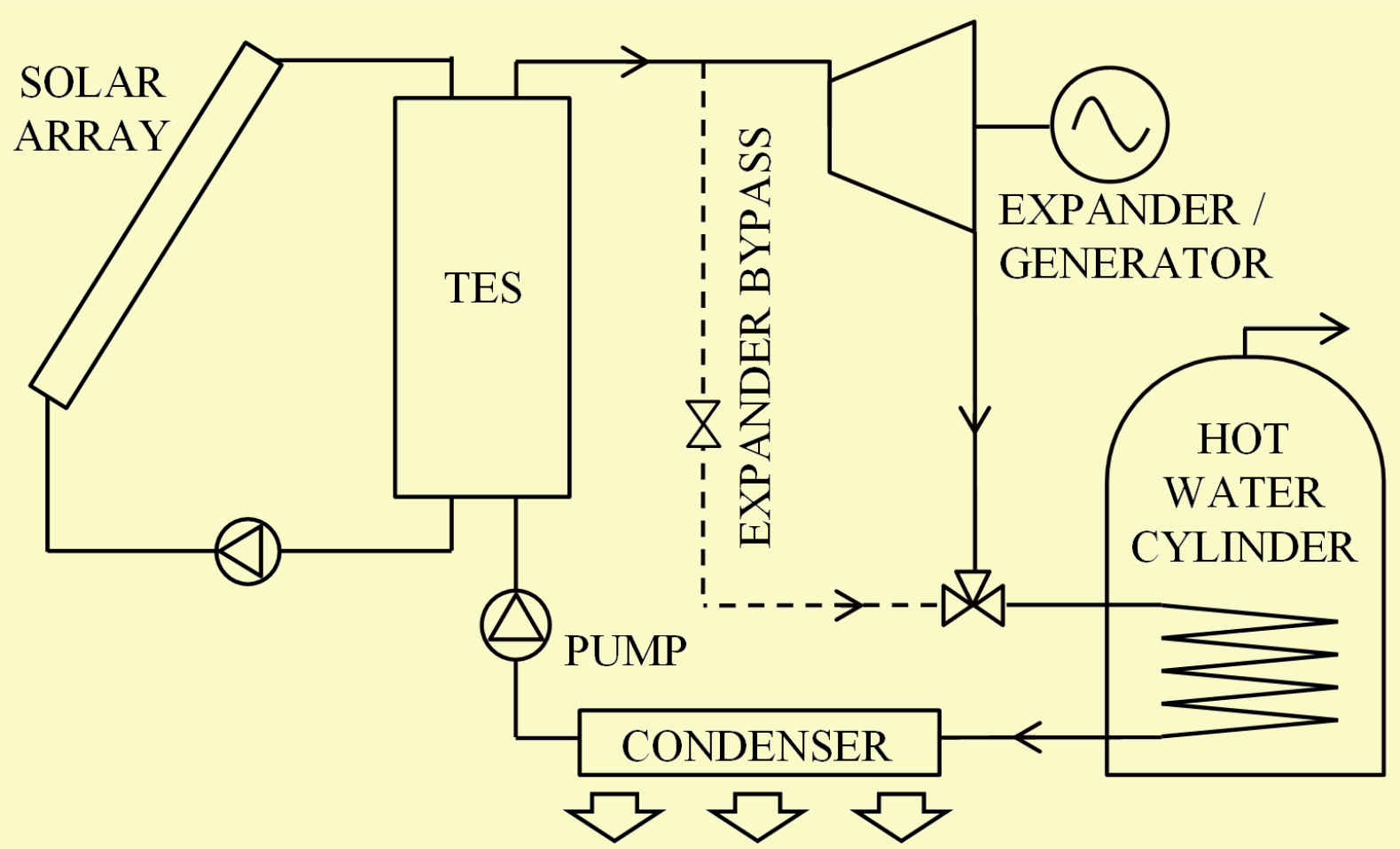


Figure 6: S-CHP system schematic

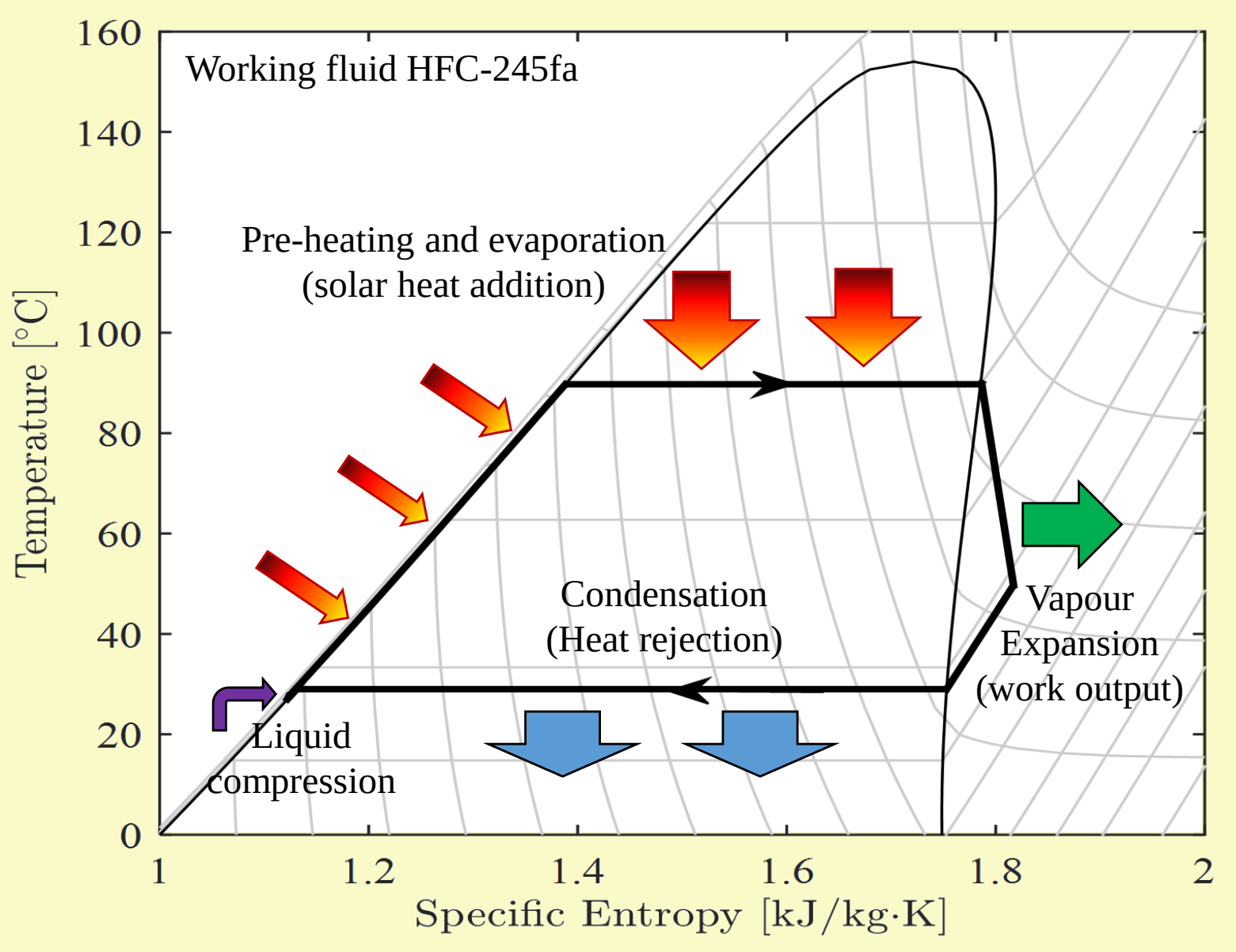


Figure 5: *T-s* diagram of an organic Rankine cycle

The daily operation of a solar thermal power system is highly dependent on the annual characteristics of the solar resource [1]. In London, a domestic-scale S-CHP system using non-concentrating collectors could provide an instantaneous electrical output of up to 1 kW, but without thermal energy storage would be subject to intermittent operation.

Solar ORC research areas:

- Suitable working fluids (including mixtures) for optimal performance with low cost stationary solar collectors
- Novel collector designs for direct evaporation of working fluid
- Positive-displacement (including reciprocating) expanders for small-scale ~1 kW systems
- Integration of thermal energy storage (TES)

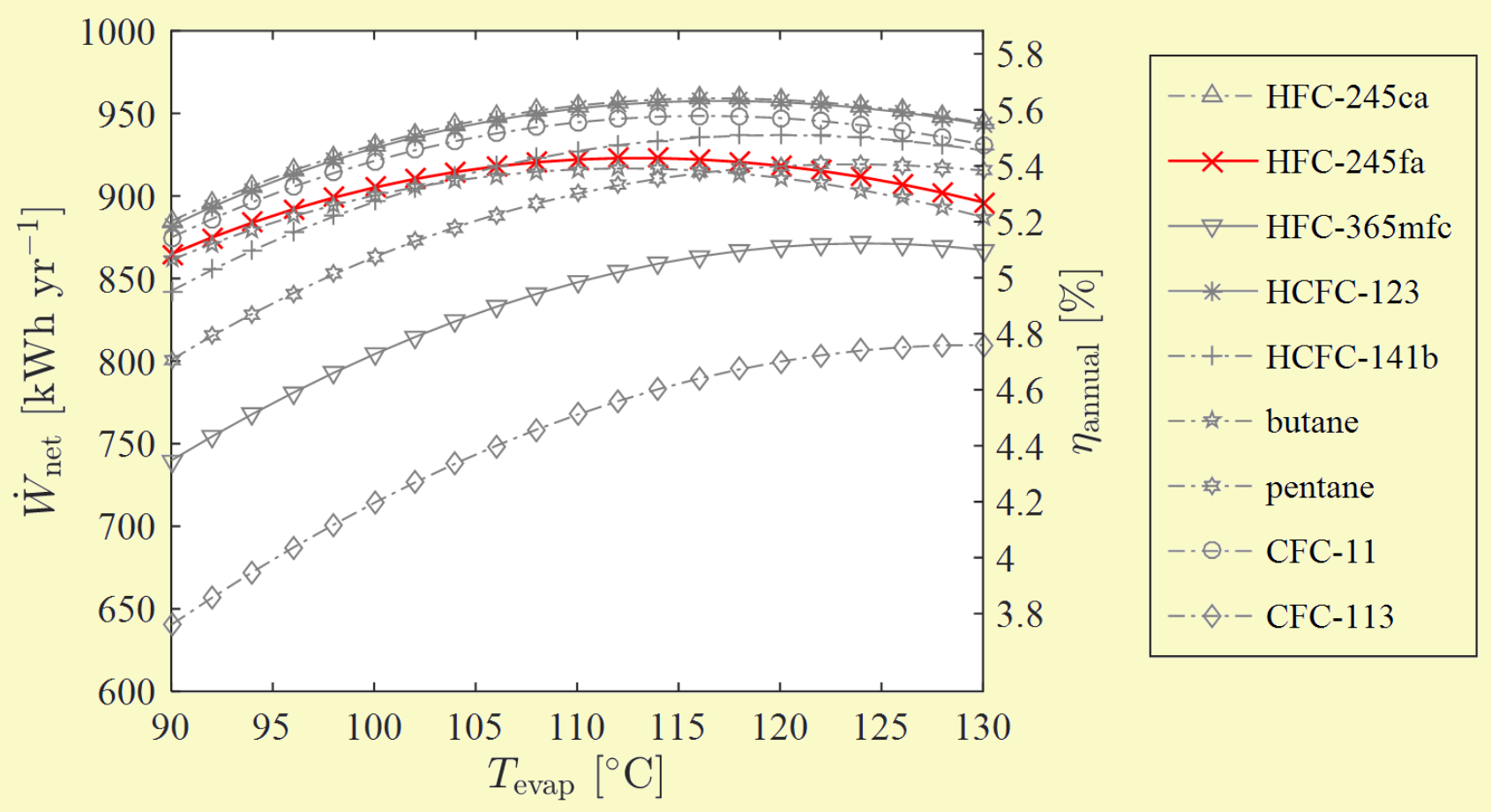


Figure 7: Annual performance of various working fluid and evaporation temperature combinations

THERMAL ENERGY STORAGE OPTIONS FOR SOLAR ORC SYSTEMS

- Direct storage in working fluid [1,2]
- Indirect sensible storage using water [3]
- Phase change materials (PCM)
- Thermochemical energy storage

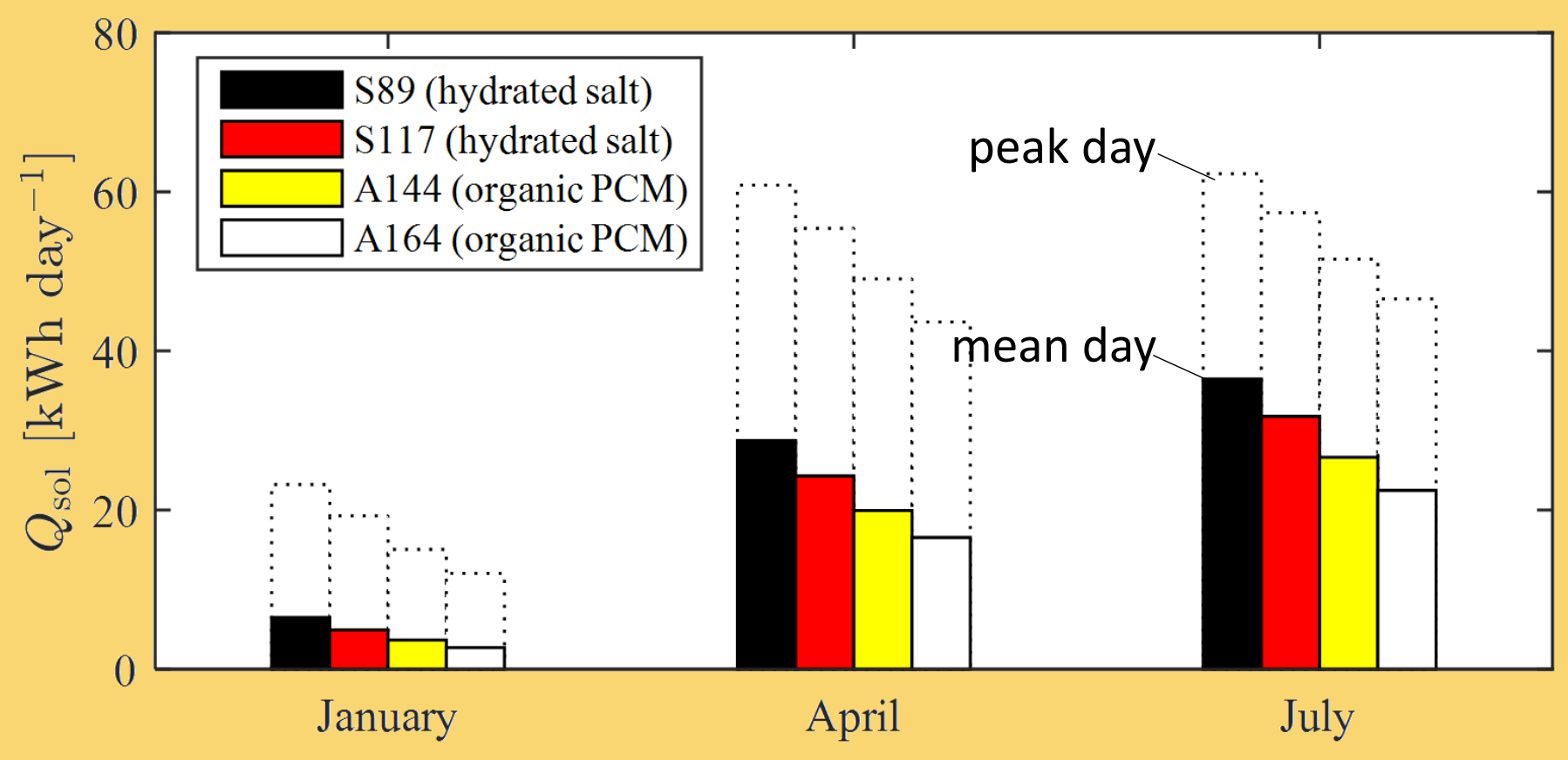
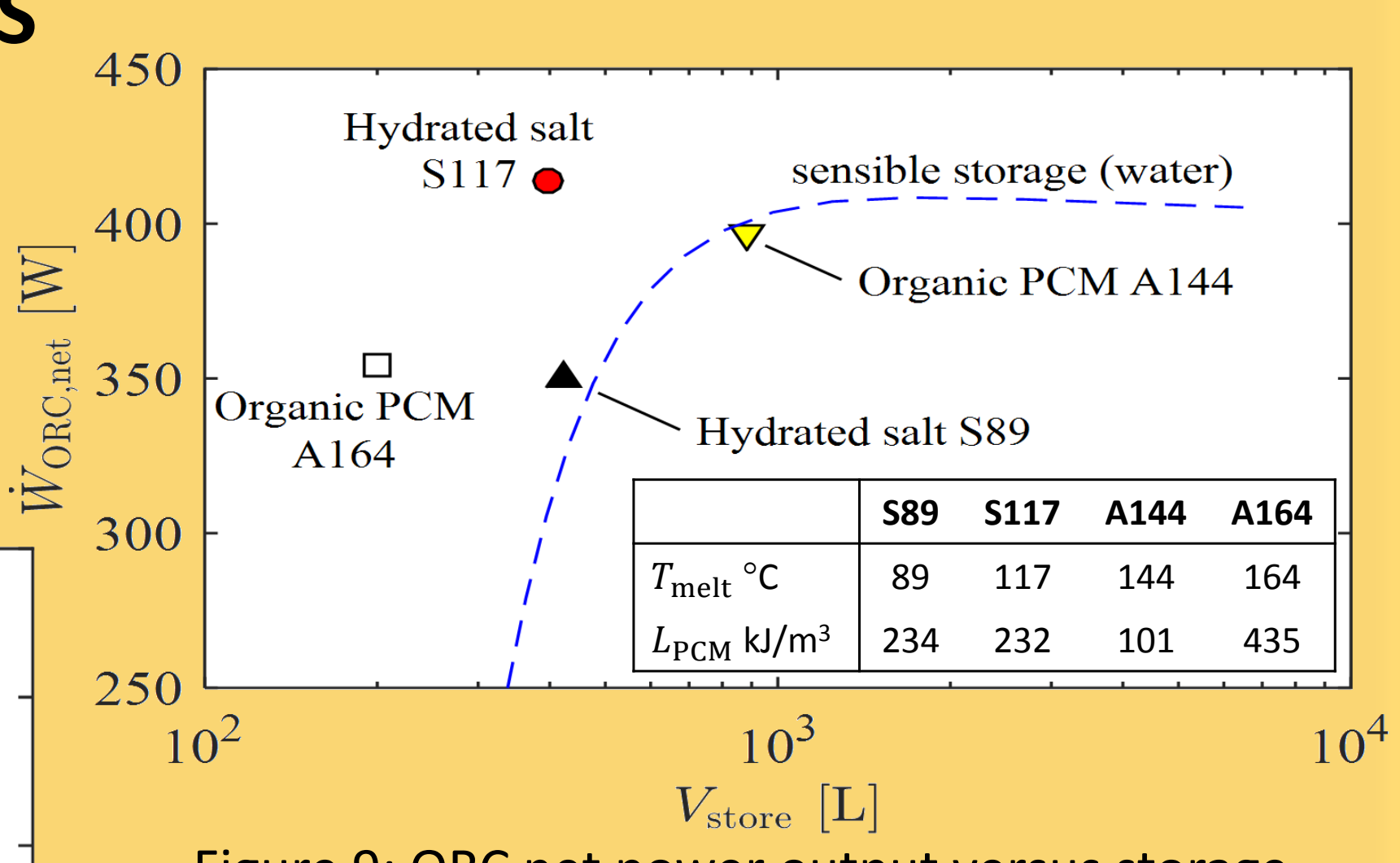


Figure 8: Summer, winter and mid-season performance for various solar collector and PCM combinations (UK)



	S89	S117	A144	A164
T_{melt} °C	89	117	144	164
L_{PCM} kJ/m^3	234	232	101	435

Figure 9: ORC net power output versus storage volume requirement various TES options (July, UK)

The operating temperature range of the TES medium is matched to the optimum ORC evaporation temperature in order to provide maximum power output from the system while minimising the required storage volume.

EXPERIMENTAL ORC SYSTEM

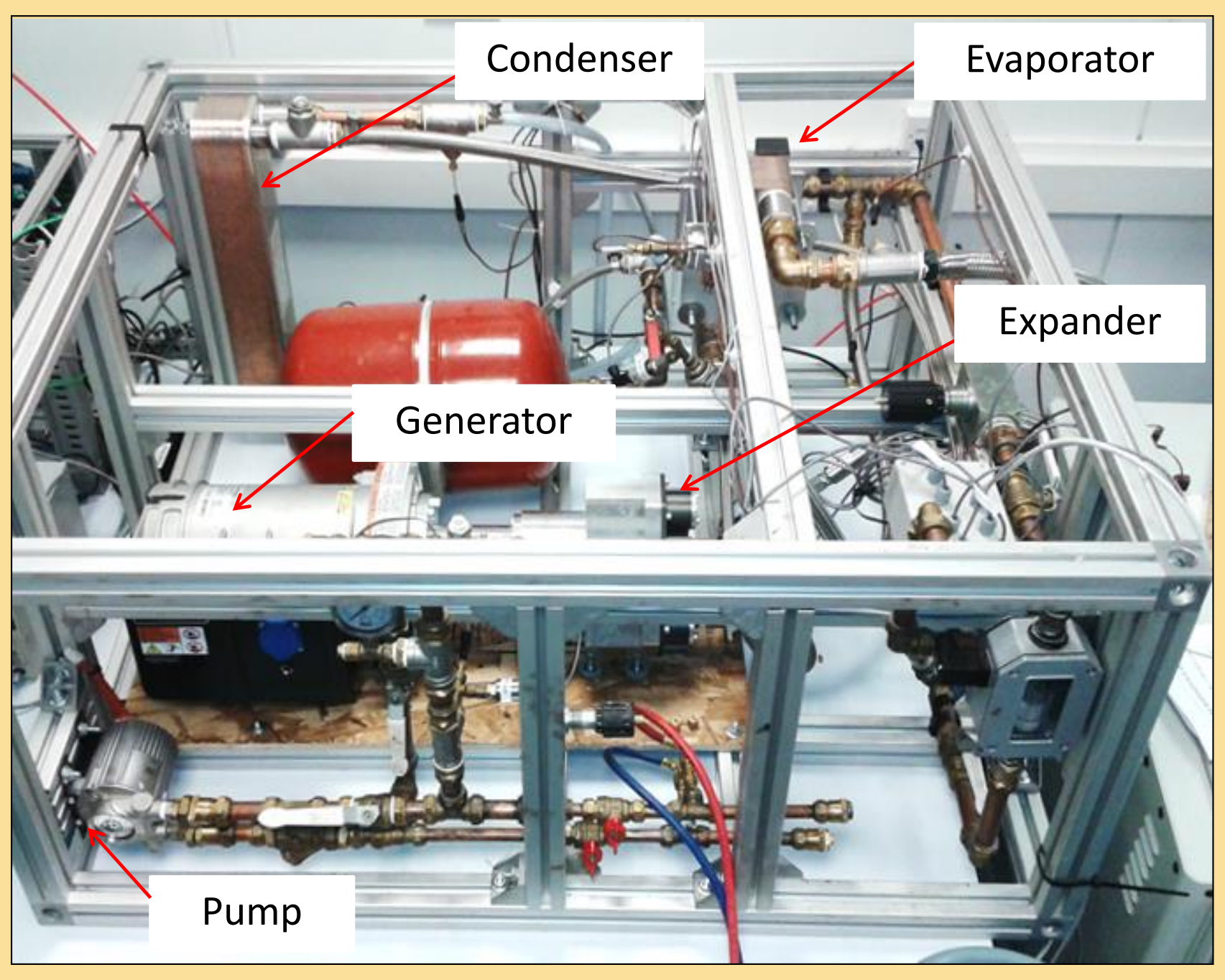


Figure 10: Experimental ORC system in CEP laboratory

Table 1: ORC operating parameters

Working fluid	HFC-245fa
Expander	1 kW volumetric (scroll) machine
T_{evap} / p_{evap}	6-10 bar / 70-90 °C
Thermal input	10-15 kW, thermal oil, 80-150 °C
T_{cond} / p_{cond}	1-2 bar / 15-30 °C

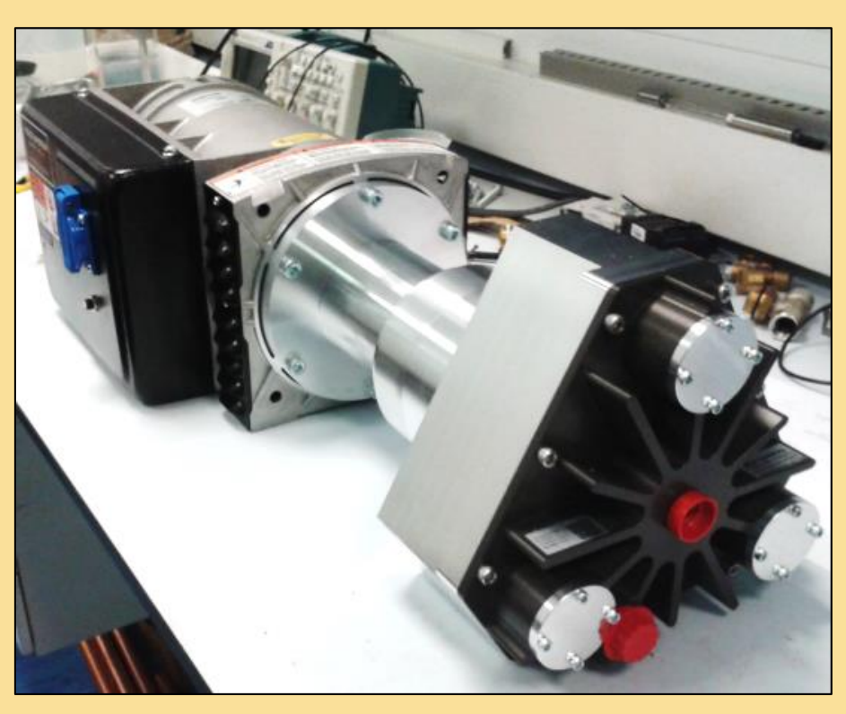


Figure 11: Expander/generator

Figure 12: Collector array

HYBRID PHOTOVOLTAIC/THERMAL (PVT)

PVT MODULE THERMAL AND ELECTRICAL ANALYSIS

In PVT modules the PV cells are cooled by a fluid and useful heat is collected in addition to the electricity generated [4].

A 3-D numerical model of the module predicts the temperature distribution on the PV cell (Fig. 13), the fluid outlet temperature and the thermal efficiency (Fig. 14a) [5]. The model is validated against experimental measurements (Fig. 15).

In a PVT module the solar cells operate at a lower temperature than conventional PV modules and achieve higher electrical efficiencies. Figure 14b shows how PV cell electrical output decreases with temperature.

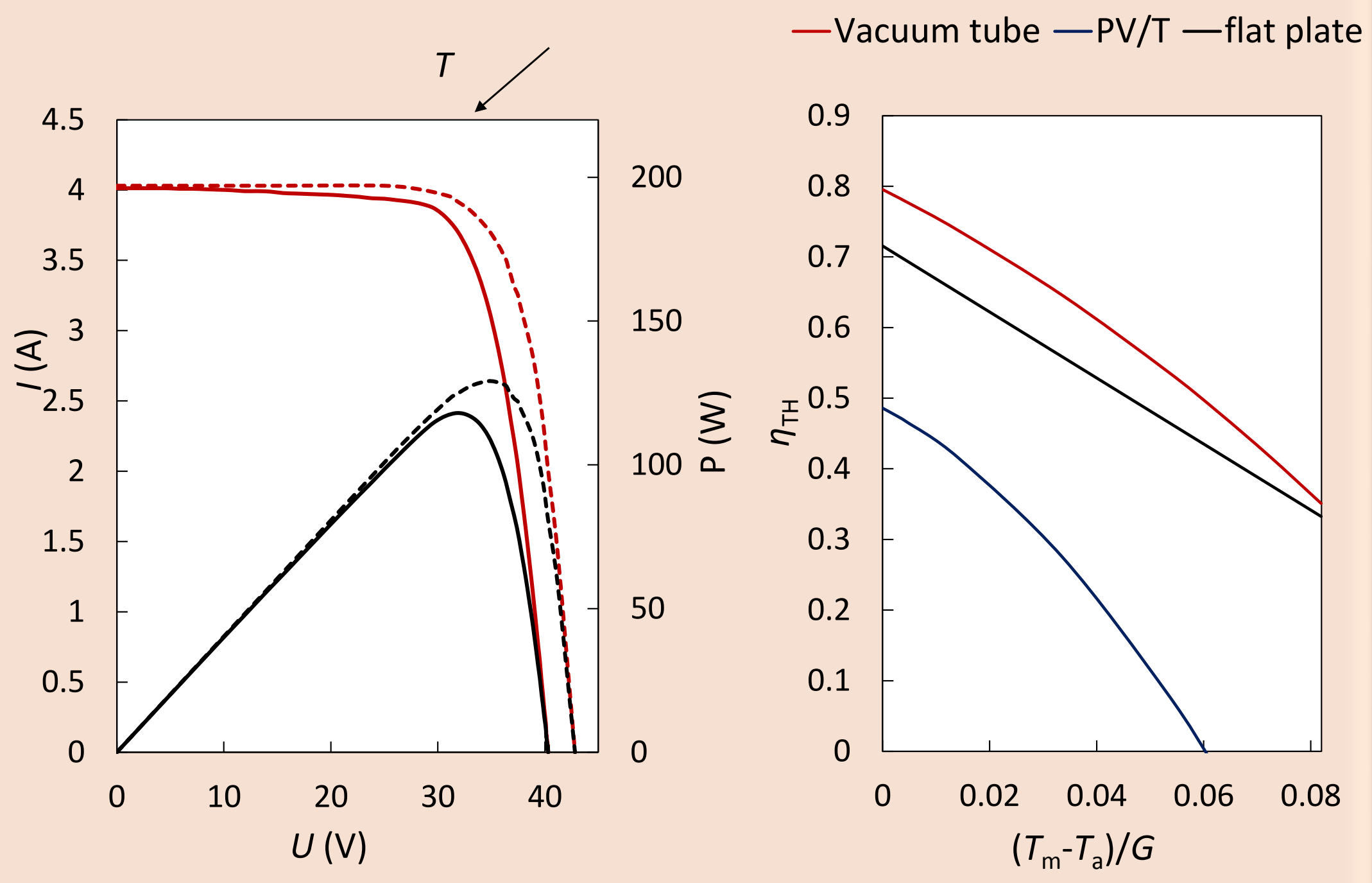


Figure 14: a) I-V curves and power of PVT modules at two temperatures (measured). b) Thermal efficiency curve of the PVT and thermal modules

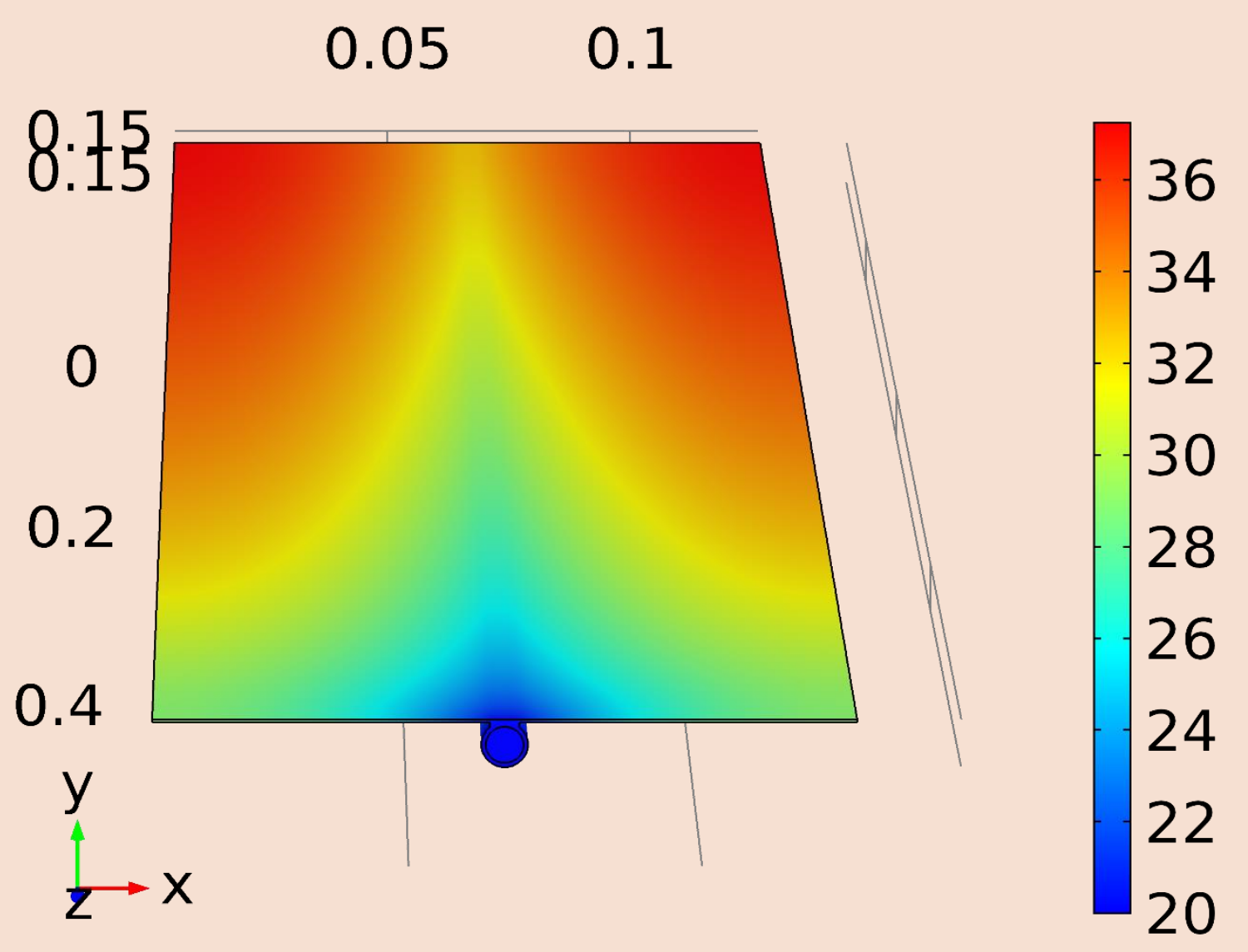


Figure 13: Temperature distribution along PVT module surface

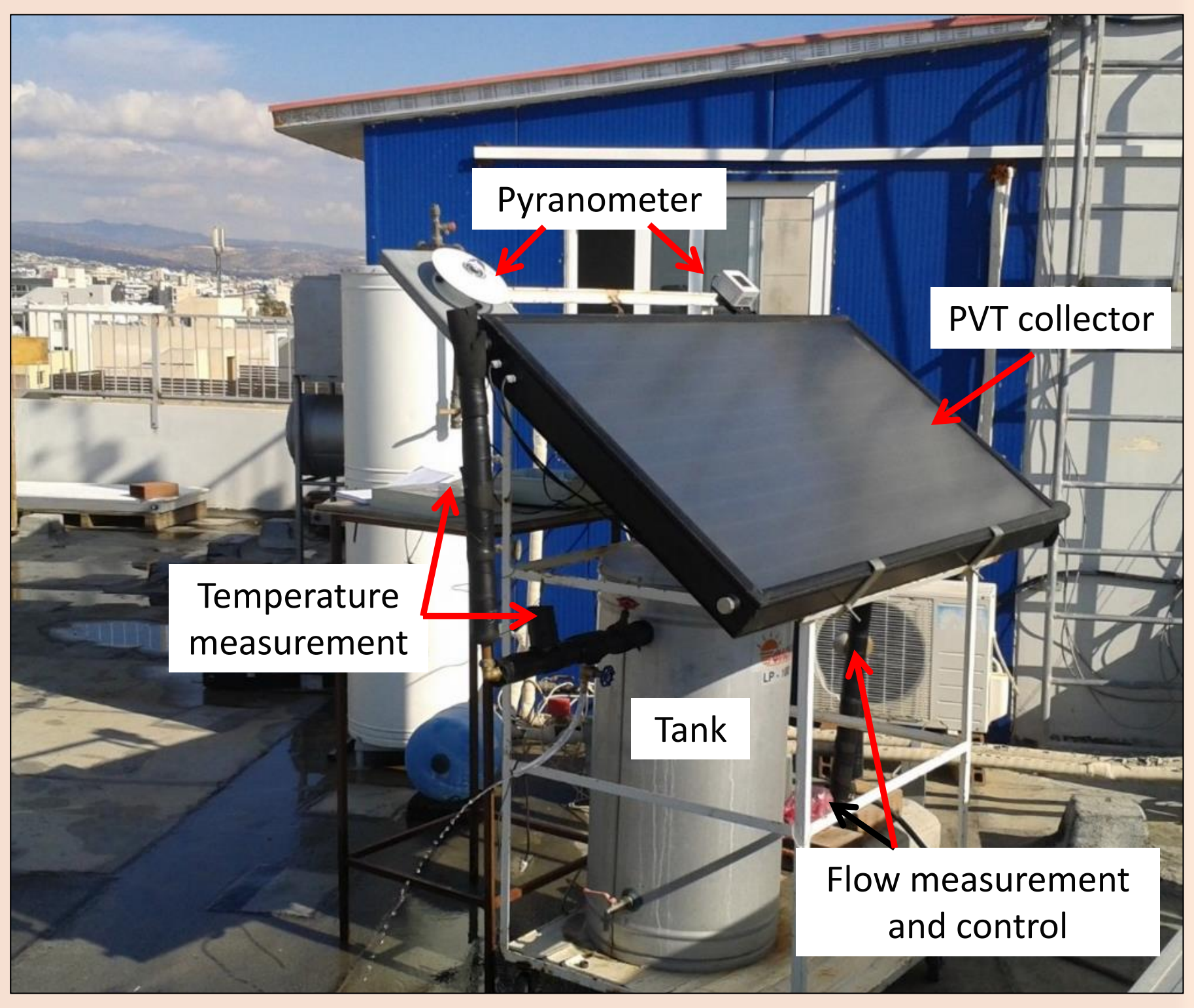


Figure 15: PVT collector testing apparatus

SYSTEM ENERGY AND COST ANALYSIS

Whole-system simulation is used to assess system performance in various geographical locations. In London, a PVT system (Fig. 16) covers a predicted 45-60% of electricity demand and 35-70% of hot water demand, with the monthly generation data shown in Fig. 17. Levelised costs for heat and power are calculated and compared with other technologies, including solar-ORC. The capital cost breakdown of a PVT system is shown in Fig. 18 [3].

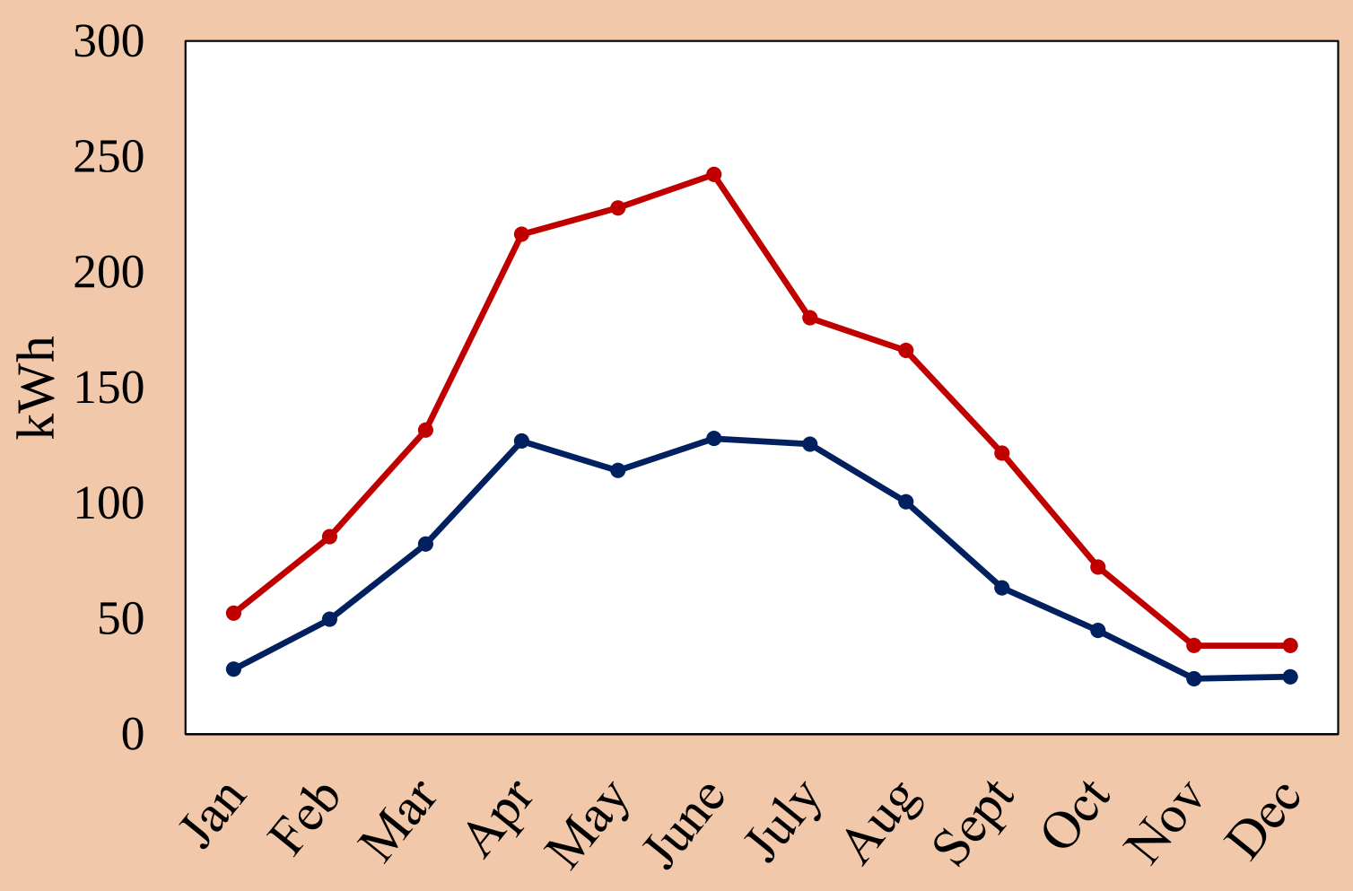


Figure 17 : Monthly generation of electricity (red line) and hot water (blue line)

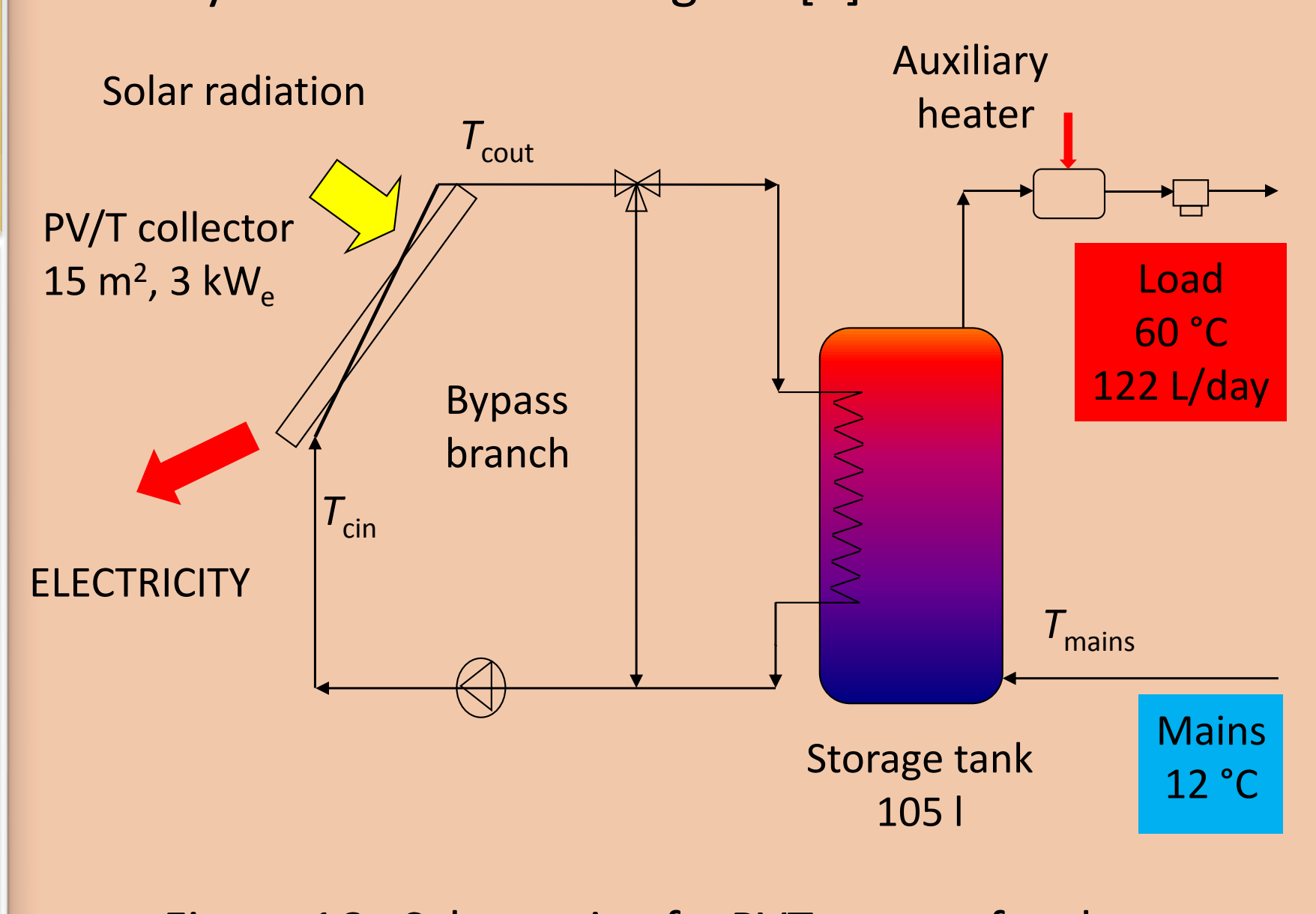


Figure 16 : Schematic of a PVT system for the provision of electricity and domestic hot water

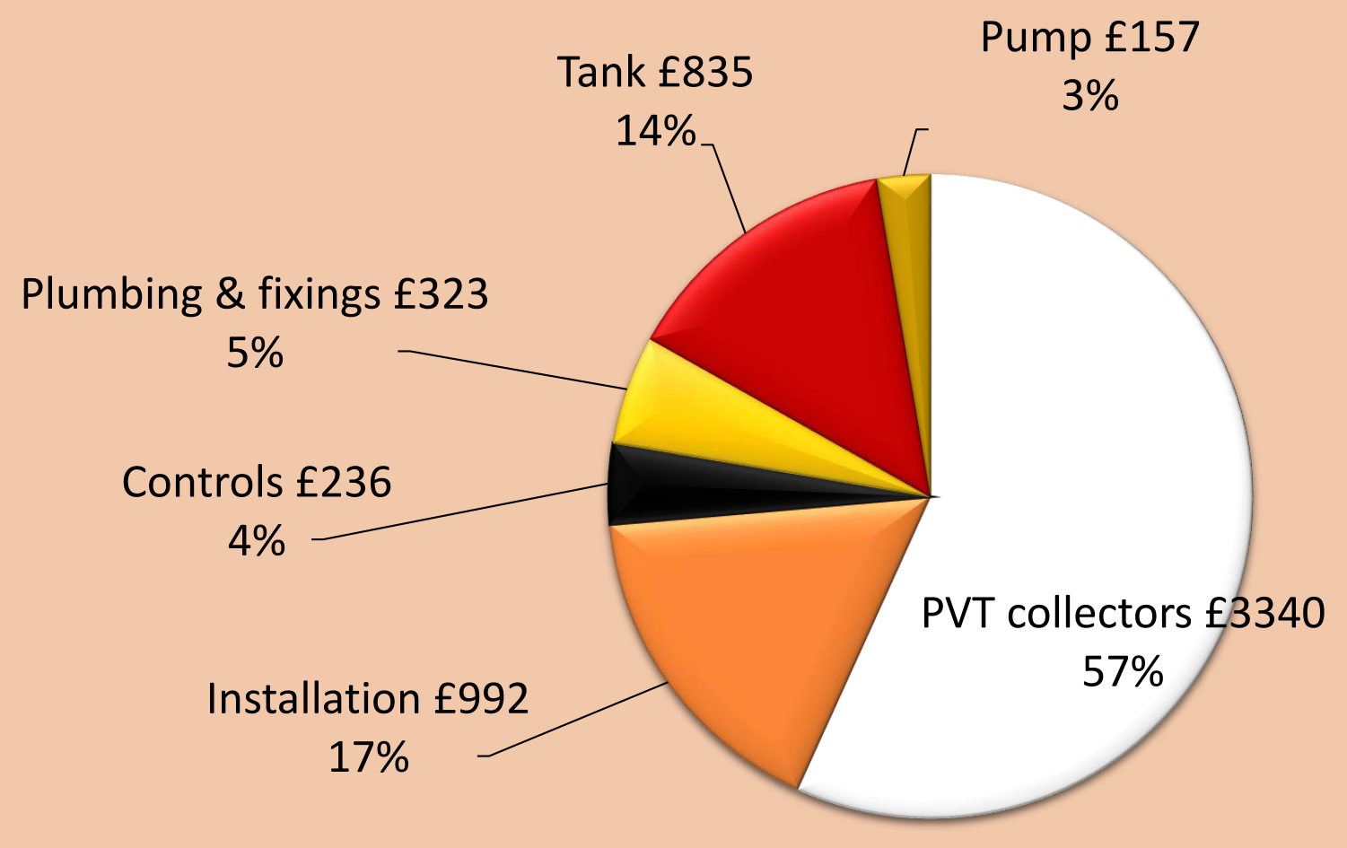


Figure 18: Capital cost breakdown of a PVT system

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[2] Casati et al., *Sol. Energy* 96, 2013,.
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[4] Santbergen and van Zolingen, *Sol. Energy Mater. Sol. Cells* 92, 2008.
[5] Guarracino et al., *Appl. Therm. Eng.,* 2016. Accepted for publication.