A SMALL-SCALE SOLAR ORGANIC RANKINE CYCLE COMBINED HEAT AND POWER SYSTEM WITH INTEGRATED THERMAL-ENERGY STORAGE

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ABSTRACT

In this paper, we examine integrated thermal energy storage (TES) solutions for a particular domestic-scale solar combined heat and power (S-CHP) system based on an organic Rankine cycle (ORC) engine and low-cost non-concentrated solar-thermal collectors. TES is an essential system component for steady operation in climates with high solar irradiance variability. The operating temperature range of the TES solution must be compatible with the solar collector array and ORC engine in order to maximise the overall efficiency of the system. Various combinations of phase change materials (PCMs) and solar collectors are compared and the S-CHP system's electrical performance is simulated for selected months in the contrasting climates of Cyprus and the UK. The key performance parameter of the ORC engine (net power output) and the required TES volume are compared and discussed. Through the selection of an appropriate PCM it is found that a higher sustained power output per required storage volume can be achieved compared to water as a sensible heat storage medium. The TES solutions that achieve the best summer performance from the ORC engine result in diurnal volume requirements of 20-90 L in Cyprus and 200-400 L in the UK.

NOMENCLATURE

Abbreviations

A	area, m^2
G	solar irradiance, W m^{-2}
K_θ	incident angle modifier, -
h	specific enthalpy, J kg^{-1}
L	latent heat capacity, J kg^{-1}
m	mass, kg
Q	heat / thermal energy, J
T	temperature, °C, K
W	mechanical / electrical work, J

Subscripts

1,2,3…	cycle state points
a	ambient air
b	beam
c	collector
d	diffuse
exp	expander
melt	melting point
r	refrigerant
u	useful energy

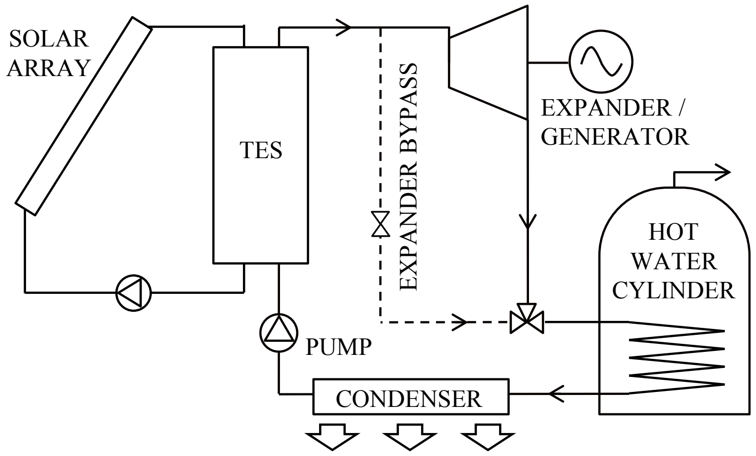
INTRODUCTION

Solar-thermal power systems have the potential to provide clean energy in the form of electricity and useful heat (domestic hot water and/or space heating) across a wide range of applications. While steam-Rankine and Stirling cycle-based systems are proven technologies for use with medium-to-high temperature concentrating solar-thermal collectors, organic Rankine cycle (ORC) systems show strong potential for use in small-scale systems (< 10 kW$_e$) with low-temperature, non-concentrating collectors (Freeman et al., 2015; Markides, 2015). The steady operation of such systems under time-varying solar irradiance is dependent on the integration of suitable thermal energy storage (TES) solutions. Large-scale steam-Rankine concentrating solar power (CSP) plants typically use indirect TES media such as molten salts (Kalogirou, 2014). TES solutions for small-scale ORC systems include direct storage in the working-fluid liquid or vapour phase (Casati et al., 2013), packed bed thermal energy storage (Quoilin et al., 2011) and solid-liquid phase change materials (Jing et al., 2010).

In earlier work (Guarracino et al., 2016), the authors presented a domestic-scale solar combined heat and power (S-CHP) system based on an ORC engine, taking a thermal input from a 15 m^2 rooftop solar thermal collector array. The possibility was investigated of using a stratified hot-water storage tank to buffer the solar energy input to the ORC as well as to provide domestic hot water. The operating temperature range of the storage medium was found to be non-optimal for both the operation of the solar collector array and the ORC engine in providing maximum work output from the system over the annual period. In this paper, a range of phase change materials (PCMs) will be considered for use as TES media in the S-CHP system. Specific attention will be given to the selection of the PCM physical properties (in particular, the melting temperature and latent heat capacity) for maximisation of both energy storage density and ORC power output.

METHODOLOGY

Figure 1 shows the layout of the S-CHP system of interest. A thermal store (TES) acts as the interface between the collector array and the ORC engine, while a hot water cylinder re-claims thermal energy from the de-superheating of the exhaust vapour from the expander. The present study considers two types of non-concentrating collector: (i) a new-generation evacuated flat-plate (EFP) collector developed especially for medium temperature process-heating applications (including ORC systems); and (ii) a standard evacuated-tube heat pipe (ETHP) collector designed for low-temperature domestic water heating applications. The collector array is modelled as south-facing, with an inclination angle of 38°, and constrained to within the dimensions of a typical domestic roof-space, assumed to be 15 m^2 (Freeman et al., 2015).



EFP collector [Ref.: TVP Solar (2013)]:
Model: *TVP solar HT-power*
A = 1.95 m^2 (module)
η_0 = 0.774
a_1 = 0.376 m^2 K W^{-1}
a_2 = 0.006 m^2 K^2 W^{-1}

ETHP collector [Ref.: ISFH (2013)]:
Model: *Thermomax HP 200*
A = 2.84 m^2 (module)
η_0 = 0.556
a_1 = 0.888 m^2 K W^{-1}
a_2 = 0.006 m^2 K^2 W^{-1}

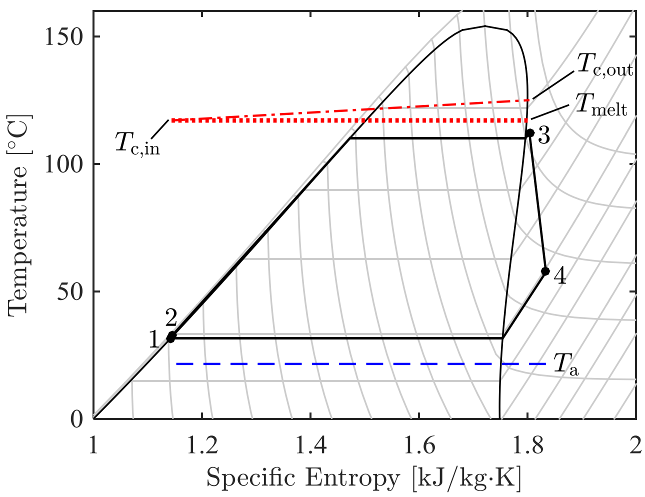
Figure 1: Schematic of the S-CHP system and efficiency-curve coefficients (stated for gross area) of the solar collectors

Calculations are performed at hourly time-intervals in MATLAB, subject to the following assumptions: (i) the system is operating under quasi-steady state conditions, with the collector thermal capacity neglected; (ii) the system is operational only for the hours of the day when the solar incidence angle on the tilted collector plane is < 70º; (iii) thermal losses from the store are negligible; and (iv) the thermal store begins each day in a fully discharged (solidified) state.

The performance of the solar collectors is simulated using hourly climate data for London and Larnaca (ASHRAE 2001). The collectors are modelled using the steady state efficiency equation (Eq. 1), which is solved by assuming that the inlet fluid temperature is equal to the melting temperature of the PCM being considered. Thus the useful solar energy gain is a function of both the choice of collector and the storage medium that governs the collector operating temperature:

$$\dot{Q}_\mathrm{u} = \eta_0 A\left(K_{\theta,\mathrm{b}} G_\mathrm{b} + K_{\theta,\mathrm{d}} G_\mathrm{d}\right) - a_1 A(\bar{T}_\mathrm{c} - T_\mathrm{a}) - a_2 A(\bar{T}_\mathrm{c} - T_\mathrm{a})^2 \, . \qquad [1]$$

The calculations used for the thermodynamic cycle analysis of the ORC engine are summarised in Figure 2. Two widely-available working fluids are compared in the analysis: (i) R245fa, which has been previously investigated for use in low temperature solar-ORC systems and has a critical temperature of 154 ºC; and (ii) pentane, which has been investigated for use in higher-temperature solar-ORC systems and has a critical temperature of 197 ºC.



$$T_1 = T_{\mathrm{a,max}} + \Delta T_{\mathrm{pinch}}$$
$$T_3 = T_{\mathrm{melt}} - \Delta T_{\mathrm{pinch}}$$
$$T_{\mathrm{c,in}} = T_{\mathrm{melt}}$$
$$h_2 = h_1 + \left(h_{2,s} - h_1\right)/\eta_{\mathrm{pump}}$$
$$h_4 = h_3 - \eta_{exp}\left(h_3 - h_{4,s}\right)$$
$$\dot{W}_{\mathrm{pump}} = \dot{m}_{\mathrm{r}}(h_2 - h_1)$$
$$\dot{W}_{\mathrm{exp}} = \dot{m}_{\mathrm{r}}(h_3 - h_4)$$
$$\dot{W}_{\mathrm{net}} = \dot{W}_{\mathrm{exp}} - \dot{W}_{\mathrm{pump}}$$
$$\eta_{\mathrm{exp}} = 75\%;\ \eta_{\mathrm{pump}} = 65\%$$
$$\Delta T_{\mathrm{pinch}} = 5\ \mathrm{K}$$
$$\Delta T_{\mathrm{superheat}} = 5\ \mathrm{K}$$
$$\Delta T_{\mathrm{subcool}} = 0$$

Figure 2: *T-s* diagram of solar-TES-ORC processes and ORC equations and parameters

The sizing of the ORC engine in relation to the solar input and the store volume requires careful consideration. If the engine is over-sized in relation to the store, its operation will be limited to short periods, whereas if it is under-sized in relation to the solar energy input, a larger storage volume will be required to make full use of any surplus energy collected when solar irradiance is abundant. In the monthly analysis, the ORC working fluid mass flow-rate is set based on Eq. 2 and the monthly mean solar energy gain (during operational hours), while the TES volume requirement is calculated as the difference between the maximum and mean solar energy yield per day, shown in Eq. 3:

$$\dot{m}_{\mathrm{r}} = \dot{Q}_{\mathrm{u,mean}}/(h_3 - h_2)\,, \qquad [2]$$
$$V_{\mathrm{store}} = \left(Q_{\mathrm{u,max}} - Q_{\mathrm{u,mean}}\right)/(\rho L)_{\mathrm{PCM}}\,. \qquad [3]$$

The required storage volumes and resulting ORC net power outputs for the various PCM options will be compared to that for an equivalent system with water as the energy storage medium. This requires the consideration of a large temperature range for sensible heat uptake rather than a small temperature range for latent heat uptake. It will therefore be assumed that the sensible storage medium operates between a minimum temperature, sufficient for the operation of the ORC engine, and a maximum temperature for which the storage medium (water) remains in its liquid state. This is taken as 130 °C, corresponding to a typical unvented hot water cylinder working pressure of 2 bar(g). The allowable daily temperature swing, and hence the required volume of the store, is dependent on the ORC evaporation temperature.

Table 1: Phase change material properties. (PCM Products Ltd., 2013)

Name	PCM type	T_{melt}, °C	L, kJ kg^{-1}	ρ, kg m^{-3}
S89	Hydrated salt PCM	89	1450	151
S117	Hydrated salt PCM	117	1550	160
A144	Organic PCM	144	880	115
A164	Organic PCM	164	1500	290

RESULTS AND DISCUSSION

Figure 3 shows the mean and maximum daily solar irradiation for each month of the year in Larnaca and London, respectively. The plots confirm that the Cyprus solar resource is both more abundant and undergoes less variation on a daily, seasonal and annual timescale than the UK. In Larnaca the mean daily irradiation on the tilted plane is 5.3 kWh m^{-2} day^{-1} compared to 2.9 kWh m^{-2} day^{-1} for London. The variation in daily irradiation for Larnaca is far smaller in summer than in winter, with a standard deviation of 0.2 kWh m^{-2} day^{-1} (3%) between the months of June to August; compared to 1.8 kWh m^{-2} day^{-1} (39%) over the same period for London. Thus a TES system designed to buffer daily variations in solar gain in Cyprus can be significantly smaller than one designed for the UK, and furthermore, can be significantly reduced in size if it is designed for summer-only operation compared to year-round operation, which is not true for the UK.

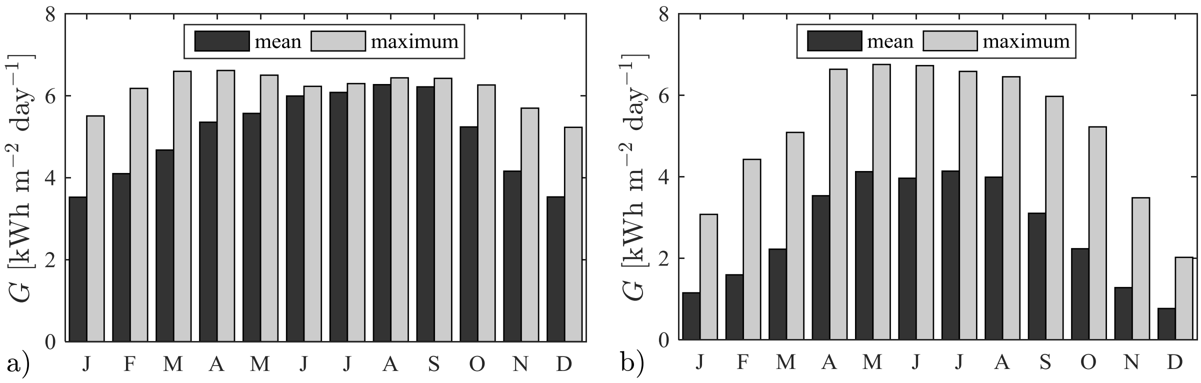


Figure 3: Mean and maximum solar irradiation per day for: a) Larnaca and b) London

Figure 4 shows the mean daily solar thermal energy collected by each collector and PCM combination in Larnaca and London, in selected months (January, April and July). The performance of the collector is highly dependent on the PCM melting temperature which is shown by the respective decrease in solar gain. The EFP collector is shown to operate with a significantly higher efficiency than the ETHP collector throughout the year in both the UK and Cyprus climates. The difference between the mean and maximum irradiation (solid and dashed bars) in Figure 4 informs the sizing of the thermal store shown in Figure 5, which is also dependent on the physical properties of the PCM listed in Table 1. It can be seen from the table that the density and mass-related latent heat capacity of the two hydrated-salt PCMs are quite similar; while for the two organic PCMs there is a considerable difference in both of these properties, resulting in a volumetric latent heat capacity that differs by a factor of four.

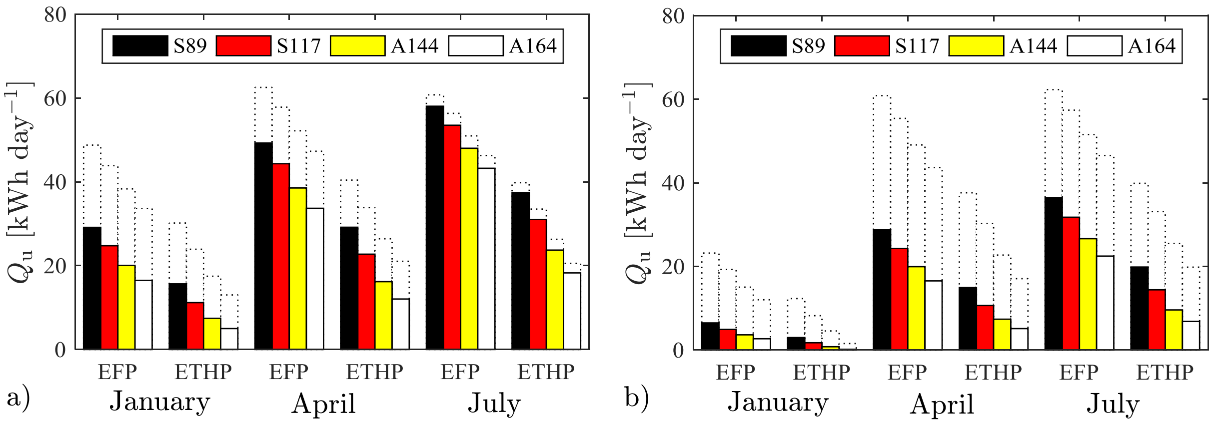


Figure 4: Useful solar energy gain as a function of collector type, TES medium and month of the year for: a) Larnaca and b) London

Figure 5 shows that, compared to the latent heat capacity, the PCM melting temperature and its effect on the collector efficiency has a relatively small impact on the required size of the store. For London, a larger storage requirement occurs in the summer and mid-season periods (240-1050 L for the EFP collector array, depending on the choice of PCM), while for Larnaca the largest storage requirement is in the winter (170-740 L), and in summer it is considerably smaller (25-105 L).

In Figure 6 the system power output and required storage volume for summer operation are plotted for each TES medium. The power output is related to the evaporation temperature of the ORC, which is in turn related to the temperature of the thermal store (see Figure 2); therefore, for the PCMs this is a fixed value, but for the water storage this is shown as a range of values corresponding to a range of allowable temperature-swings for the daily storage cycle. For Larnaca in the month of July, the highest net power output of 687 W is achieved with the EFP collector and the organic PCM A144, requiring a storage volume of 92 L. PCM A164 meanwhile provides only a slightly lower net power output (678 W) but requires a far smaller storage volume (19 L) due to its higher latent heat capacity. For London, by comparison, the highest net power output is 405 W, and is achieved with the EFP collector and the hydrated salt PCM S117, confirming that the optimal collector/ORC operating temperatures are lower than those for Cyprus. The required storage volume is 397 L, which gives a power output per storage volume ratio that is ~7 times lower than that for Larnaca. By choosing the PCM with the highest latent heat capacity (A164) instead, the storage volume requirement is reduced to 199 L, but at the expense of a reduction in net power output of 14%.

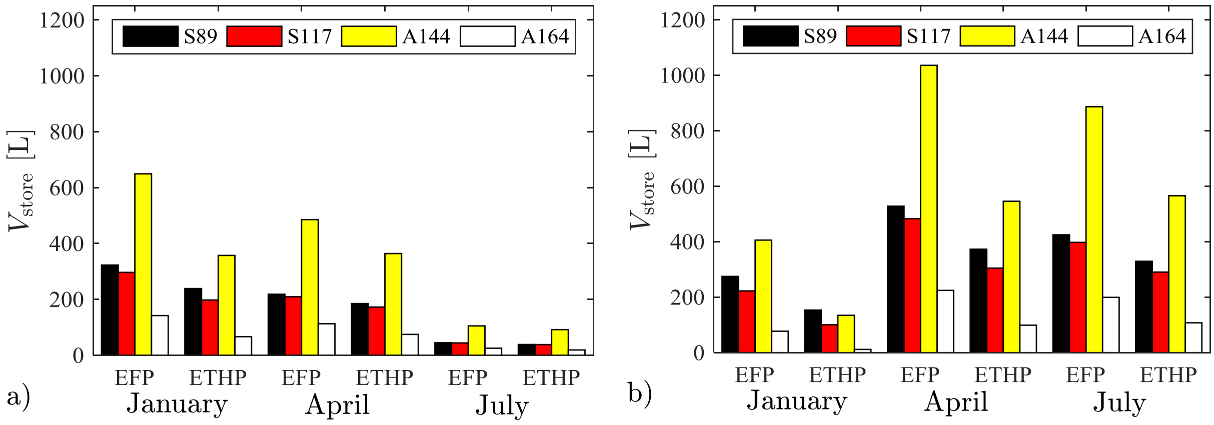


Figure 5: TES volume requirement as a function of collector type, TES medium and month of the year for: a) Larnaca and b) London

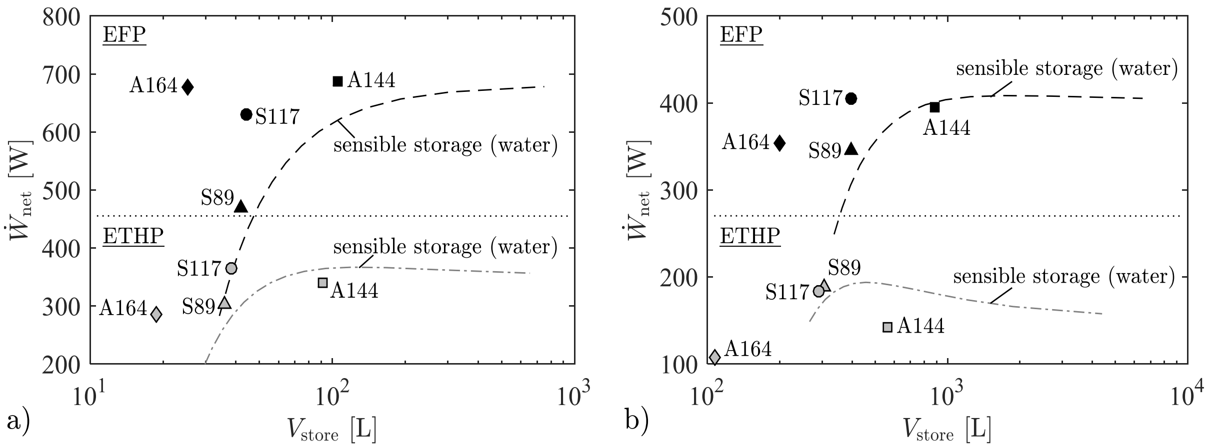


Figure 6: ORC power output for operation in the month of July for: a) Larnaca and b) London, plotted against store volume requirement for each TES options and for EFP collector array (black markers) and ETHP collector array (grey markers)

The choice of working fluid makes a relatively small difference in the above results over the range of conditions considered. For Larnaca, pentane gives a 5% increase in the maximum net power output relative to R245fa, whereas for London R245fa gives a 4% increase relative to pentane. The EFP collector system provides a higher net power output for all of the TES options investigated in both climates. For the sensible heat storage option using water, a small temperature variation (and hence a large storage volume) is required to achieve a sufficient evaporation temperature and a power output that is comparable to that achieved with the PCMs. The PCMs therefore generally show a higher power output per required storage volume than the water storage option, with the exception of A144, which has a low latent heat capacity compared to the other PCMs.

When the S-CHP system sizing is performed for winter operation, there are two important implications for the ORC system compared to the summer case. Firstly, a lower average power output is observed (55% lower for Larnaca and 75% lower for London), and secondly, a lower optimal PCM melting temperature for maximum power output is required. The PCM that gives the highest system performance in each geographical location is therefore different in winter compared to summer months, however, the EFP collector still gives the highest power output in both cases.

FURTHER DISCUSSION AND CONCLUSIONS

The work presented in this paper has been concerned with evaluating a range of latent TES options for use in a particular domestic-scale solar-powered combined heat and power system based on an ORC engine for operation in the contrasting climates of Cyprus and the UK. The S-CHP system evaluated here was constrained to an array size that is equivalent to a domestic rooftop area (15 m^2). PCMs for latent thermal energy storage have been shown to provide a superior power output from the S-CHP system for a smaller equivalent storage volume than liquid water (used as a benchmark sensible storage medium). However, this is dependent on the selection of a PCM with a melting temperature that is matched to the optimal operating temperatures of the collector and ORC engine.

The resulting maximum net power output for summer operation in both Cyprus and the UK is below 1 kW, which is typically the lower limit of "small-scale" systems described in the ORC literature. Furthermore, the expander volume ratio corresponding to the best-case system configuration presented here is found to be 8.7 for London (with R245fa) and 11.6 for Larnaca (with pentane). Commercially available and experimental small-scale positive displacement expanders based on scroll machines tend to have built-in volume ratios < 5. This suggests that in order to avoid losses in efficiency associated with part-load/off-design operation, the proposed solar ORC system would benefit from a specially-designed expander. Alternatively, the system could be sized for a higher nominal power output over a reduced number of operating hours. One possibility is to operate the solar collector array during the day to fully charge the store, and operate to the ORC engine in the evening at full output to off-set grid electricity use during hours of peak demand (when grid electricity is most expensive).

Taking the PCM with the highest volumetric latent heat capacity (A164) and assuming an ORC engine sized for 1 kW output, the system can provide approximately 1.5 hours of continuous operation per 100 L of thermal energy storage. Future work will consider the relative benefits in terms of daily work output, system run-time and potential energy (heat and power) bill savings as a result of using thermal energy storage to off-set the ORC operation to coincide with evening peak electricity demand.

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