Towards the optimization of a domestic-scale organic Rankine cycle system for combined heating and power provision in the UK

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PhD project aims

To assess the potential to provide combined heating and power from small-scale solar thermal technology in the United Kingdom.

To design and model a domestic-scale system based on ORC technology and powered by heat from a roof-top solar collector array.

To investigate the most suitable system components based on the size of the system and the nature of the UK solar resource.
Conventional domestic solar technologies

Consider a 15 m² roof

- Cover with PV (MC-Si) at ≈ € 5200 (system cost including inverter + install)
- Electrical power output ≈ 1750 kWhₐ/yr ≈ 200 We(avg) (50% electricity demand)
- Annual electricity bill savings (up to) 270 €/year

- Assuming 25 year system life and annual running cost = 1% of capital cost.
- Typical performance and demand figures taken from DECC and The Energy Saving Trust.
Conventional domestic solar technologies

Consider a 15 m² roof

Solar hot water option (evacuated tube):

- System cost: 5 m² / 30 tube collector array + cylinder + plumbing + install ≈ € 4500
- Hot water provision ≈ 1450 kWh_th/year ≈ 60 litres hot water per day (50% of demand)
- Annual savings on gas bill ≈ 75 €/year

- Assuming 25 year system life and annual running cost = 1% of capital cost.
- Typical performance and demand figures taken from DECC and The Energy Saving Trust.
Conventional domestic solar technologies

Consider a 15 m² roof

Cover remaining 70% with PV

PV system cost. 10 m² ≈ € 4000

Electrical power output ≈ 1150 kWhₑ/year
(130 Weₑₑavg) ≈ 35% electricity demand

Electricity bill savings ≈ 180 €/year

Total energy bill savings ≈ 255 €/year

Solar hot water option (evacuated tube):

• System cost: 5 m² / 30 tube collector array +
cylinder + plumbing + install ≈ € 4500

• Hot water provision ≈ 1450 kWhₜₜ/year
≈ 60 litres hot water per day (50% of demand)

• Annual savings on gas bill ≈ 75 €/year

• Assuming 25 year system life and annual running cost = 1% of capital cost.
• Typical performance and demand figures taken from DECC and The Energy Saving Trust.
**Solar-ORC system**

**Consider a 15 m² roof**

**Solar thermal heat and power system**
- Entire roof covered with solar thermal collectors
- Power generation via an ORC engine
- Cost of ORC components + install + additional collectors $\approx €3000$
- Power generation in the region of 700-950 kWh/yr (80-110 We average) $\approx$ up to 30% demand
- 90-140 €/year electricity bill savings

- Assuming 25 year system life and annual running cost = 1% of capital cost.
- Typical demand figures taken from DECC.
Previous work – developing a system model

- Initial configuration: indirect heating of ORC up-stream of hot water generator
- Simple component sub-models
- R245fa working fluid
- Fixed fluid flow-rates
- 15 m² solar collector array area
- London solar irradiance data
- Demand profiles for domestic electricity and hot water use
- Assumed that heat rejection is to mains water at fixed temperature (10°C)

Freeman et al. (2013)
Collector comparison

- Non-concentrating **evacuated tube** collector at fixed orientation due south and 36° tilt angle
- Concentrating **parabolic trough** collector with perfect 2-axis solar tracking
- Collectors modelled using manufacturers efficiency curves
- Semi-optimized for fixed flow-rates and simulated over an annual period

Results of annual simulation with ORC model:
- Evacuated tube ORC system: 588 kWh/year (67 We<sub>avg</sub>)
- Parabolic trough ORC system: 657 kWh/year (75 We<sub>avg</sub>)
Solar collector selection

Evacuated Tube (ET) Collectors

Thermomax DF-100
Microtherm SK-6 (CPC)

Parabolic Trough Collectors (PTC)

Solitem PTC-1000
NEP Polytrough 1800

Flat Plate (FP) and PV-Thermal (PV-T) Collectors

Thermomax FN (Flat plate)
Volther PowerTherm (PV-T)

Compound parabolic concentrator
Calculation of maximum power

Maximum power = exergy flow at collector outlet:

\[
\dot{W}_{\text{max}} = \int d\dot{W} = \int_{T_0}^{T_{1,i}} \left(1 - \frac{T_0}{T_1}\right) \dot{m}c \cdot dT_1
\]

\[
= (\dot{H}_{\text{sc, out}} - \dot{H}_0) - T_0 (\dot{S}_{\text{sc, out}} - \dot{S}_0)
\]
Solar collector maximum work

Maximum power output: (peak irradiance)

Evacuated tube
120 W/m² (reversible) and 65 W/m² (endoreversible) at 270 °C outlet temperature.

Parabolic trough
240 W/m² (reversible) and 145 W/m² (endoreversible) at 550 °C outlet temperature.

Annual maximum work (15 m² evacuated tube array):
590–993 kWh (67-113 W_{avg}), endoreversible

Freeman et al. (2013)
Controlling for optimum temperatures

Objective function:
• Maximise ORC power output

Variables:
• Working fluid flow rate
• Solar collector flow rate
• Evaporation pressure

Constraints:
• Maximum collector/ORC fluid temperatures
• Minimum/maximum pressures
• Pinch point in evaporator

Assumptions:
• Zero solar fluid flow to hot water cylinder.
• Constant cold sink (water) temperature = 10 °C
• Cycle condensation temperature = 17 °C
Model variants

Initial fixed flow-rate model:

- Modelled using “time-marching” approach
- Exiting temperature for interval (i) becomes the initial temperature in interval (i+1)

\[ T_{\text{sc,in}}(i+1) = T_{\text{sc,in}}(i) + \left( \dot{Q}_{\text{sc}}(i) - \dot{Q}_{\text{ORC}}(i) - \dot{Q}_{\text{hwc}}(i) \right)/\dot{m}(i) c_p \]

Fixed pressures and flow rates:

\[ P_{\text{evap}} = 10 \text{ bar}, \quad \dot{m}_{\text{sc}} = 0.03 \text{ kg/s}, \quad \dot{m}_{\text{wf}} = 0.01 \text{ kg/s}, \]
**Model variants**

**Variable flow-rate model:**
- Modelled using a “quasi-equilibrium” approach
- Temperatures in the system are solved for an equilibrium state for each time interval

\[ \dot{Q}_{sc}(i) = \dot{Q}_{ORC}(i) + \dot{Q}_{hwc}(i) \]

\[ T_{sc,in}(i) \]

**Fixed pressures and collector flow rate:**
*Variable* ORC working fluid flow rate.

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\[ T_{sc,in} \]

\[ T_{sc,out} \]

\[ T_{wf,evap} \]

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**Graphs:**
- Chart showing ORC work output [W] over time [hour].
- Chart showing temperature [°C] over time [hour].
Controlling for optimum temperatures

Starting point:
- Initial inlet temperature
- Environmental parameters known
- ORC condensation temperature/pressure (State 1) is known
Controlling for optimum temperatures

Starting point:
- Initial inlet temperature
- Environmental parameters known
- ORC condensation temperature/pressure (State 1) is known
- Find the collector outlet temperature and flow rate corresponding to maximum exergy output for given $T_{sc,in}$, $T_{ext}$ and $G$
Controlling for optimum temperatures

Calculation procedure
• Choose initial $T_{\text{sc, in}}$
• Set optimal $T_{\text{sc, out}}$
Controlling for optimum temperatures

Calculation procedure
- Choose initial $T_{sc,in}$
- Set optimal $T_{sc,out}$
- Calculate $T_3$ and $\dot{m}_{wf}$
- Try higher values of $P_{evap}$ until pinch limit reached
- Calculate power output from ORC engine.
Controlling for optimum temperatures

Calculation procedure

- Choose initial $T_{sc,in}$
- Set optimal $T_{sc,out}$
- Calculate $T_3$ and $m_{wf}$
- Try higher values of $P_{evap}$ until pinch limit reached
- Calculate power output from ORC engine.
- Choose a new $T_{sc,in}$
Controlling for optimum temperatures

Calculation procedure
• Choose initial $T_{sc,\text{in}}$
• Set optimal $T_{sc,\text{out}}$
• Calculate $T_3$ and $m_{wf}$
• Try higher values of $P_{\text{evap}}$ until pinch limit reached
• Calculate power output from ORC engine.
• Choose a new $T_{sc,\text{in}}$
• Repeat calculation procedure until $\dot{W}$ is maximised
Optimal performance region

- **Solar Irradiance** [W/m²]
- **T_{sc,in} [°C]**
- **Output power [W]**

- **Optimal performance region**
- **Undesirable region**

- $T_{sc,out,opt} > T_{max}$
- $P = P_{max}$
Optimal performance region
Results (annual average day)

- Mean day work output = 1.9 kWh/day = 79 W average
- 16.5% increased power output compared to system where only working fluid flow rate is varied
Results (annual average day)
Conclusions

- Domestic heat and power systems based on solar-ORC technology have the potential to be a versatile and cost-effective alternative to conventional PV and solar hot water systems.

- Modulation of system flow-rates and evaporation pressure has demonstrated an increase in the power output of the system under variable (solar) heat input.

- A methodology has been proposed for calculating the maximum power settings based on exergy analysis of the solar collector.

- Cost and practicality limitations are to be considered for implementation in a real control strategy.


Here comes the sun: a field trial of solar water heating systems, The Energy Saving Trust, 2011.

Typical domestic energy consumption figures factsheet, Office of Gas and Electricity Markets, 2011.