

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

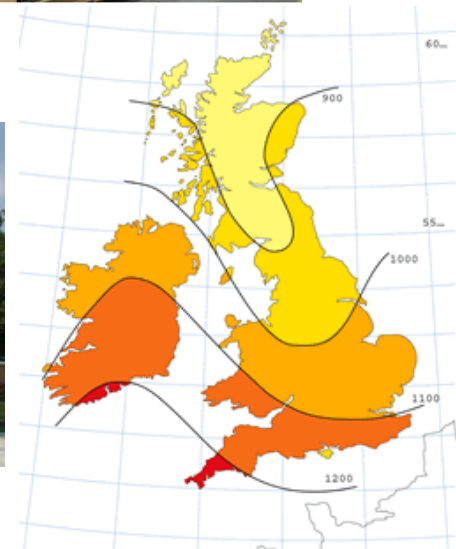
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PhD project aims

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

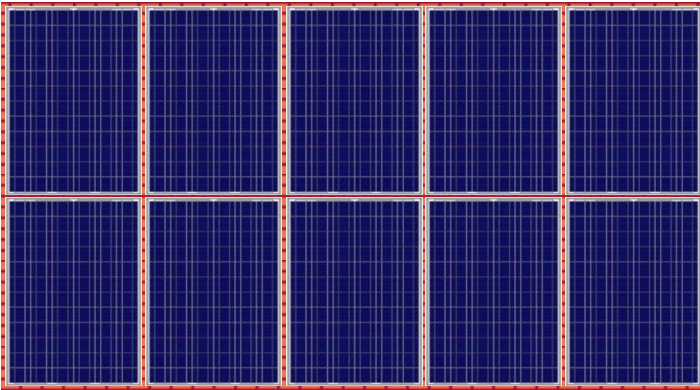
To design and model a **domestic-scale** system based on **ORC** technology and powered by heat from a roof-top solar collector array

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

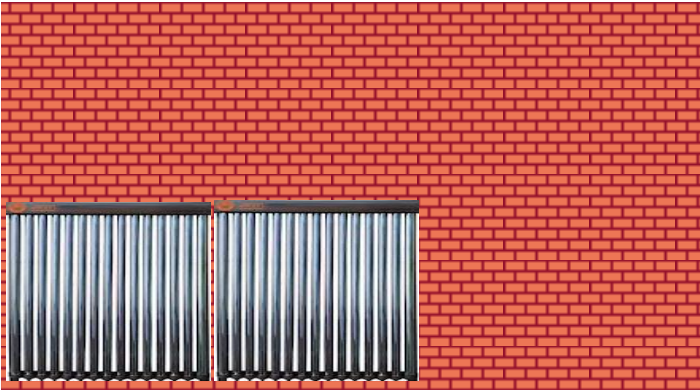


- Cover with PV (MC-Si) at $\approx \text{€ } 5200$ (system cost including inverter + install)
- Electrical power output $\approx 1750 \text{ kWh}_e/\text{yr}$
 $\approx 200 \text{ We}_{(\text{avg})}$ (50% electricity demand)
- Annual electricity bill savings (up to) 270 €/year

- 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

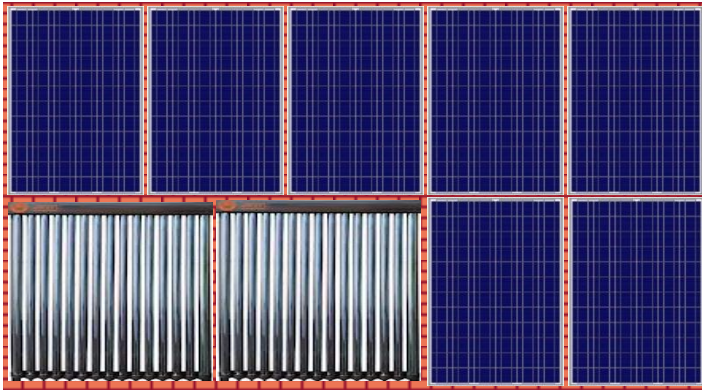


Solar hot water option (evacuated tube):

- System cost: 5 m² / 30 tube collector array + cylinder + plumbing + install \approx € 4500
- Hot water provision \approx 1450 kWh_{th}/year
 \approx 60 litres hot water per day (50% of demand)
- Annual savings on gas bill \approx 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 \approx € 4000

Electrical power output \approx 1150 kWh_e/year
(130 We_{avg}) \approx 35% electricity demand

Electricity bill savings \approx 180 €/year

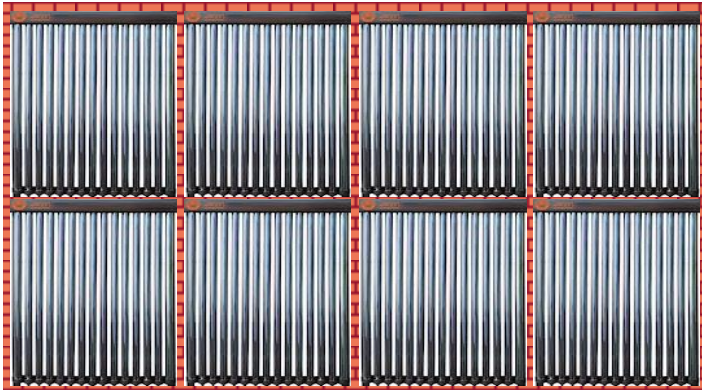
Total energy bill savings \approx 255 €/year

Solar hot water option (evacuated tube):

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



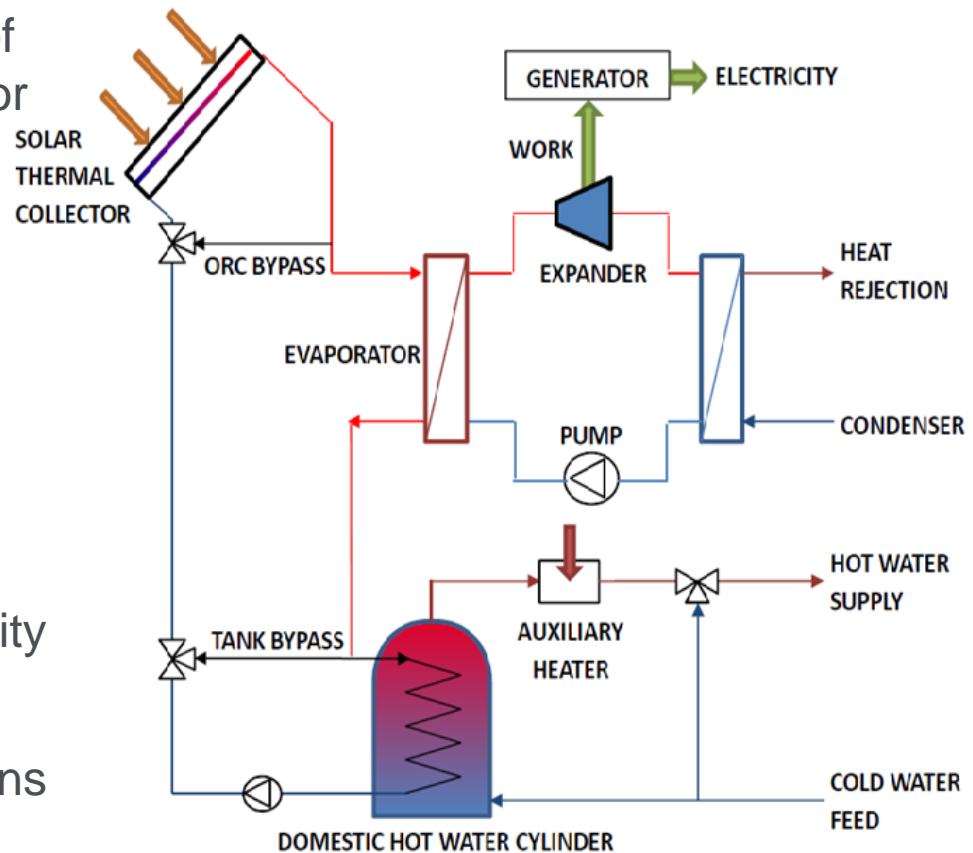
Solar thermal heat and power system

- 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)



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:

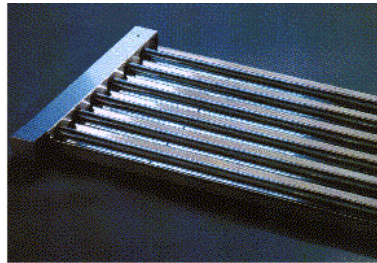
- Evacuated tube ORC system: **588 kWh/year** ($67 We_{avg}$)
- Parabolic trough ORC system: **657 kWh/year** ($75 We_{avg}$)

Solar collector selection

Evacuated Tube (ET) Collectors



Thermomax DF-100)



Microtherm SK-6
(CPC)



Compound parabolic concentrator

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)

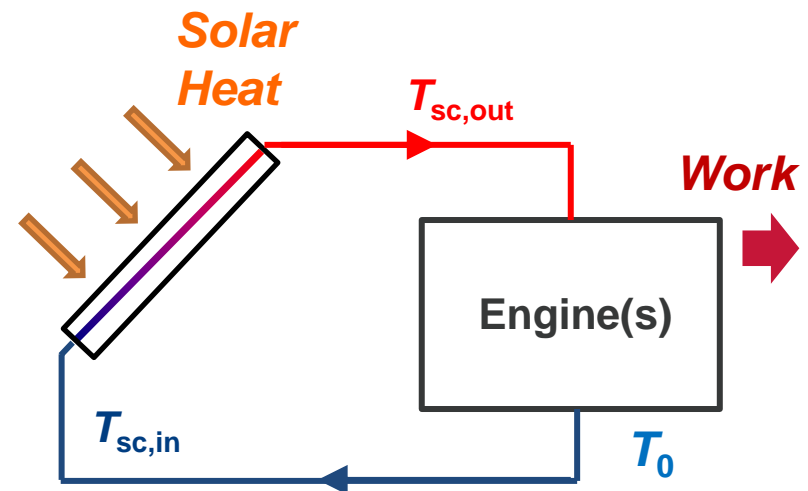
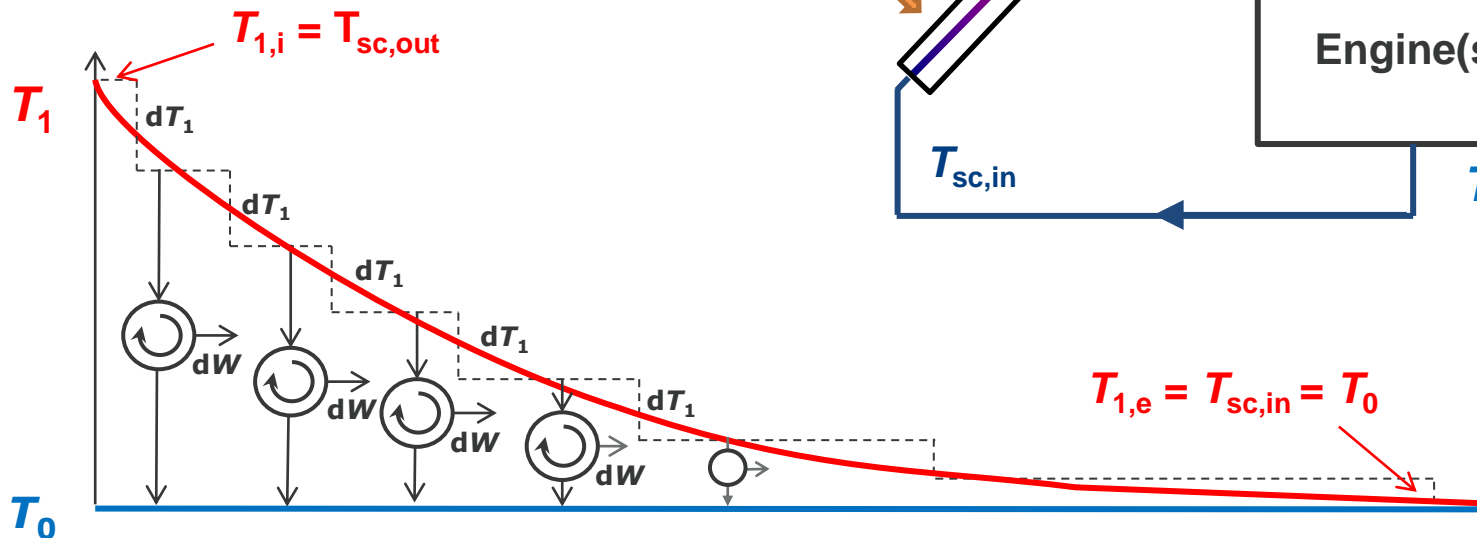


Calculation of maximum power

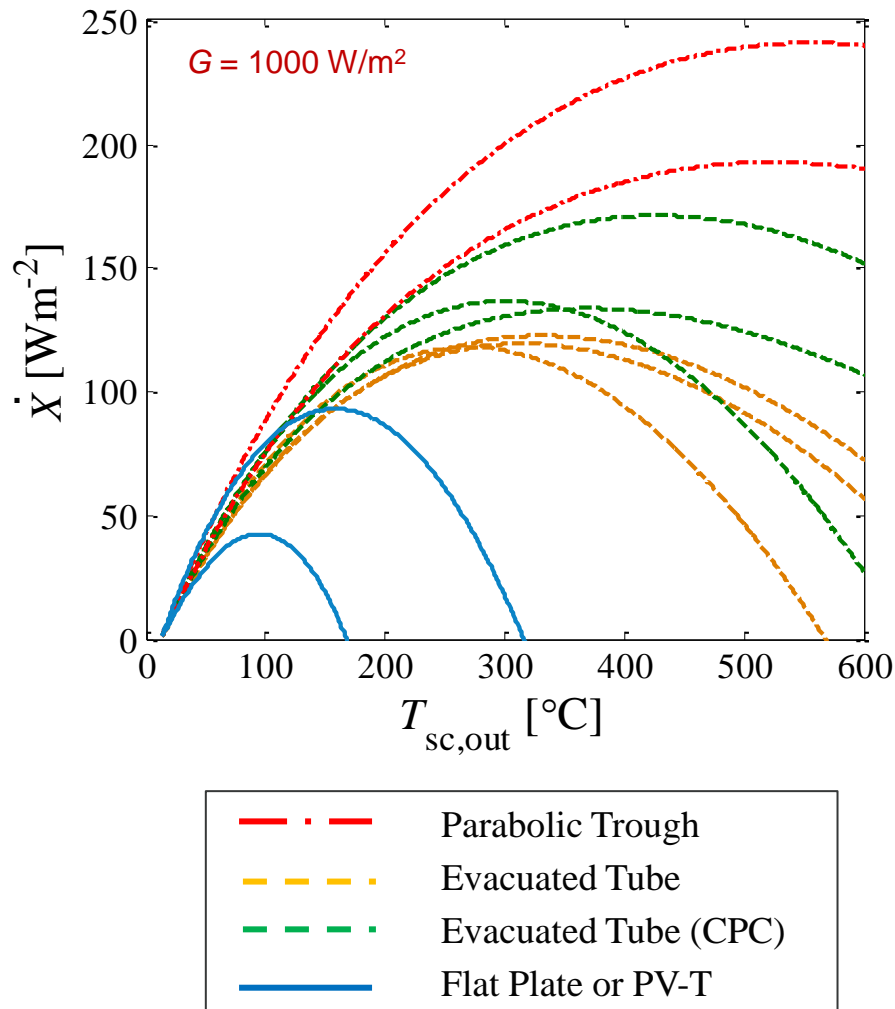
Maximum power = exergy flow at collector outlet:

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

$$= (\dot{H}_{\text{sc,out}} - \dot{H}_0) - T_0 (\dot{S}_{\text{sc,out}} - \dot{S}_0)$$



Solar collector maximum work



**Maximum power output:
(peak irradiance)**

Evacuated tube

120 W/m^2 (reversible) and
65 W/m^2 (endoreversible)
at 270 $^{\circ}\text{C}$ outlet temperature.

Parabolic trough

240 W/m^2 (reversible) and
145 W/m^2 (endoreversible)
at 550 $^{\circ}\text{C}$ outlet temperature.

**Annual maximum work
(15 m^2 evacuated tube array):**

590–993 kWh (67–113 W_{avg}),
endoreversible

Controlling for optimum temperatures

Objective function:

- Maximise ORC power output

Variables:

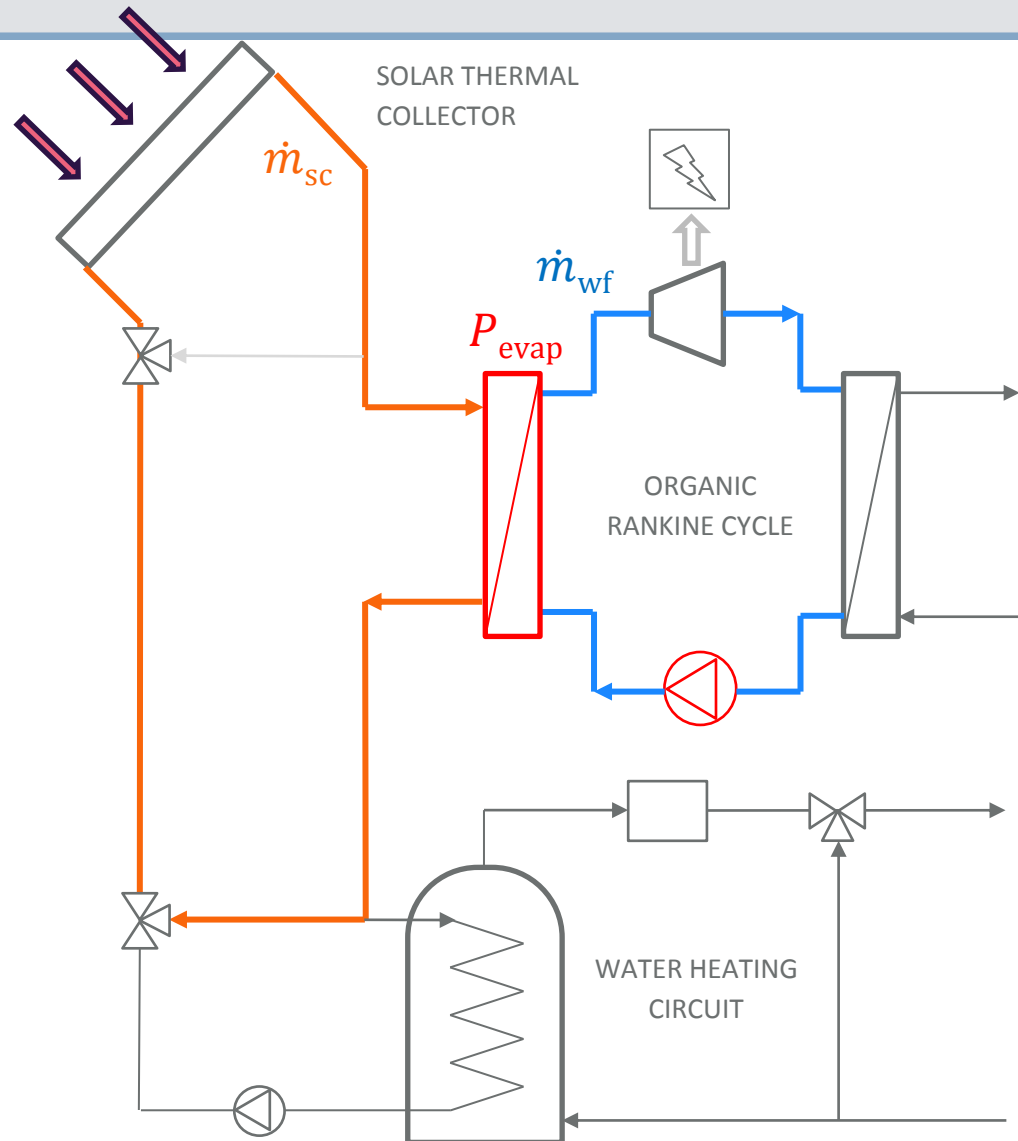
- Working fluid flow rate
- Solar collector flow rate
- Evaporation pressure

Constraints:

- Maximum collector/ORC fluid temperatures
- Minimum/maximum pressures
- Pinch point in evaporator

Assumptions:

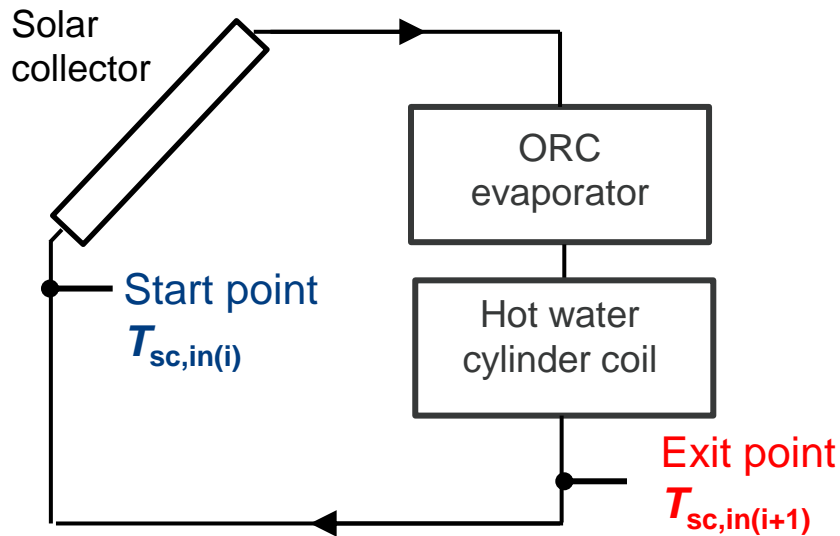
- Zero solar fluid flow to hot water cylinder.
- Constant cold sink (water) temperature = 10 °C
- Cycle condensation temperature = 17 °C



Model variants

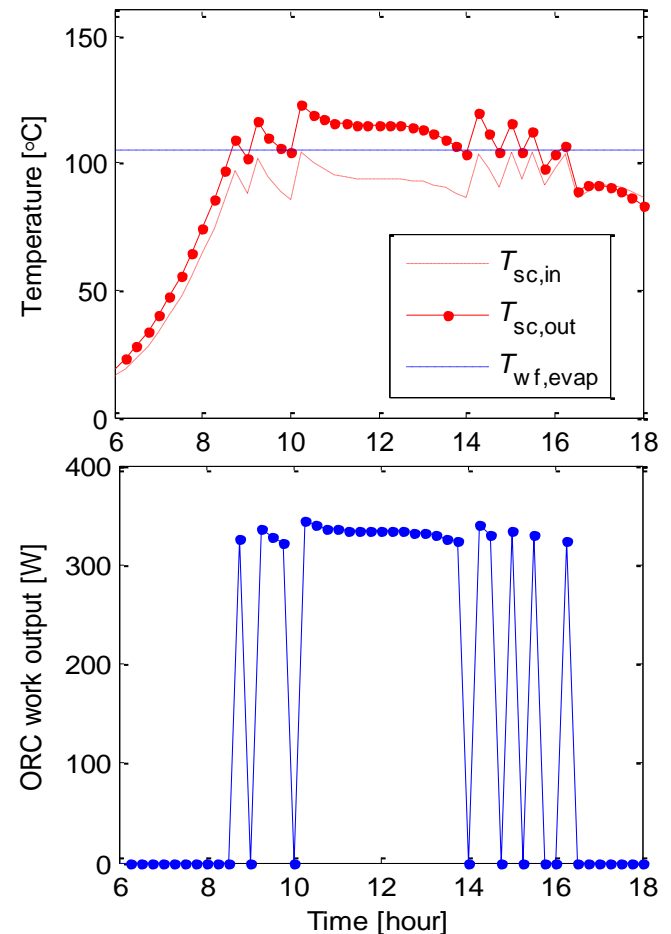
Initial fixed flow-rate model:

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



$$T_{sc,in(i+1)} = T_{sc,in(i)} + (\dot{Q}_{sc(i)} - \dot{Q}_{ORC(i)} - \dot{Q}_{hwc(i)}) / \dot{m}_{(i)} c_p$$

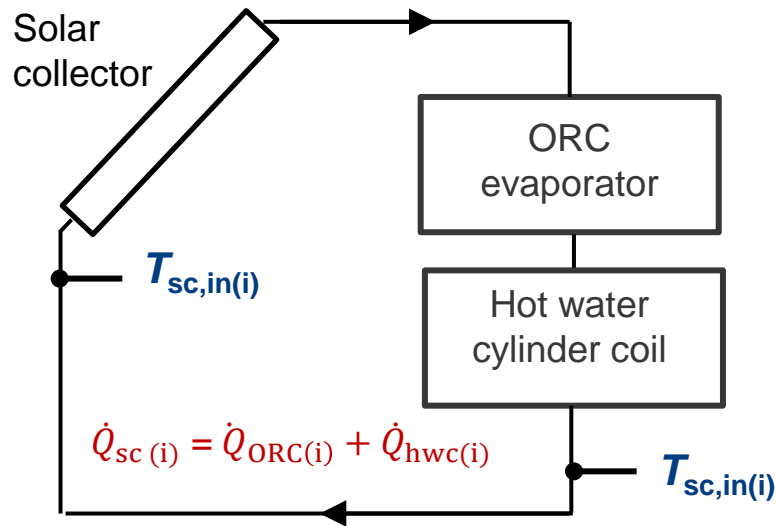
Fixed pressures and flow rates:
 $P_{evap} = 10 \text{ bar}$, $\dot{m}_{sc} = 0.03 \text{ kg/s}$, $\dot{m}_{wf} = 0.01 \text{ kg/s}$,



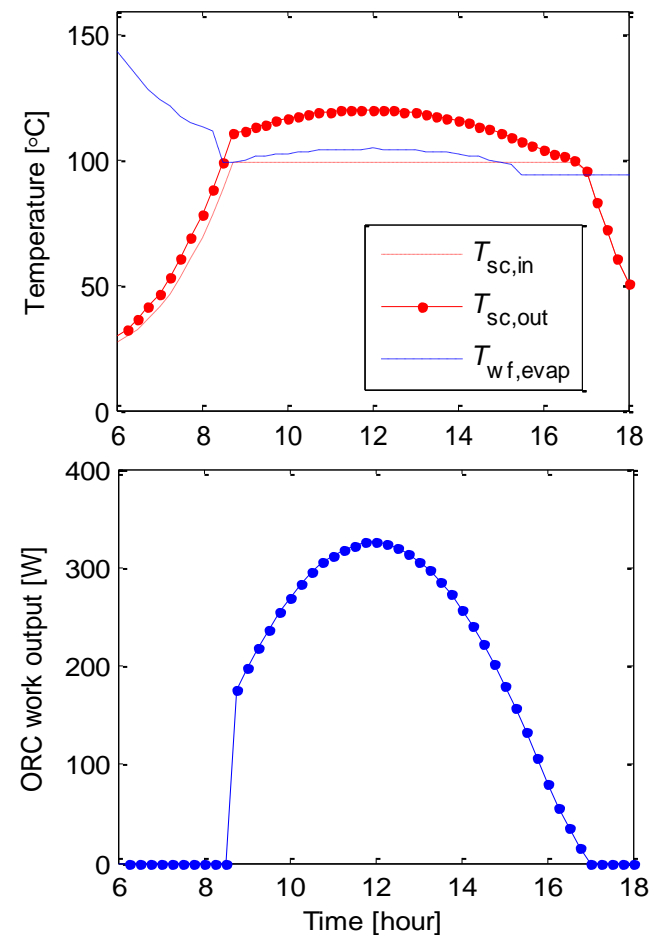
Model variants

Variable flow-rate model:

- Modelled using a “quasi-equilibrium” approach
- Temperatures in the system are solved for an equilibrium state for each time interval



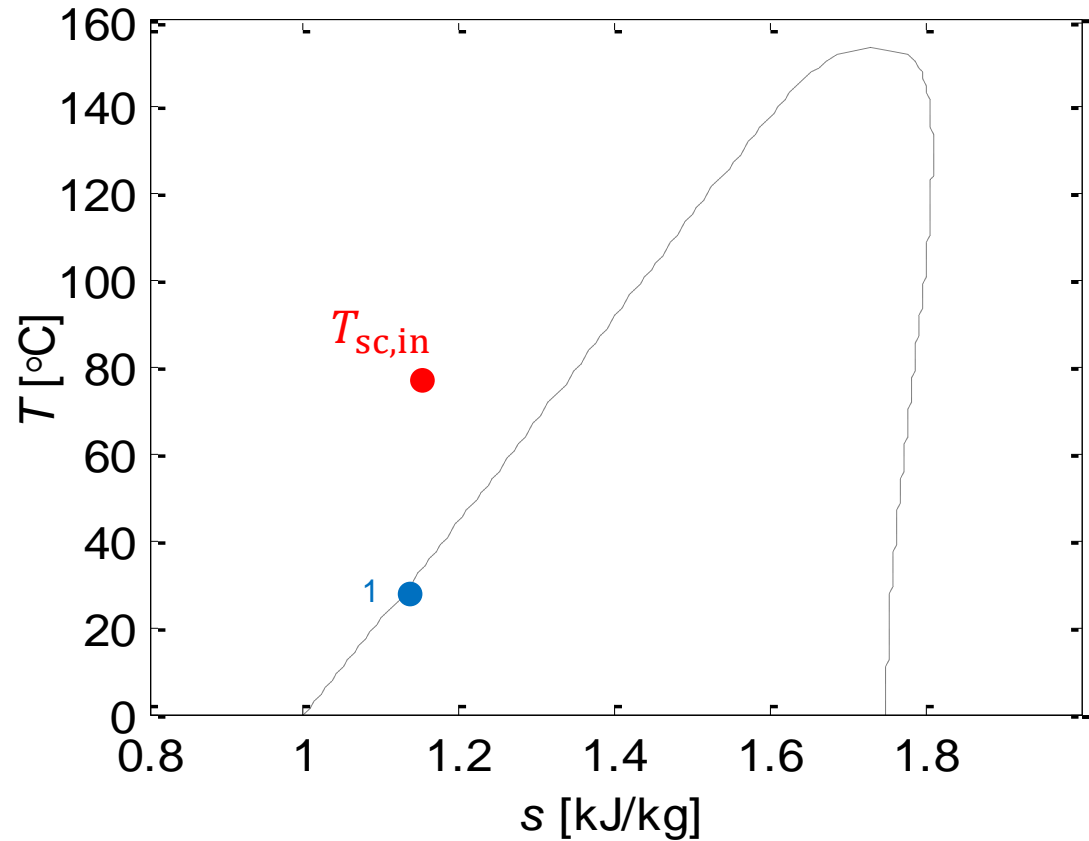
Fixed pressures and collector flow rate:
Variable ORC working fluid flow rate.



Controlling for optimum temperatures

Starting point:

- Initial inlet temperature
- Environmental parameters known
- ORC condensation temperature/pressure (State 1) is known



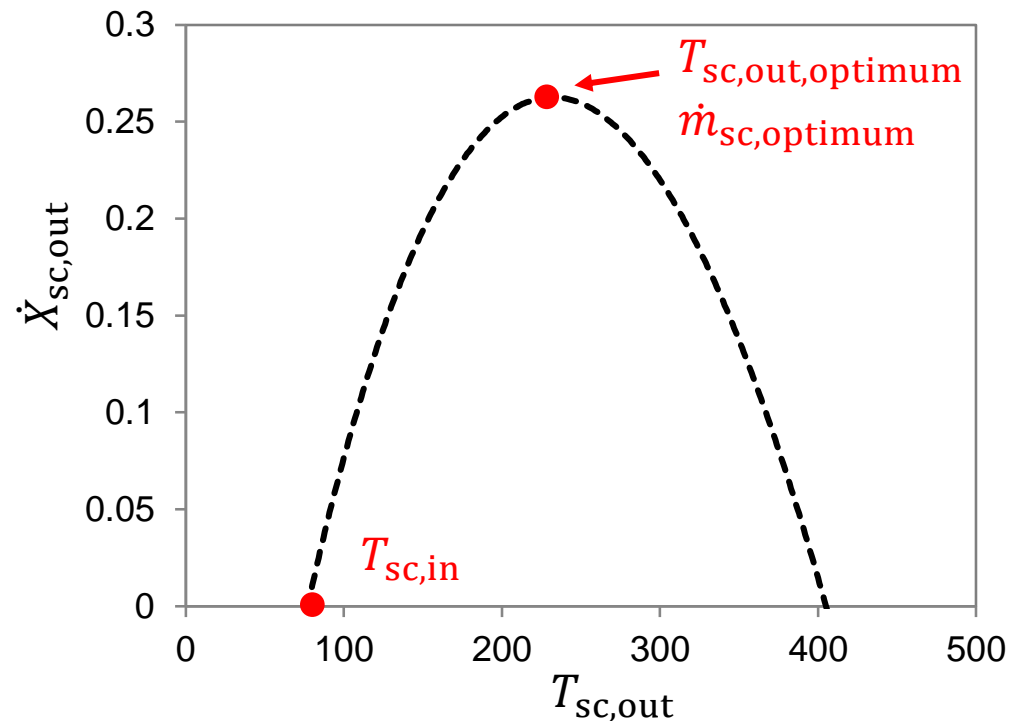
Controlling for optimum temperatures

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

Input variables:

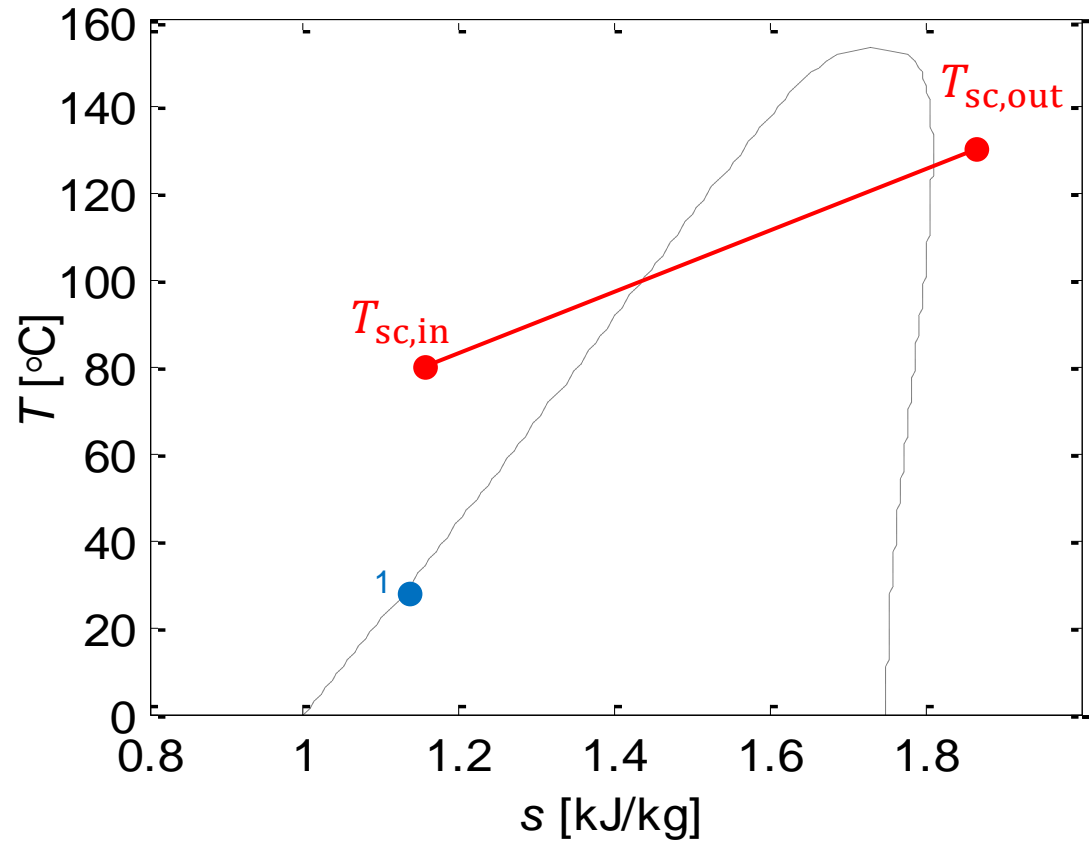
$$T_{sc,in}, G, T_{ambient}, T_0$$



Controlling for optimum temperatures

Calculation procedure

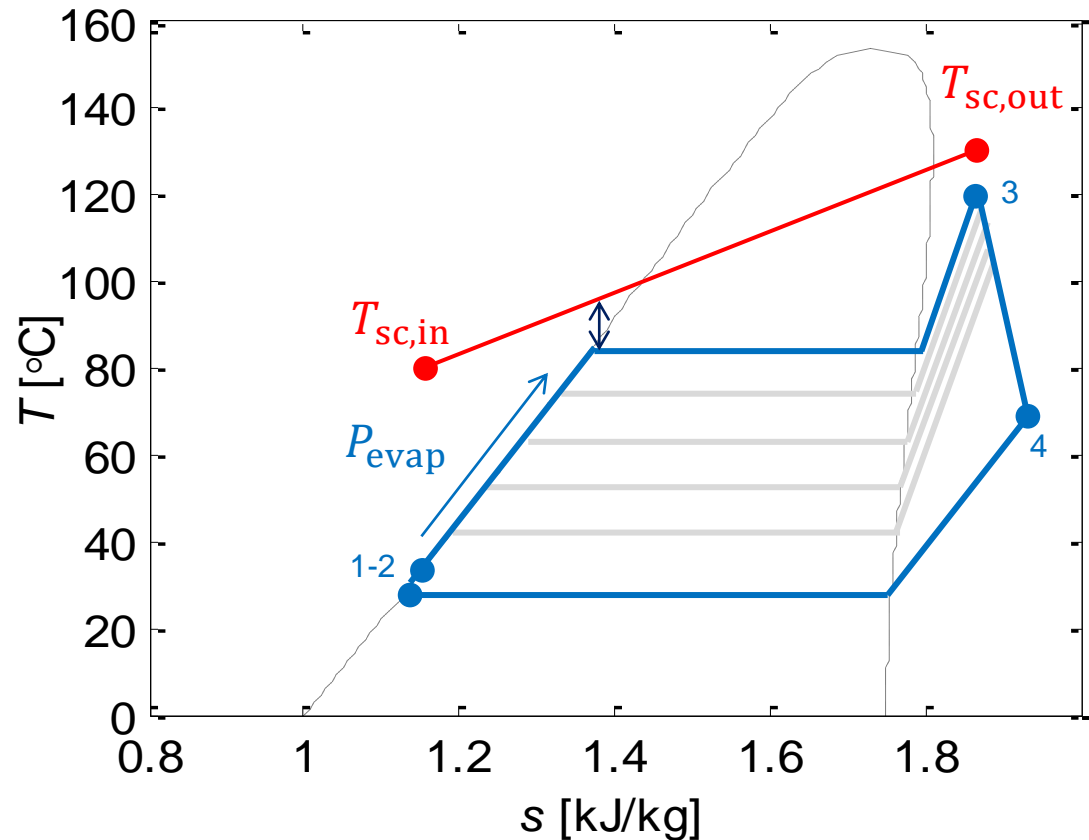
- Choose initial $T_{sc,in}$
- Set optimal $T_{sc,out}$



Controlling for optimum temperatures

Calculation procedure

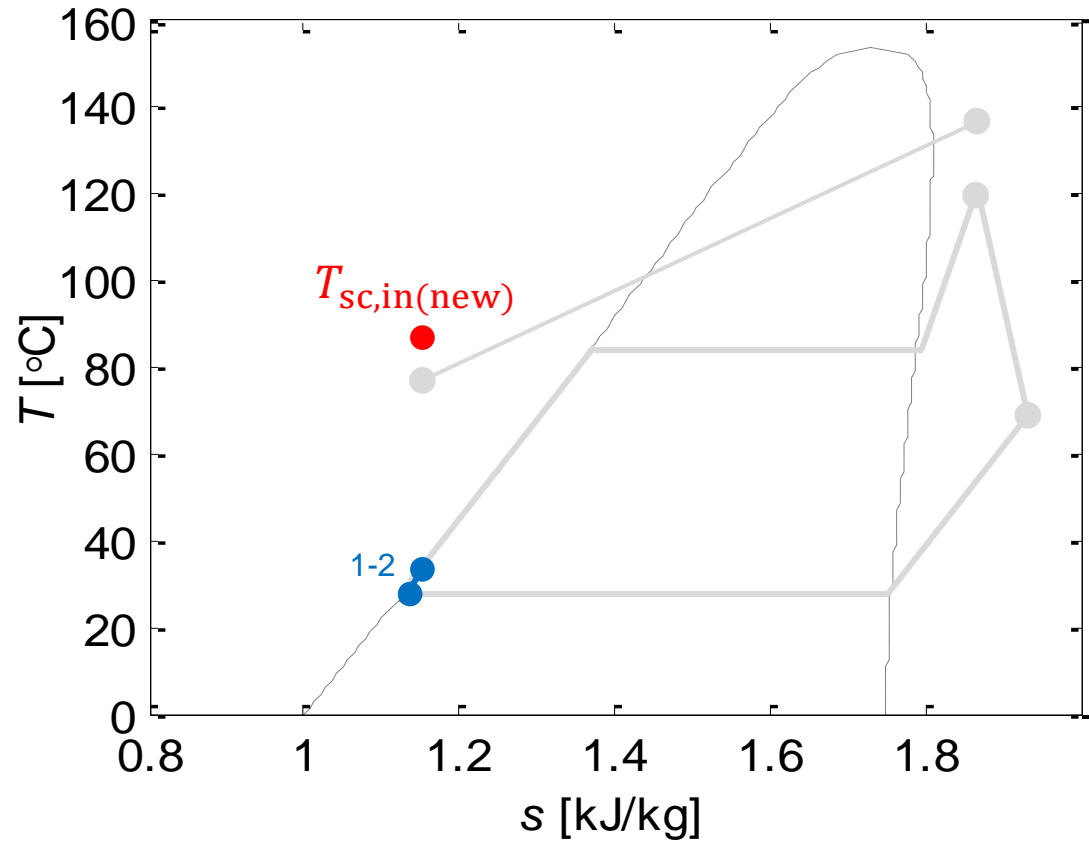
- Choose initial $T_{sc,in}$
- Set optimal $T_{sc,out}$
- Calculate T_3 and \dot{m}_{wf}
- Try higher values of P_{evap} until pinch limit reached
- Calculate power output from ORC engine.



Controlling for optimum temperatures

Calculation procedure

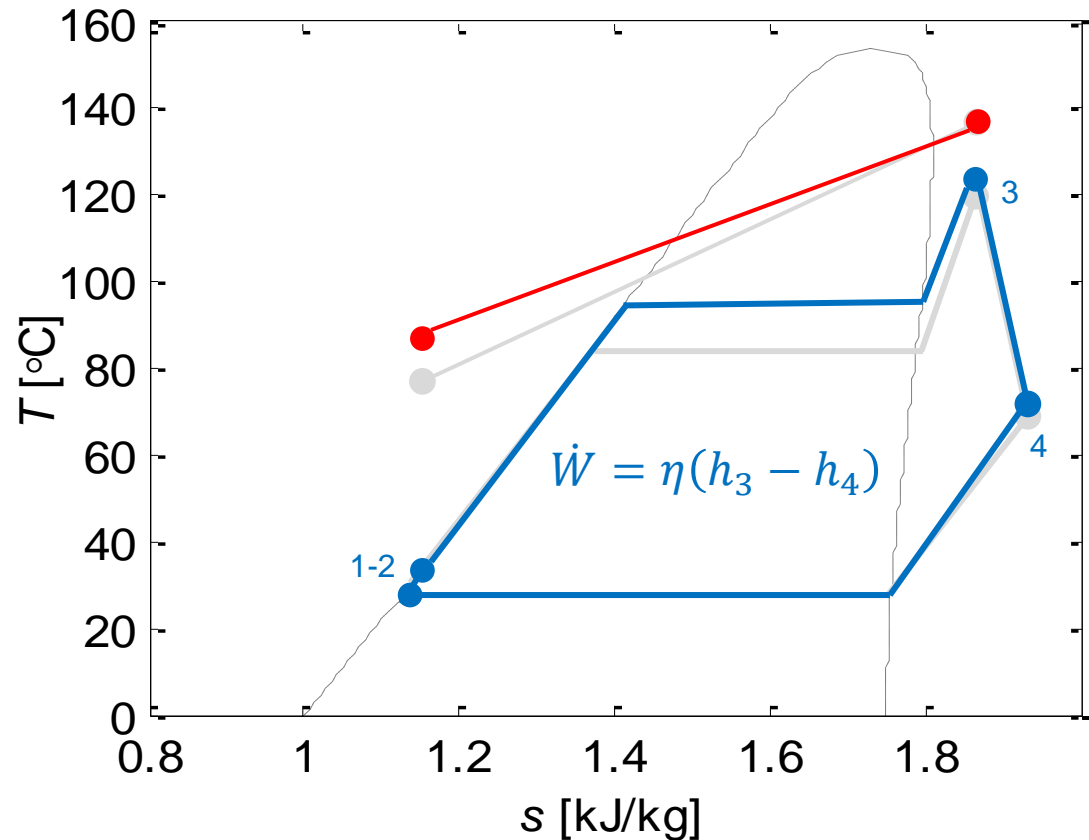
- Choose initial $T_{sc,in}$
- Set optimal $T_{sc,out}$
- Calculate T_3 and \dot{m}_{wf}
- Try higher values of P_{evap} until pinch limit reached
- Calculate power output from ORC engine.
- Choose a new $T_{sc,in}$



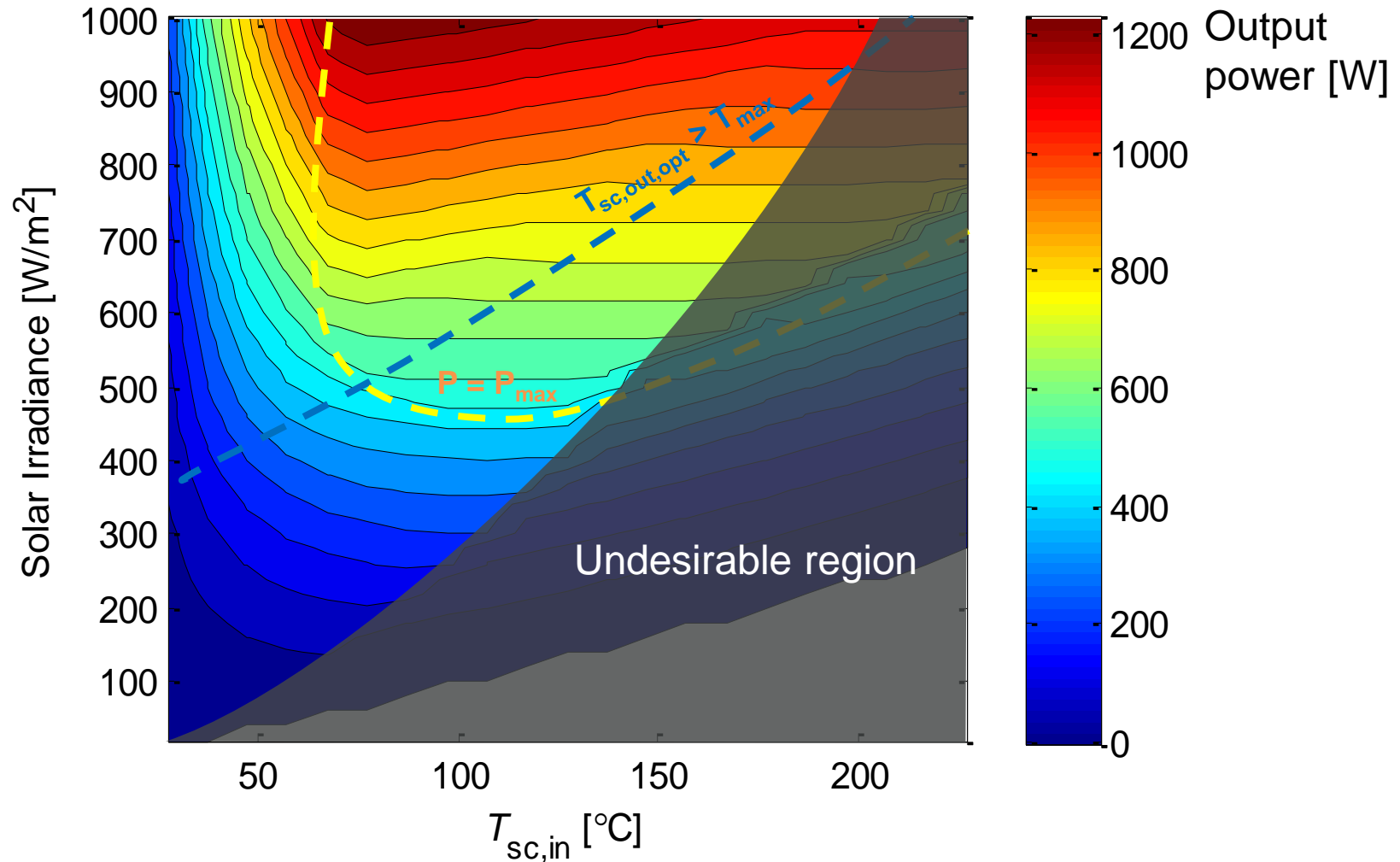
Controlling for optimum temperatures

Calculation procedure

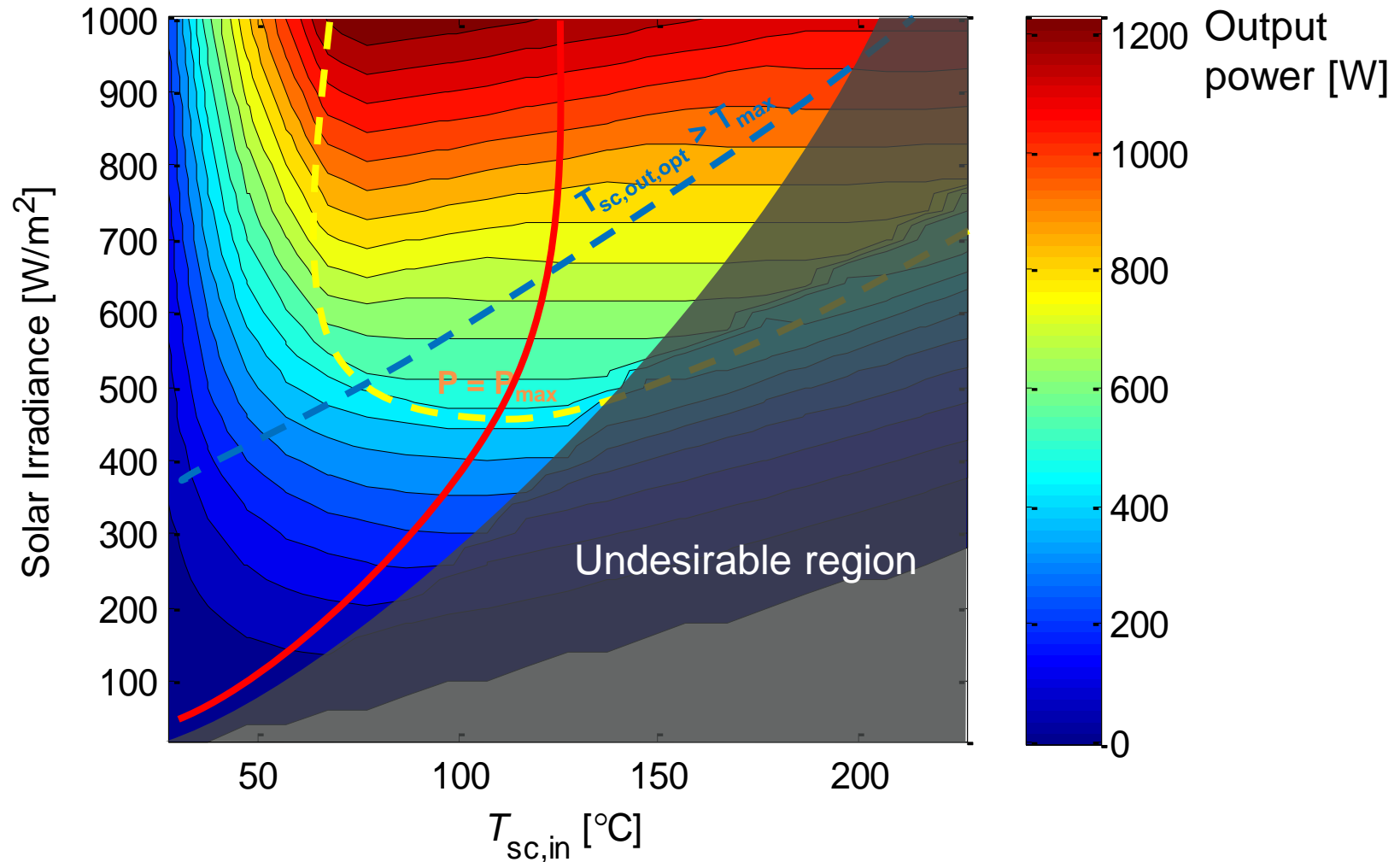
- Choose initial $T_{sc,in}$
- Set optimal $T_{sc,out}$
- Calculate T_3 and \dot{m}_{wf}
- Try higher values of P_{evap} until pinch limit reached
- Calculate power output from ORC engine.
- Choose a new $T_{sc,in}$
- **Repeat calculation procedure until \dot{W} is maximised**



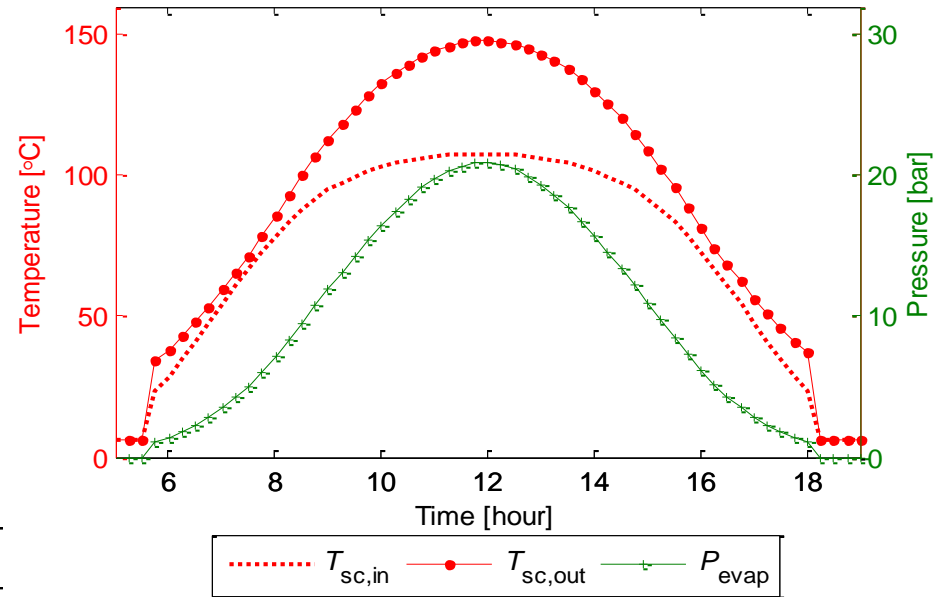
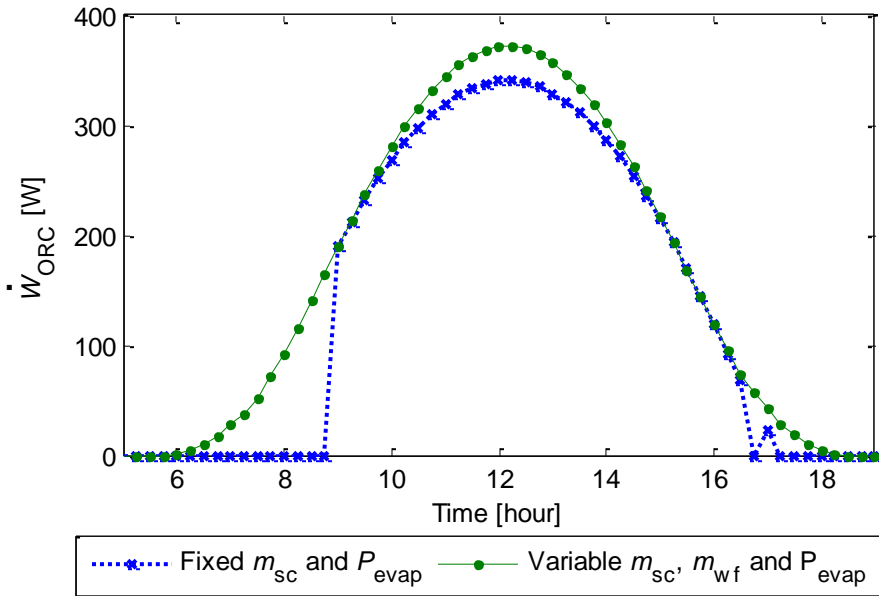
Optimal performance region



Optimal performance region

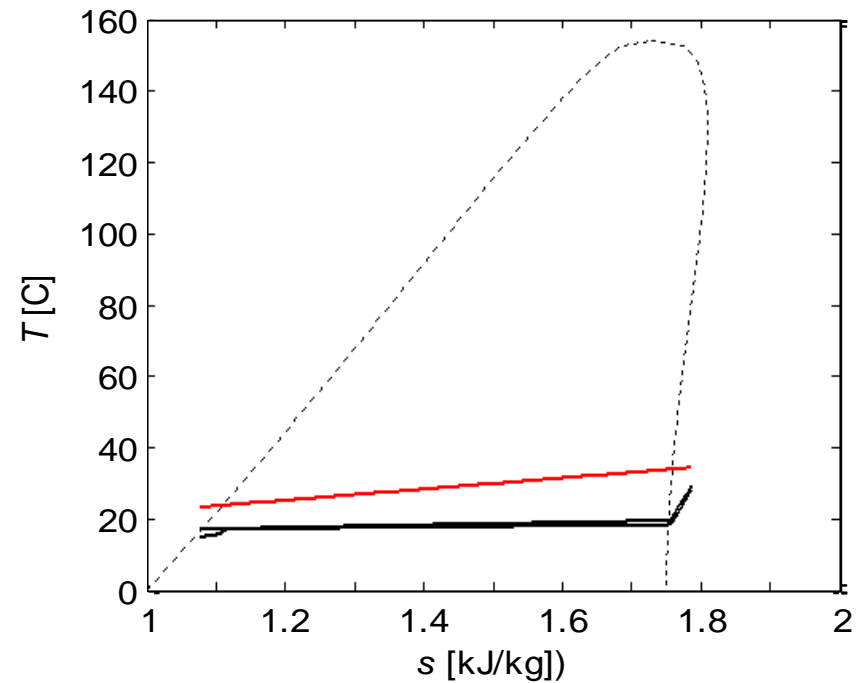
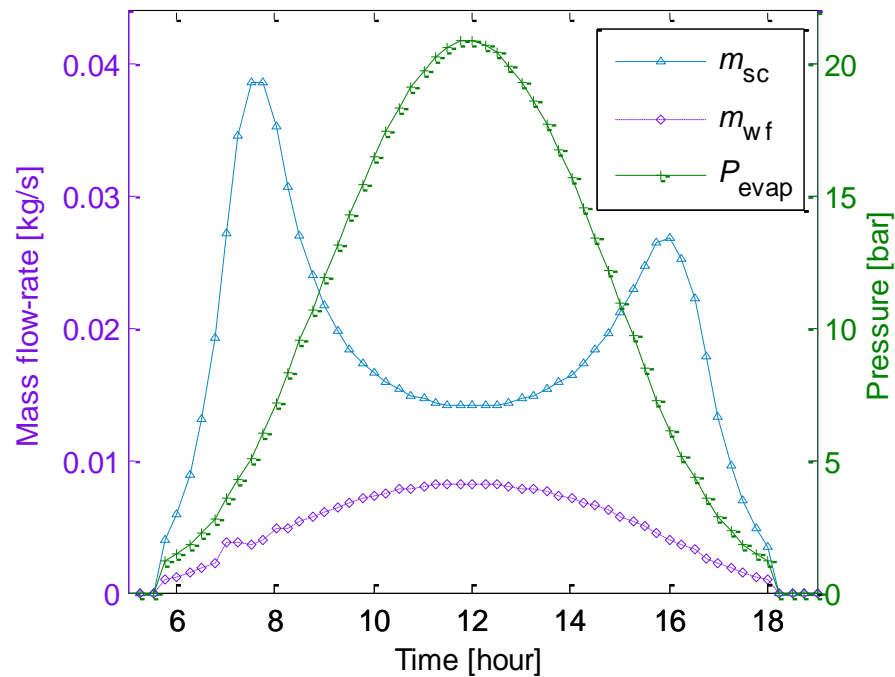


Results (annual average day)



- 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

Thank you

A buyer's guide to solar electricity panels, The Energy Saving Trust, 2012.

Freeman, J., Hellgardt, K., Markides C.N., An assessment of a solar-powered organic Rankine cycle system for combined heating and power in domestic applications, In: *Proceedings of the 5th International Conference on Applied Energy*, Pretoria, South Africa, 1-4 July, 2013.

Freeman, J., Markides, C.N., Hellgardt K., An assessment of solar-thermal collector designs for small-scale combined heating and power applications in the UK, In: *Proceedings of 13th UK Heat Transfer Conference*, 2-3 September, 2013.

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.