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

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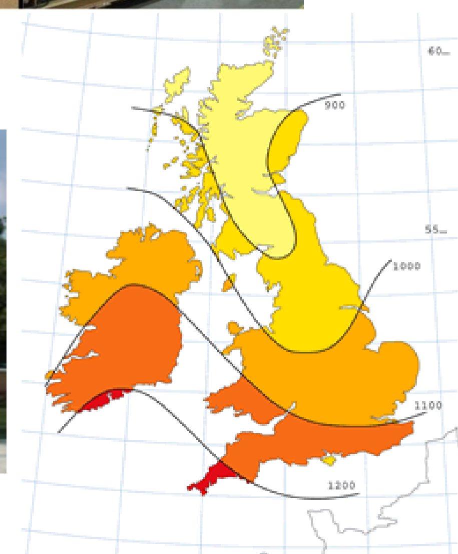
PhD project aims

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



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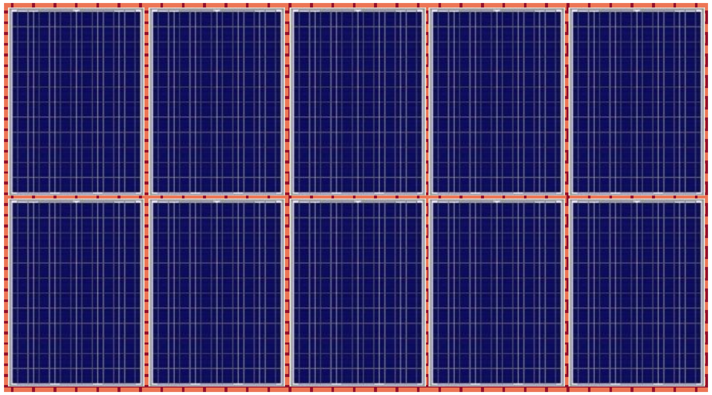
Conventional domestic solar technologies

Consider a 15 m^2 roof



- Cover with PV (MC-Si) at ≈ € 5200 (system cost including inverter + install)
- Electrical power output ≈ 1750 kWh_e/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.

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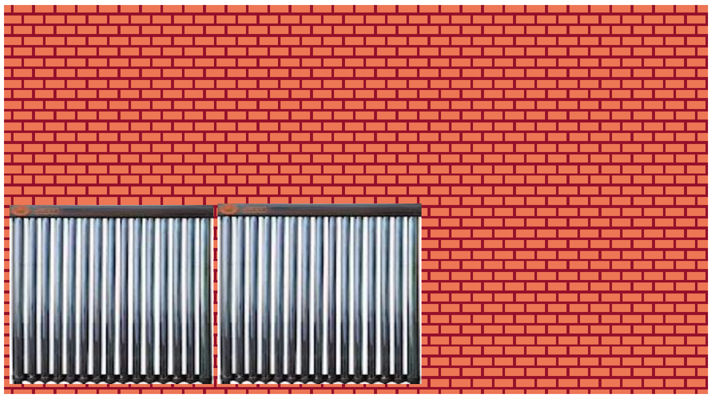
Conventional domestic solar technologies

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.

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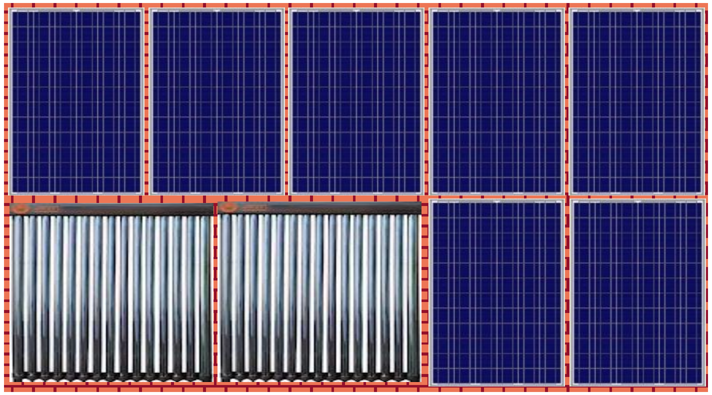
Conventional domestic solar technologies

Consider a 15 m^2 roof



Cover remaining 70% with PV

PV system cost. 10 m^2 ≈ € 4000

Electrical power output ≈ 1150 kWh$_e$/year (130 We$_{avg}$) ≈ 35% electricity demand

Electricity bill savings ≈ 180 €/year

Total energy bill savings ≈ 255 €/year

Solar hot water option (evacuated tube):

- System cost: 5 m^2 / 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

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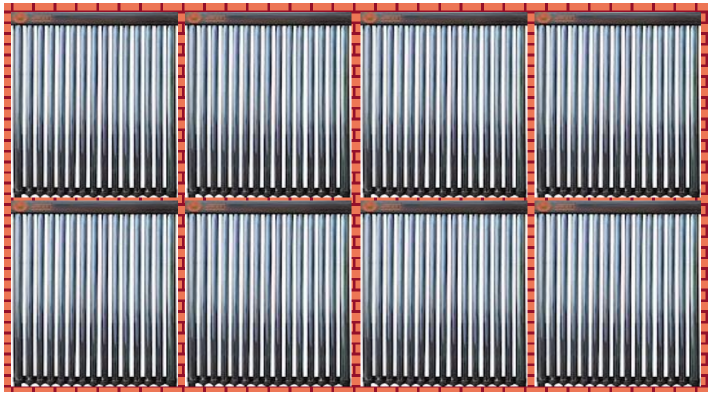
Solar-ORC system

Consider a 15 m² roof



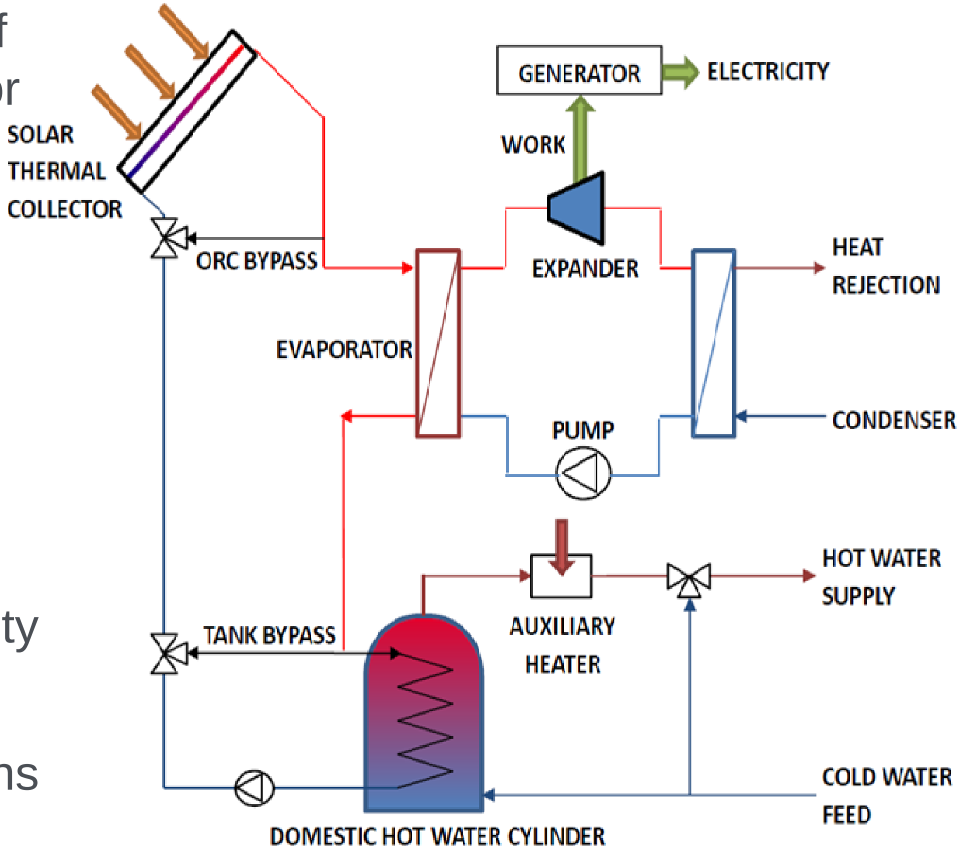
Solar thermal heat and power system

- Entire roof covered with solar thermal collectors
- Power generation via an ORC engine
- Cost of ORC components + install + additional collectors ≈ € 3000
- Power generation in the region of 700-950 kWh/yr (80-110 We average) ≈ 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 m^2 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)



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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

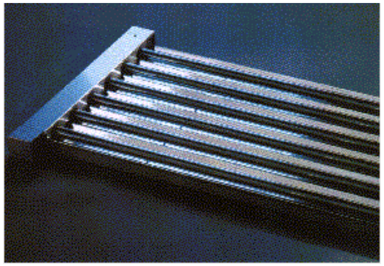
Results of annual simulation with ORC model:

- 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)

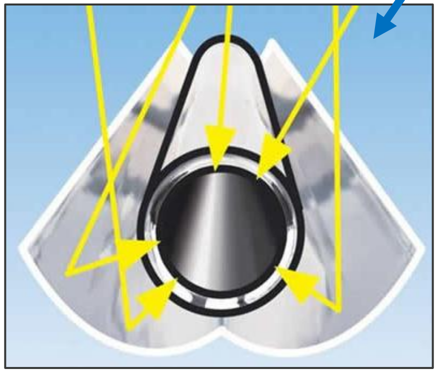


Microtherm SK-6 (CPC)

Parabolic Trough Collectors (PTC)

Solitem PTC-1000

NEP Polytrough 1800



Compound parabolic concentrator

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

Thermomax FN (Flat plate)

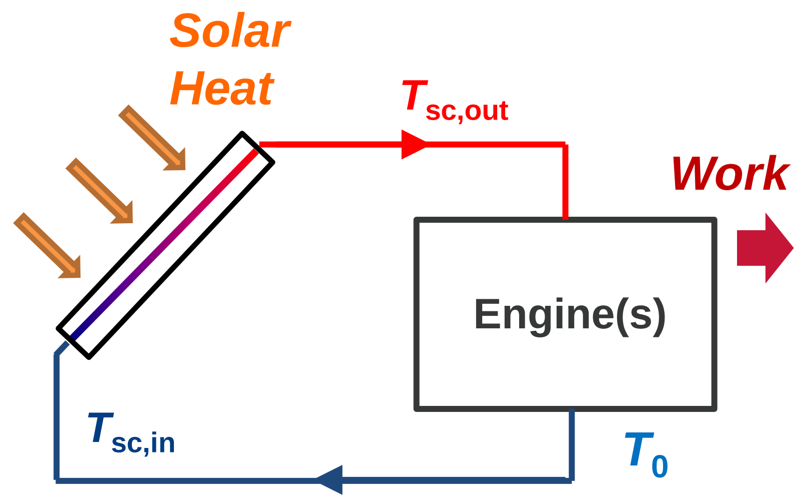
Volther PowerTherm (PV-T)

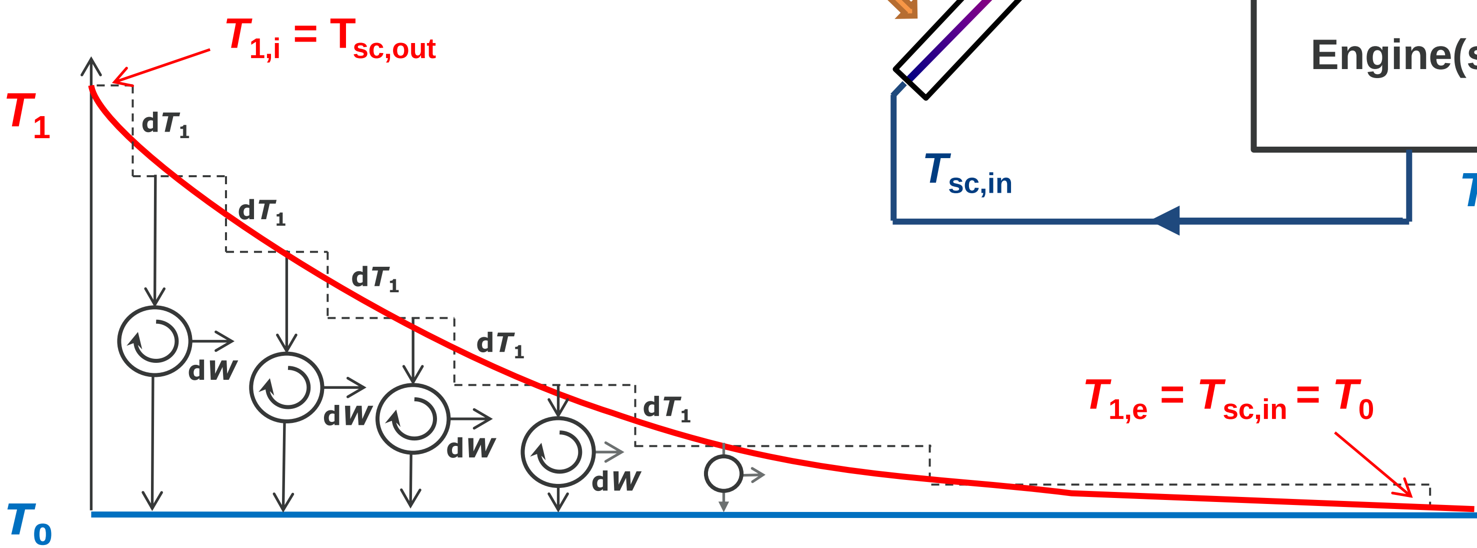
Calculation of maximum power

Maximum power = exergy flow at collector outlet:

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

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





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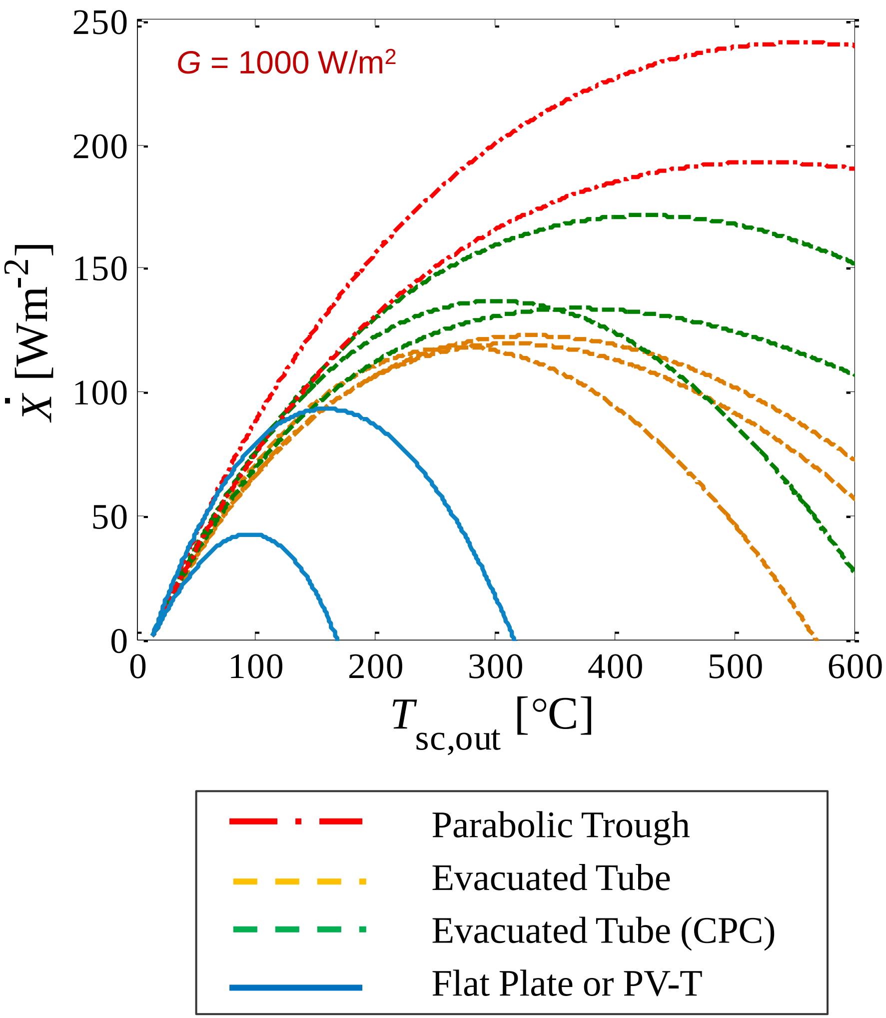
Solar collector maximum work



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

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Controlling for optimum temperatures

Objective function:

- Maximise ORC power output

Variables:

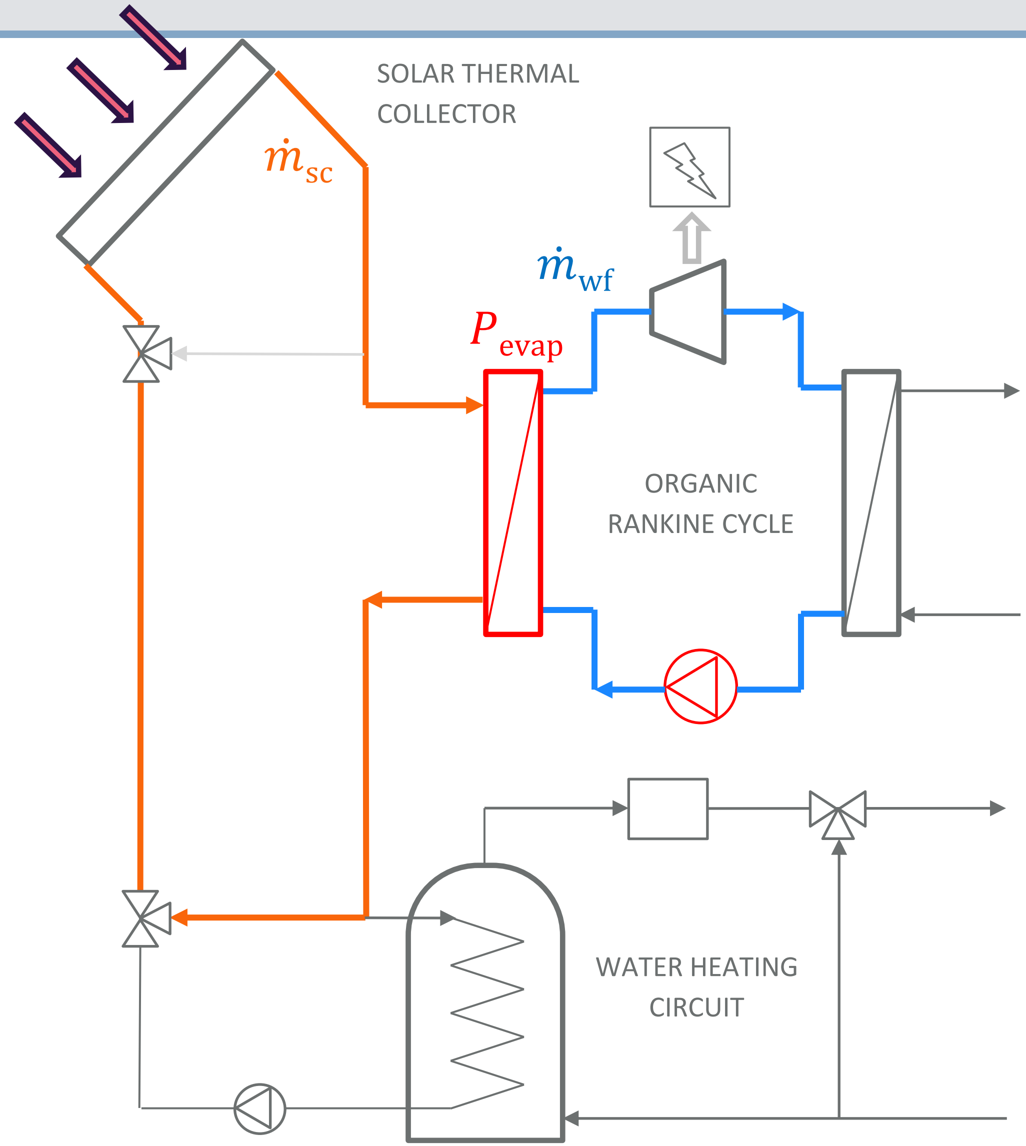
- Working fluid flow rate
- Solar collector flow rate
- Evaporation pressure

Constraints:

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

Assumptions:

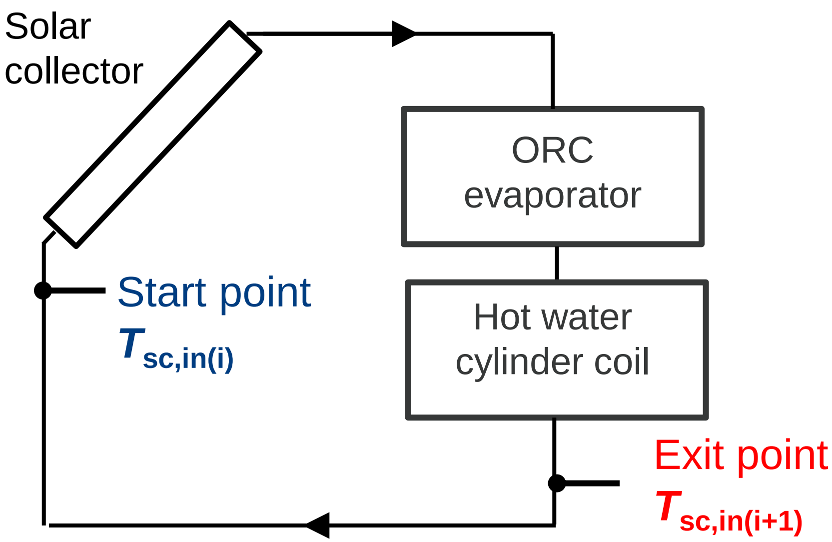
- Zero solar fluid flow to hot water cylinder.
- Constant cold sink (water) temperature = 10 °C
- Cycle condensation temperature = 17 °C



Model variants

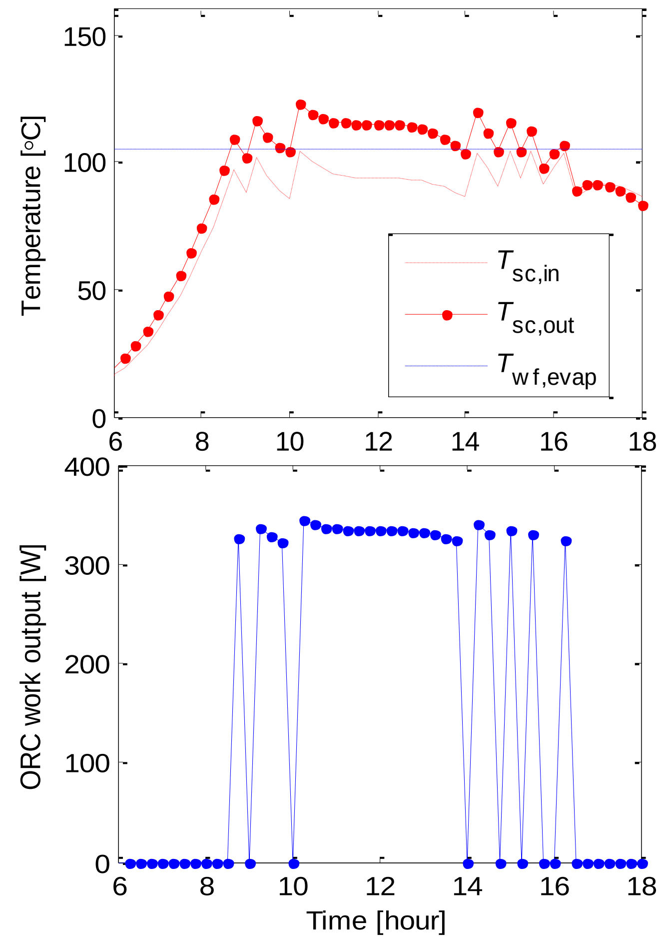
Initial fixed flow-rate model:

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



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

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



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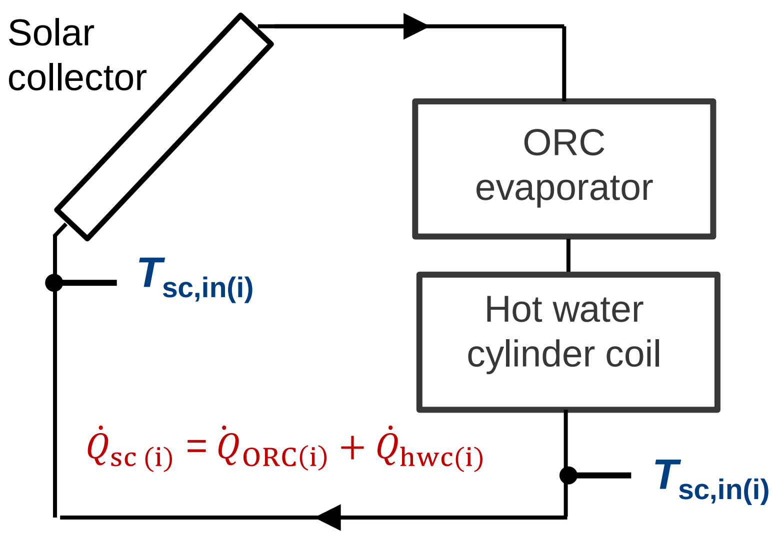
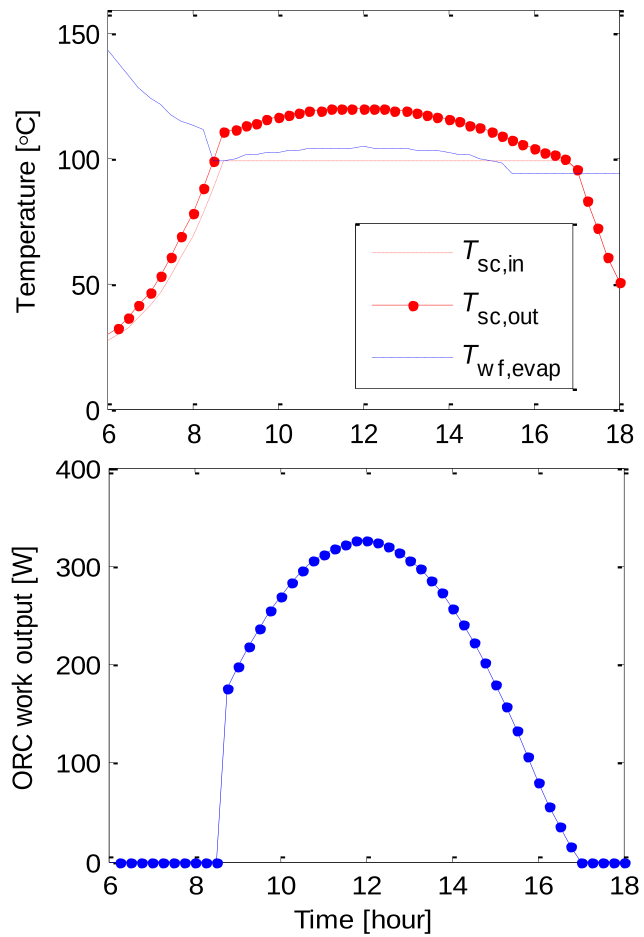
Model variants

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.



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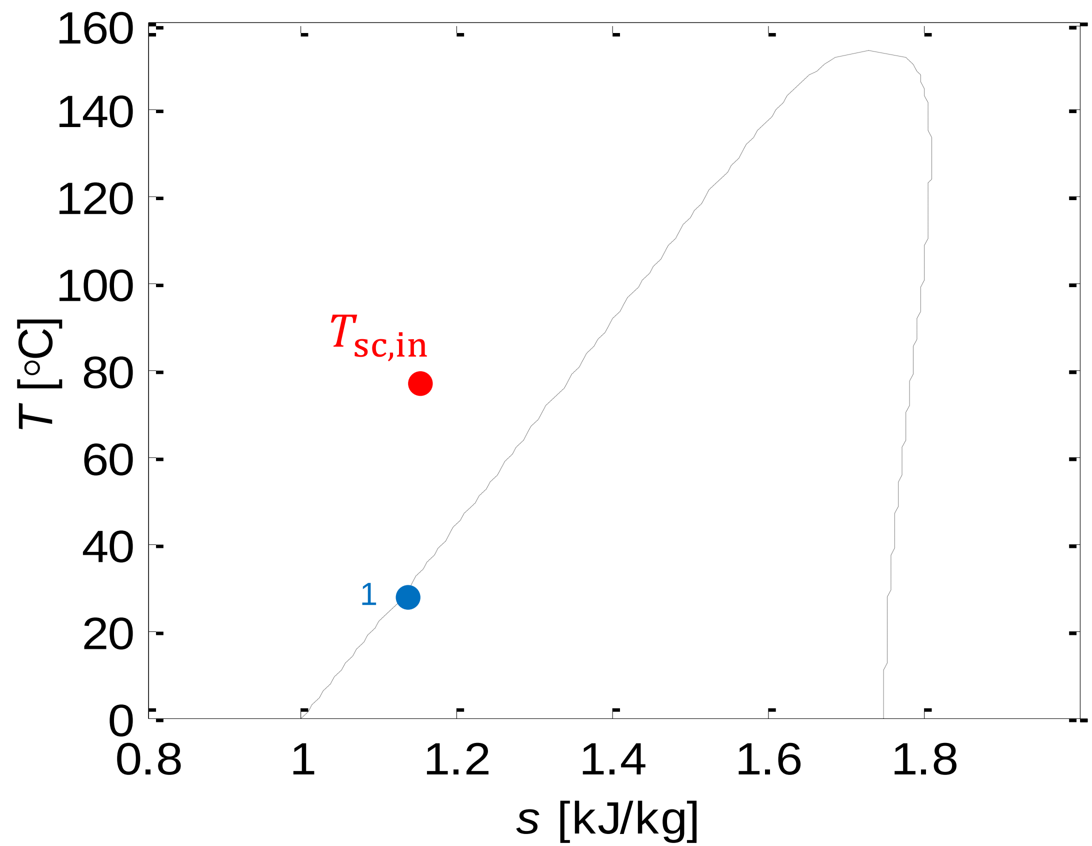
Controlling for optimum temperatures

<u>Starting point:</u>

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



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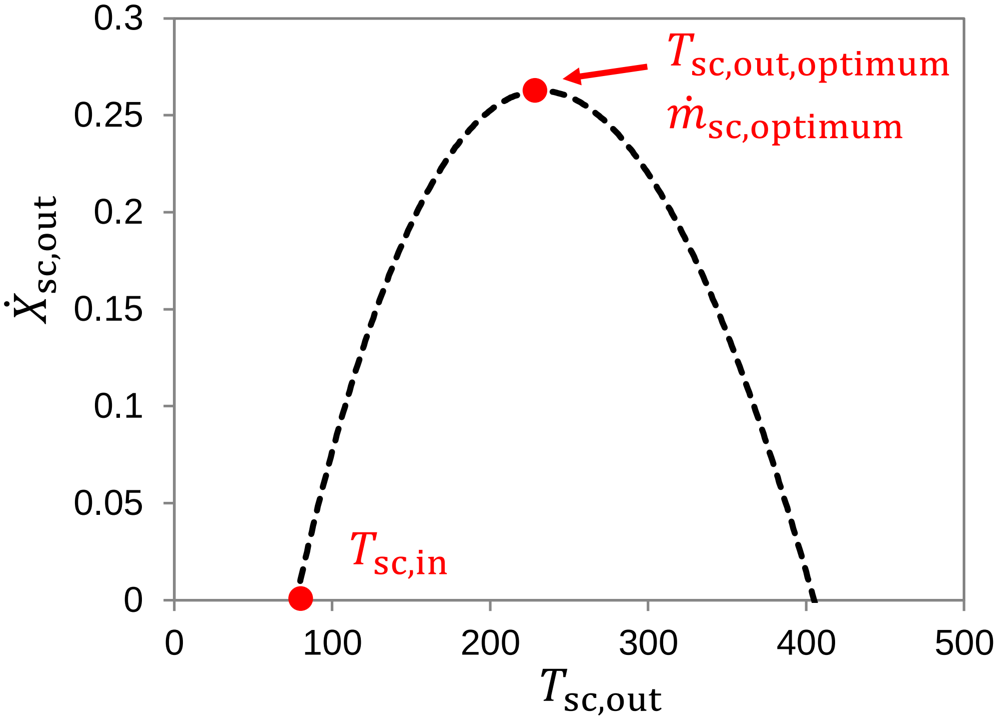
Controlling for optimum temperatures

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 $T_{\mathrm{sc,in}}$, T_{ext} and G

Input variables:

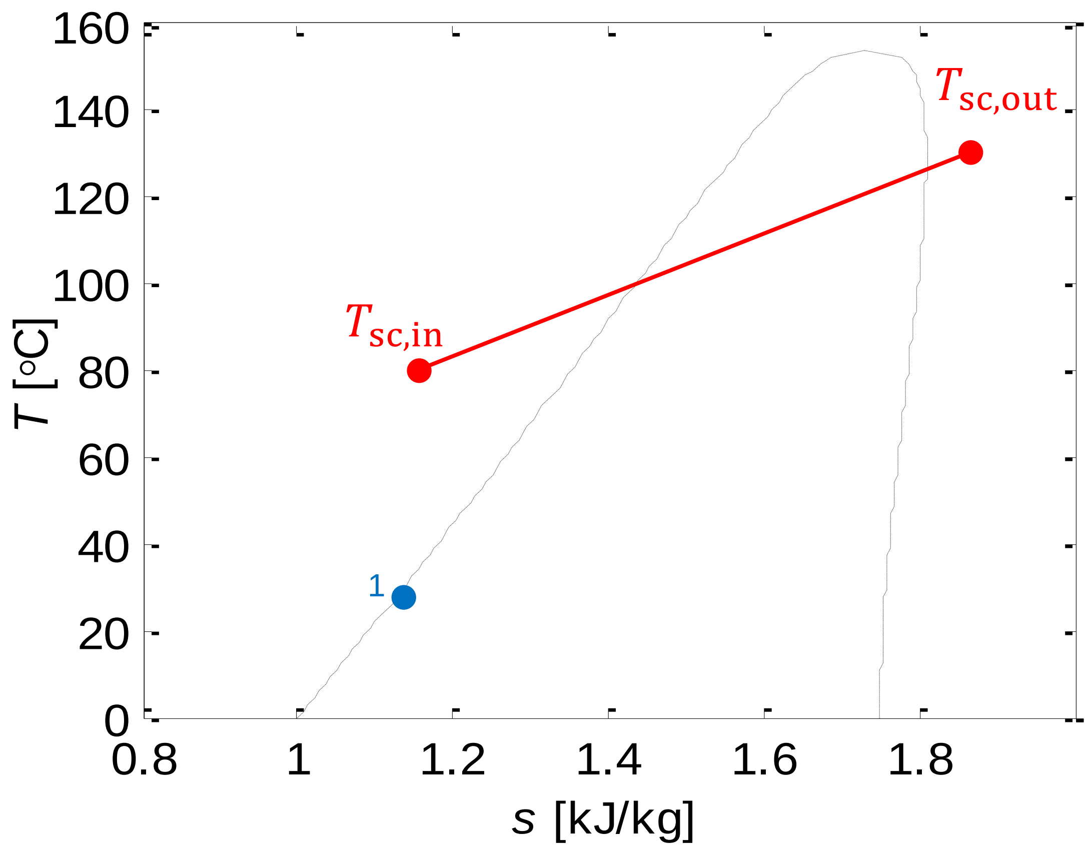
$T_{\mathrm{sc,in}}$, G, T_{ambient}, T_0



Controlling for optimum temperatures

Calculation procedure

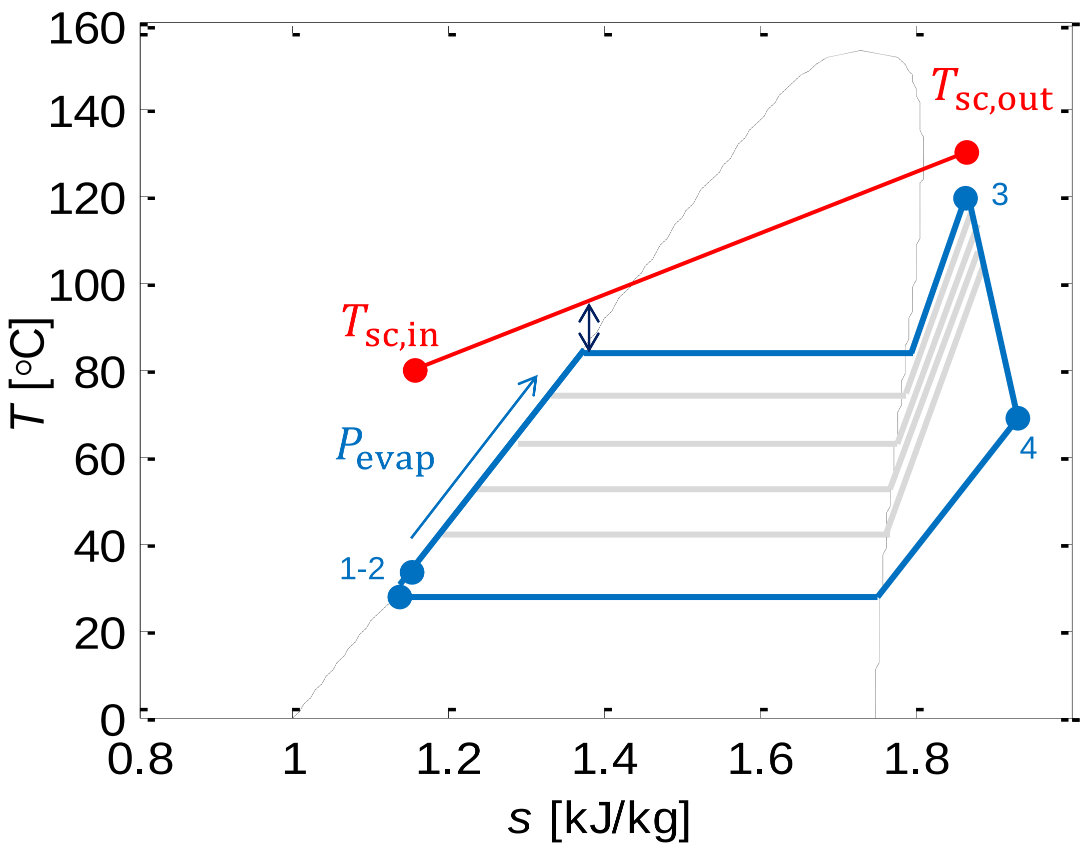
- Choose initial $T_{sc,in}$
- Set optimal $T_{sc,out}$



Controlling for optimum temperatures

<u>Calculation procedure</u>

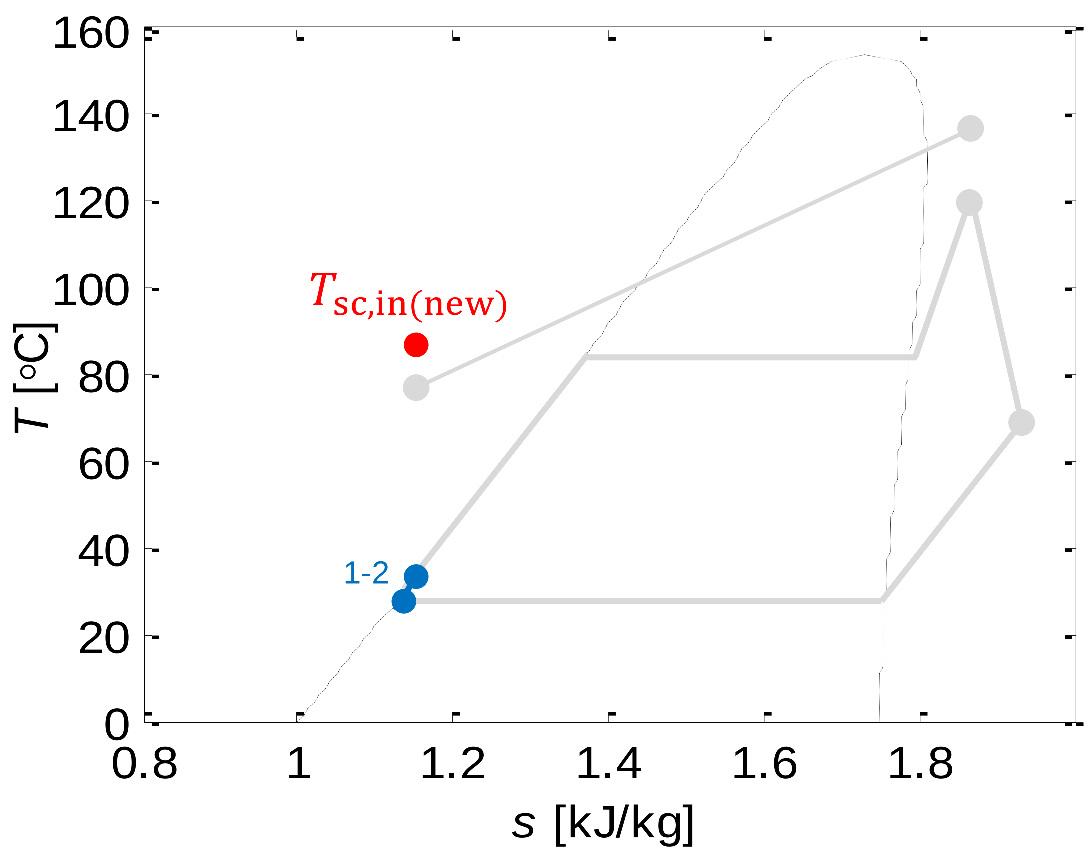
- Choose initial $T_{\mathrm{sc,in}}$
- Set optimal $T_{\mathrm{sc,out}}$
- Calculate T_3 and $\dot{m}_{\mathrm{wf}}$
- Try higher values of P_{evap} until pinch limit reached
- Calculate power output from ORC engine.



Controlling for optimum temperatures

<u>Calculation procedure</u>

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



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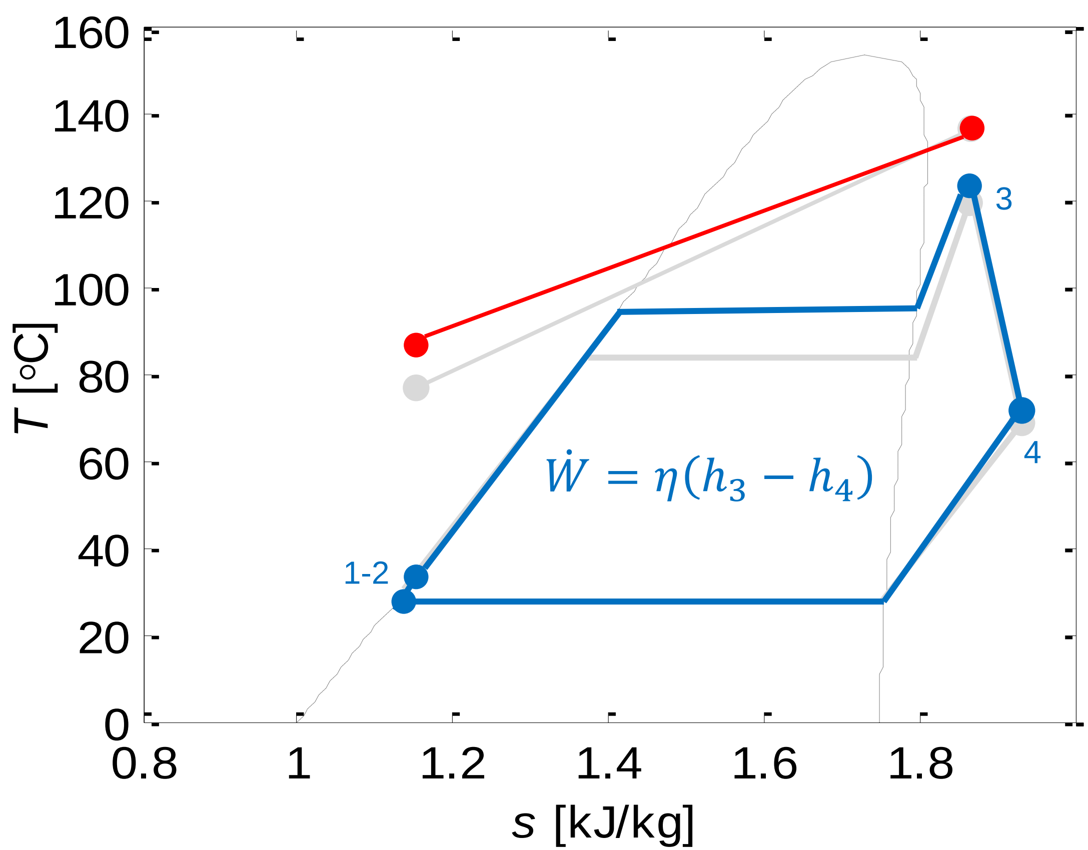
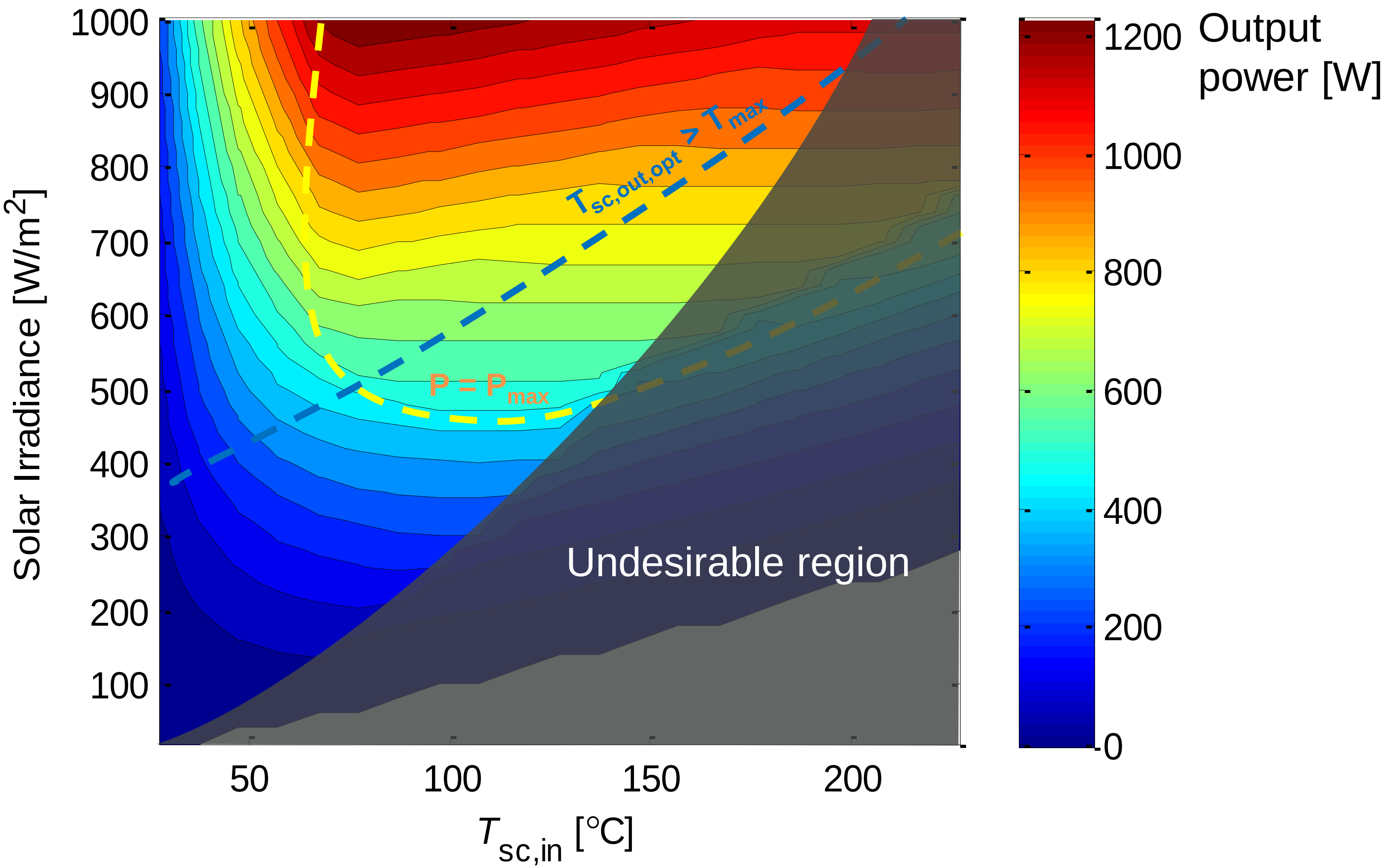
Controlling for optimum temperatures

Calculation procedure

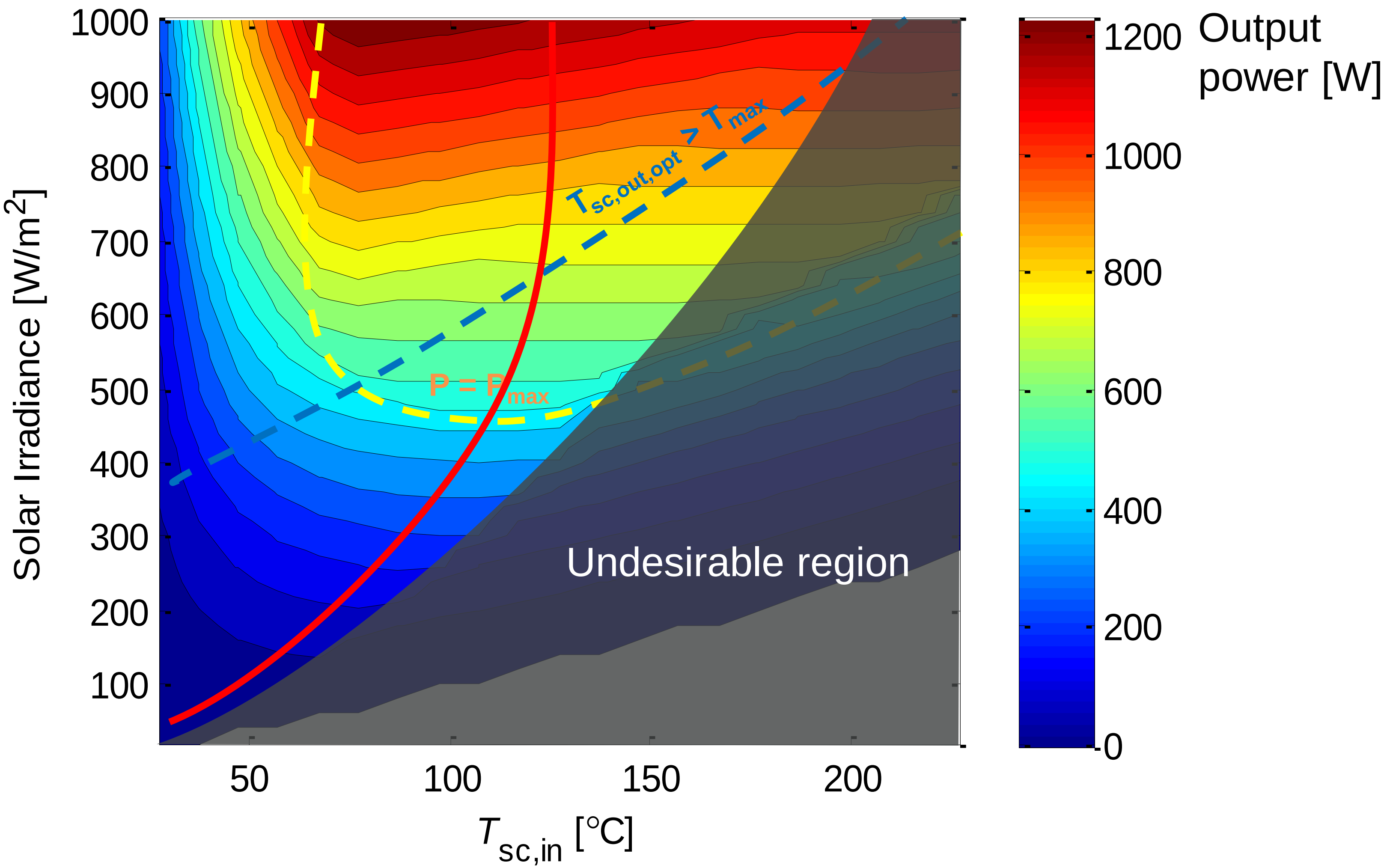
- Choose initial $T_{\text{sc,in}}$
- Set optimal $T_{\text{sc,out}}$
- Calculate T_3 and $\dot{m}_{\text{wf}}$
- Try higher values of P_{evap} until pinch limit reached
- Calculate power output from ORC engine.
- Choose a new $T_{\text{sc,in}}$
- Repeat calculation procedure until $\dot{W}$ is maximised



Optimal performance region



Optimal performance region



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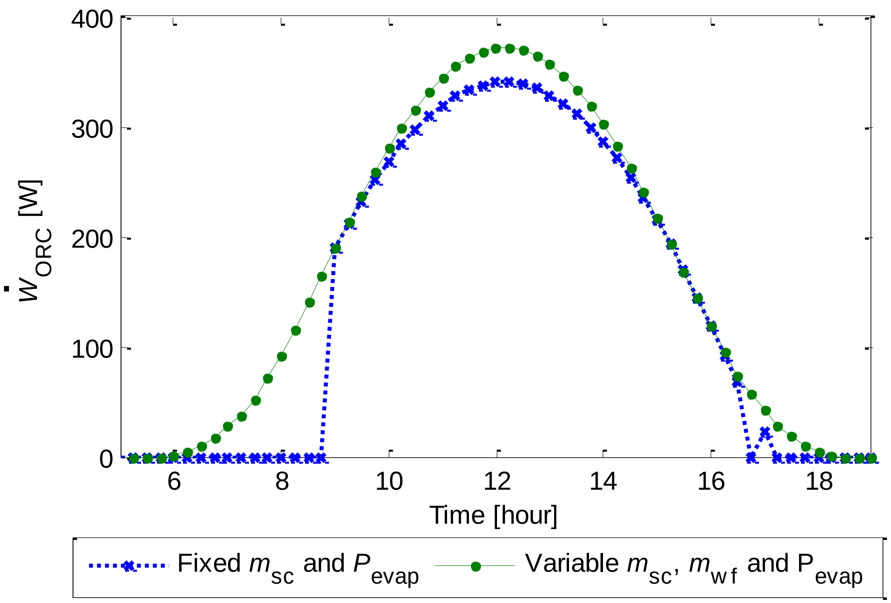
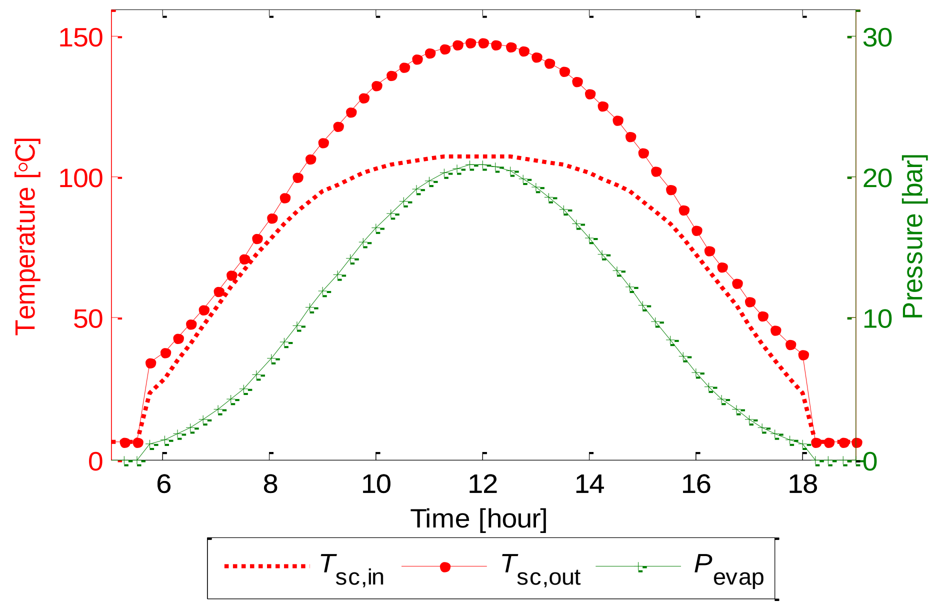
Results (annual average day)





- 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

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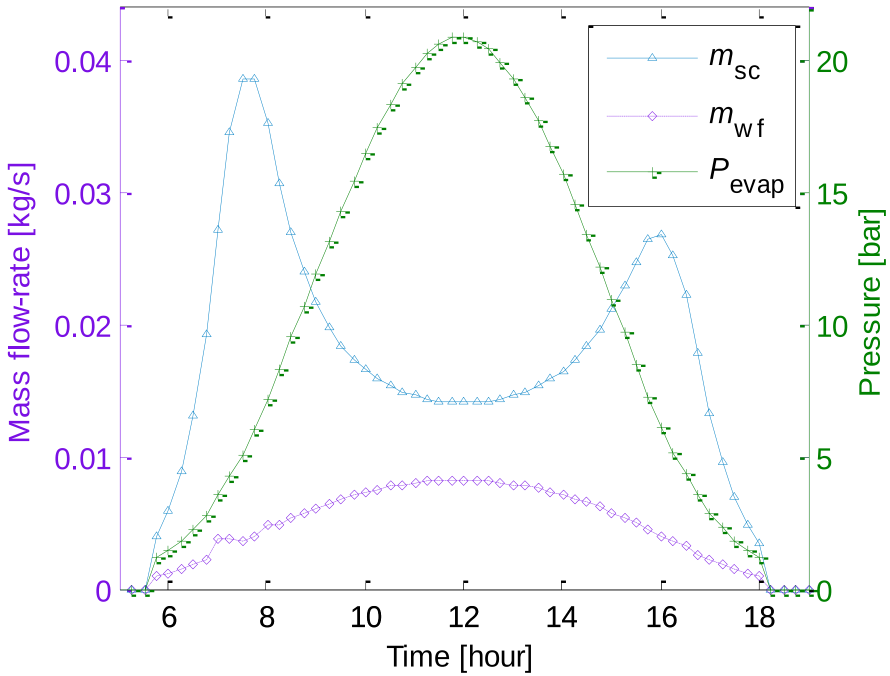
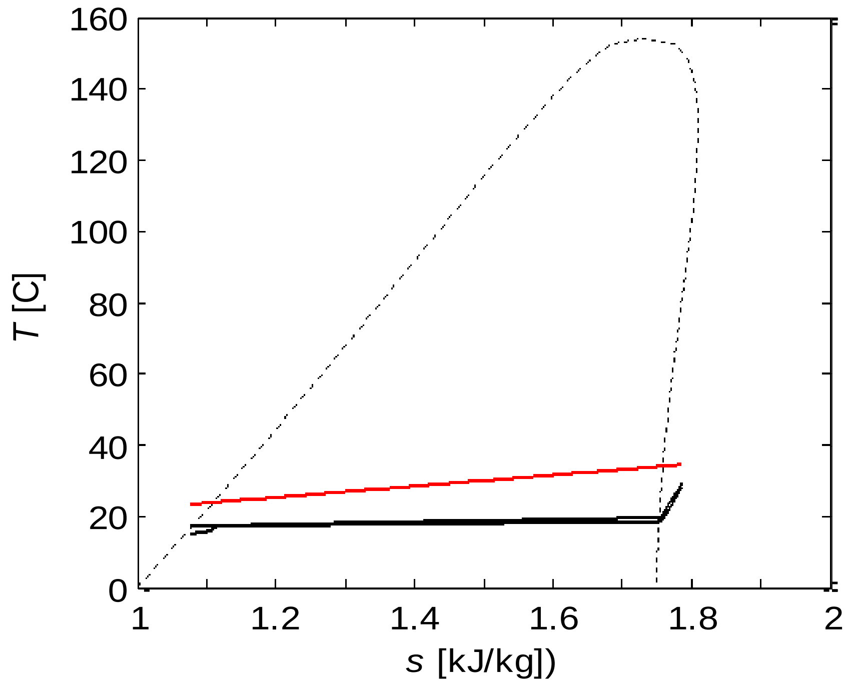
Results (annual average day)





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

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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.