IMPROVING PERFORMANCE OF EXTREMUM-SEEKING CONTROL APPLIED TO A SCO2 BRAYTON CYCLE IN A SOLAR THERMAL POWER PLANT

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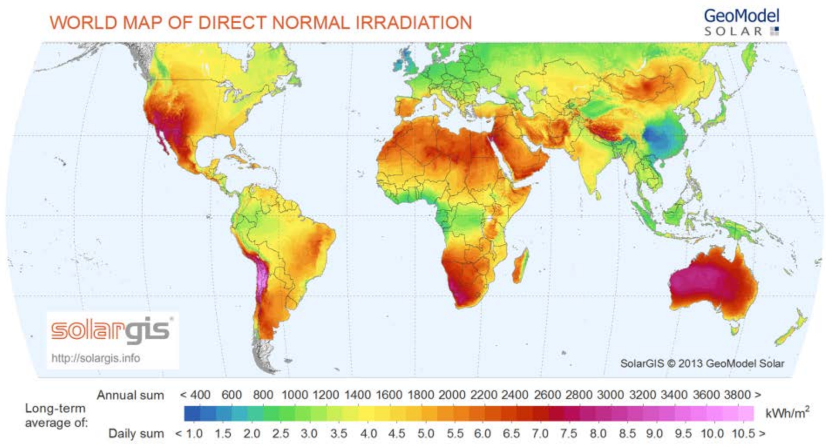
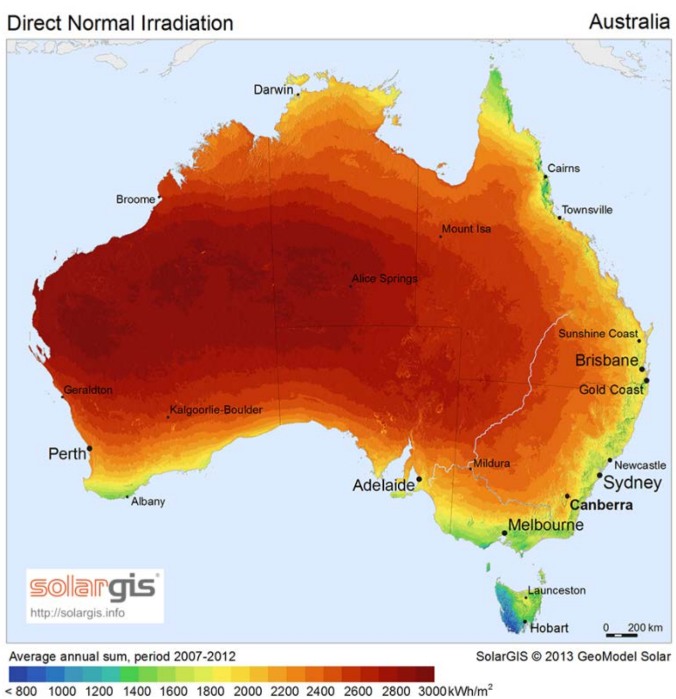
Drivers behind the use of a direct-heated sCO2 cycle and research into dynamics and control





1. **Australia has an abundant solar resource**

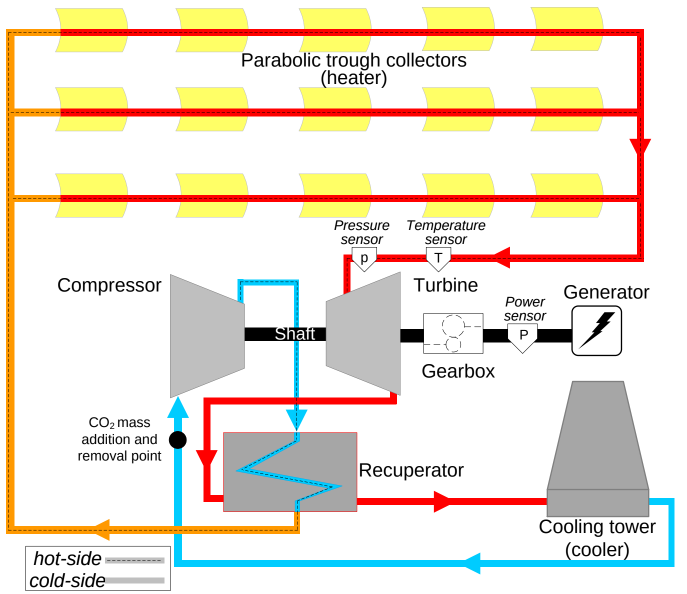
2. **Significant potential for small to medium scale (<10 MW) sCO2 power plants to supplement or replace diesel fired generation in remote communities and mining towns**

3. **Solar-to-electricity conversion efficiencies** can be **improved** by **using sCO2** and **direct-heating** (eliminate HTF loop and hence thermal losses)
   - **Direct-heated sCO2 cycle: single-phase flow, non-toxic, non-flammable, compact plant, suitable for high temperature operation**
   - **sCO2 cycle offers scalability , potential to reduce costs of electricity produced in CST power plants!**

4. Plant has **to be air-cooled**
   - Best solar insolation located in **arid areas, unavailability of water, more efficient heat-exchange with single-phase sCO2**

5. Air-temperatures are generally higher than 26°C for most of the day at potential power plant sites ***resulting in a fully supercritical cycle*** *CO_2 critical temperature, pressure: 31.1°C, 7.38 MPa*

Modelled sCO2 Brayton cycle features



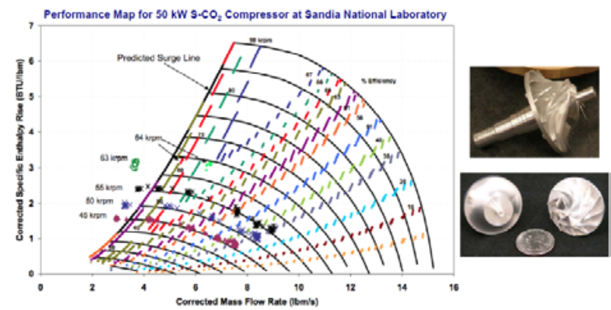
Turbine inlet temperature	350°C
Turbine inlet pressure	20 MPa
Compressor inlet temperature	32°C
Compressor inlet pressure	7.8 MPa
Generator/ Turbine/ Compressor efficiency	1/ 0.83/ 0.69
CO2 mass-flow rate	19.6 kg/s
Cooling air mass-flow rate	365 kg/s
Thermal efficiency with recuperation	23.4%
Design net heat input/ ambient air temperature	4.73 MW/ 26°C
Net-power generation	1 MWe
Compressor/ Turbine rotational speed	60,000 rpm
Compressor/ Turbine wheel diameter	65.8 mm/ 92 mm
System specific charge at design condition	300 kg/m^3
CBC Hot side: Cold side volume-ratio	~1

- 1 MWe net output designed for an average ambient temperature of 26°C (6°C HX approach) at Longreach, QLD
- Recuperated closed-cycle, three heat-exchangers
- Single compressor, single turbine, single-shaft operation
- Direct-heating of closed-loop (no-secondary oil circuit)
- Turbine pressure and temperature sensor for ESC, Inventory manipulation at compressor inlet
- System modelled in *Dymola*®; object-oriented commercial package for modelling and simulation of complex physical systems

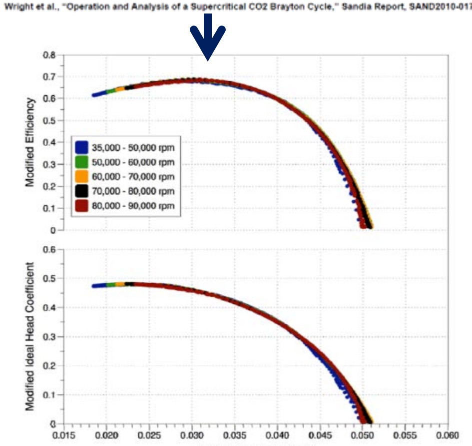
1. Singh, R., Miller, S. A., et al. 2013. "Dynamic characteristics of a direct-heated supercritical carbon-dioxide Brayton cycle in a solar-thermal power plant." Energy **50**: 194-204.
2. Singh, R., Rowlands, A. S., et al. 2013. "Effects of relative volume-ratios on dynamic performance of a direct-heated supercritical carbon-dioxide closed Brayton cycle in a solar-thermal power plant." Energy **55**: 1025-1032.

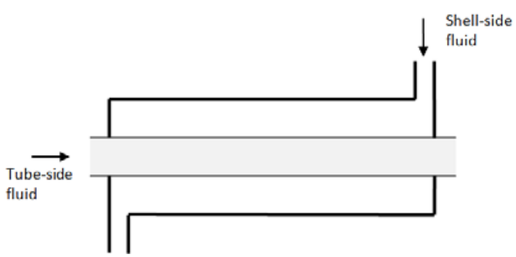
Overview of component modelling

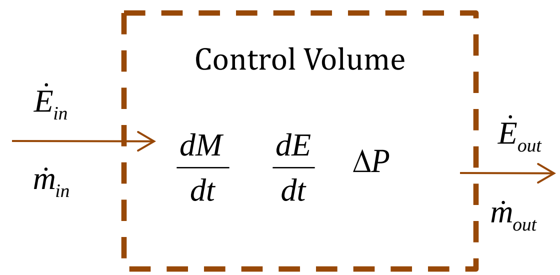
- Control oriented cycle model - objective to model system as simply as possible whilst resolving physical phenomenon, **zero and one-dimensional models used**
- Compressor possesses pump-like characteristics due to high densities at operating point (~ 600 kg/m^3)
- Using similitude and pump-scaling laws – based on SANDIA Labs 50 kW sCO2 radial compressor test data and *flow, head, and efficiency coefficients* (Dyreby, Klein et al. 2011) used in off-design performance calculations
- More ideal-gas-like conditions at turbine inlet
- **Radial turbine modeled as a fixed area nozzle** with mass flow driven by the pressure drop across it, Spouting Velocity utilised
- **Heat-exchangers modeled as simple counter-flow double-pipe types**
- Mass and Energy Conservation laws used as governing equations



Wright et al., "Operation and Analysis of a Supercritical CO2 Brayton Cycle," Sandia Report, SAND2010-0171, pp. 1-101 (2010)

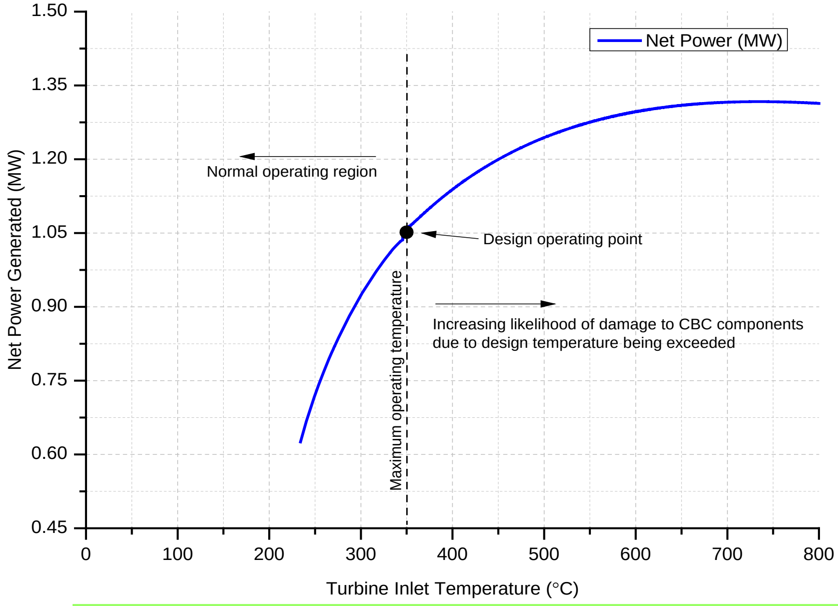




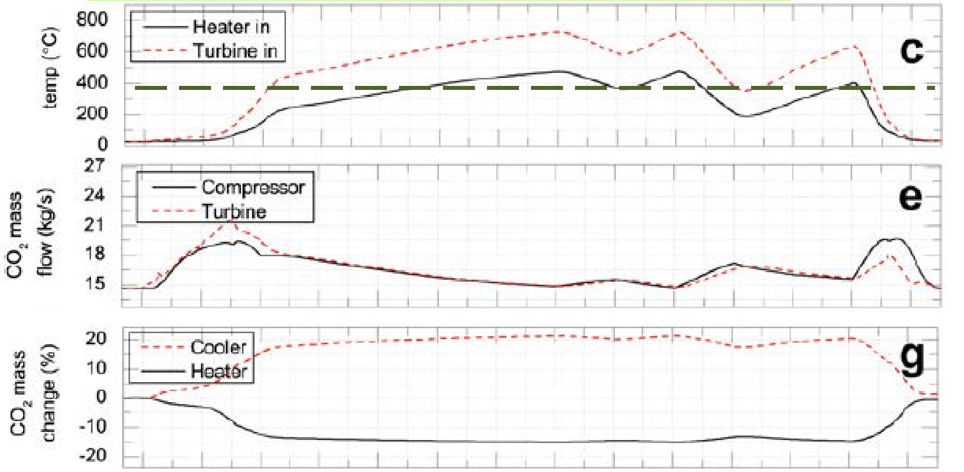


1. Dyreby, J. J., Klein, S. A., et al. 2011. Modeling off-design operation of a supercritical carbon dioxide Brayton cycle (11SM1-3). Supercritical CO_2 Power Cycle Symposium Boulder, Colorado, USA, May 24-25.

The need for a control strategy



Plant operation in summer, selected results



(Singh, Miller et al. 2013; Singh, Rowlands et al. 2013)

- Operating at design point conditions delivers maximum power, however potential damage could result to cycle **beyond 350°C turbine inlet temperature and pressure > 25 MPa.**
- Preceding investigations in absence of control have demonstrated turbine inlet temperature and pressure overshooting allowable limits during summer operation.
- ***Control of the cycle is required!***
- **CO2 inventory manipulation has also been shown using simulations to deliver design point operation.**

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sCO2 CBC control issues and Extremum-Seeking Control (ESC)

- Control of the sCO2 Brayton cycle in a CST power plant presents a **constrained optimal control problem**

→ **Maximise net power output .**

→ **Operate cycle within allowable bounds, Turbine Inlet Pressure <25MPa and Temperature ~350°C.**

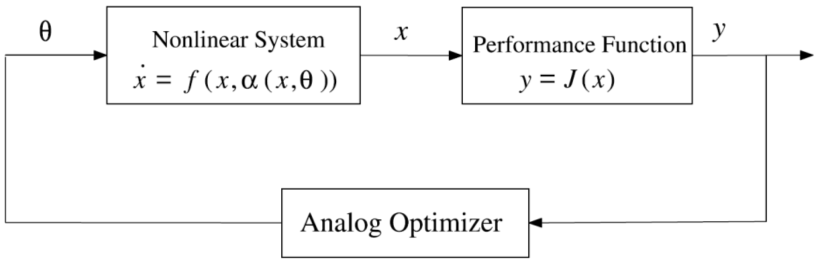
- ***Fluctuating Heat Source and Cooling Medium – Several possible optimum operating conditions depending on combination of solar heat input and ambient air temperature.***

- Model-based optimal control approaches require simple low-order models of the power cycle for controller development.

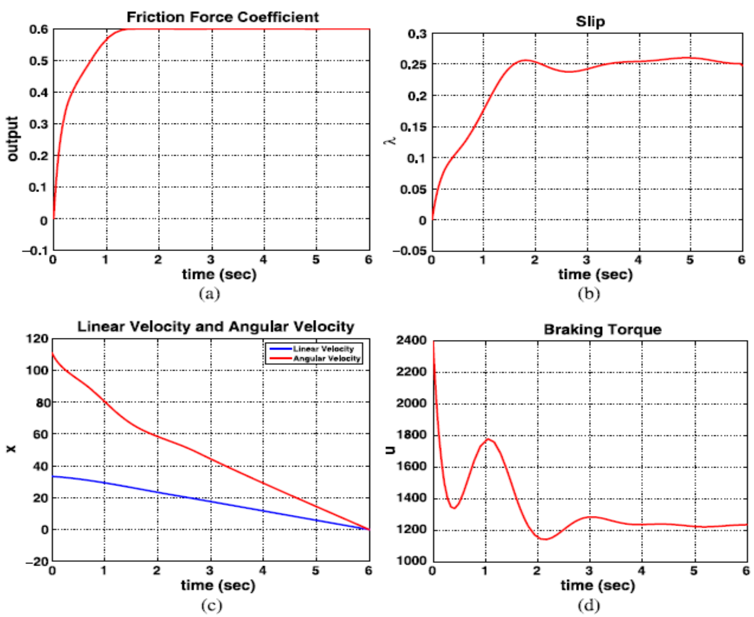
- Simple low order models are difficult due to the fine spatial resolution of the heat-exchanger volumes required to capture the highly nonlinear behaviour of supercritical-CO2.

- **Suggests the use of a model-free optimal control method,** such as **Extremum-Seeking (ES) control.**

Extremum-Seeking Control (ESC)



ABS Example

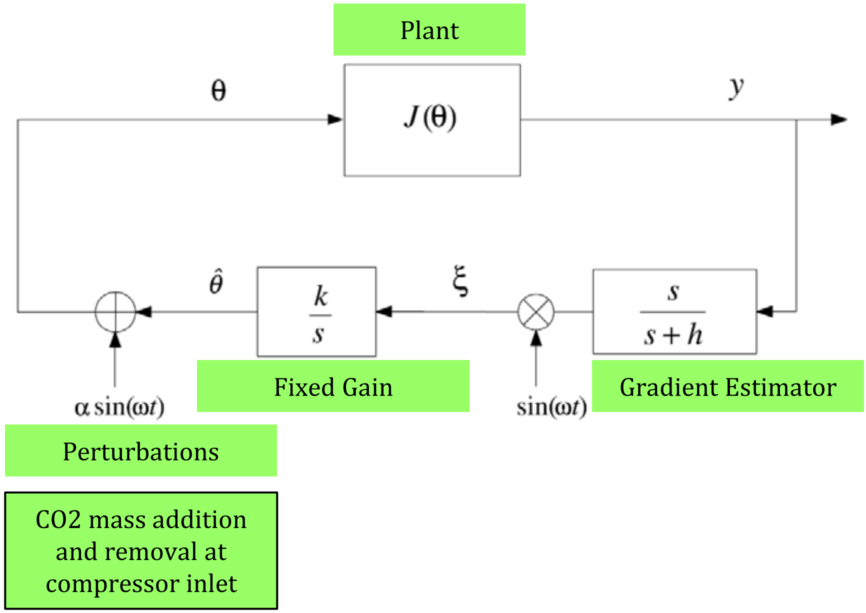


- Goal of extremum-seeking (ES) is to find the input, which minimises or maximises *y* using only measurements of the output.
- Non-model based real-time optimal control approach for nonlinear dynamic systems.
- Minimal plant information is required, the plant having a nonlinear equilibrium map which possesses a local minimum or maximum.
- Recent resurgence due to the development of the first stability analysis of sinusoidally perturbed ES on a general, non-linear plant.
- Recent applications: *Automotive, Solar PV, Wind, Bioreactors, Gas turbine combustors, UAVs.*
- Gradient-based optimisation methods: *Sliding-mode, **Perturbation Based (popular).***
- Can readily be extended to 'multidimensional input' plants.

Introduction and examples

Zhang, C. and R. Ordóñez. 2012. Extremum-seeking control and applications - a numerical optimization-based approach. London, Springer-Verlag.

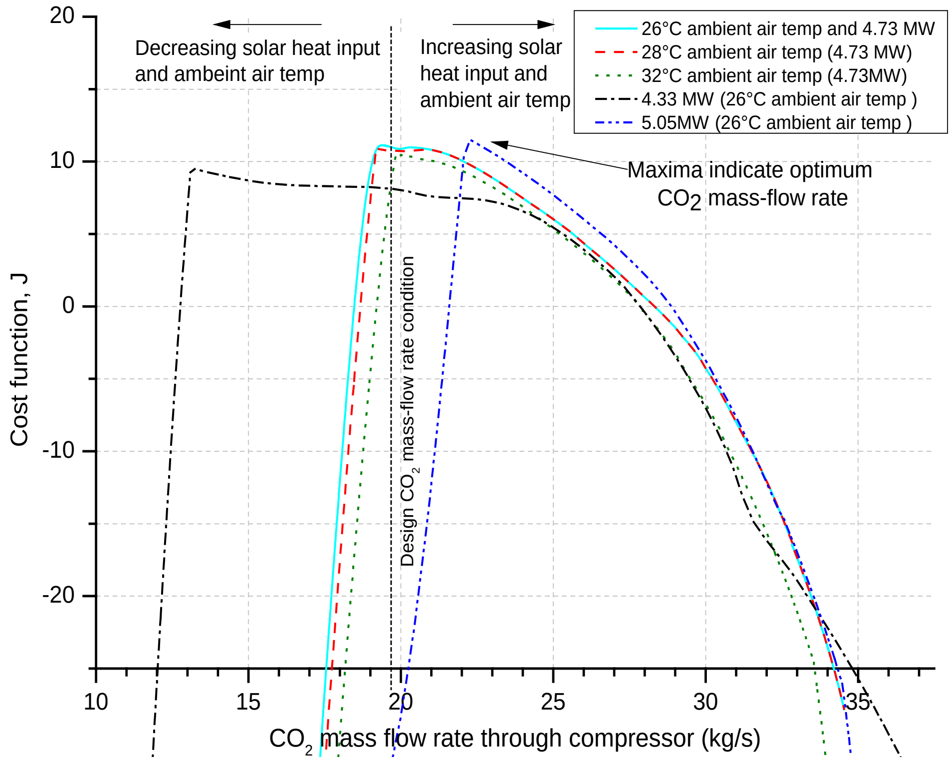
Perturbation-based Extremum-Seeking Control (PESC)



- Plant is treated as *'black-box'* - requires minimum previous knowledge on the plant.
- Continuous measurements made by the ESC are used as inputs to appropriate filters which estimate the gradient of the plant performance function with respect to the steady state plant input.
- Gradient estimation is then used with an appropriate optimisation routine to tune the plant input to achieve convergence towards optimal plant operation.
- Fixed controller parameters regardless of operating conditions
- "Grey-box" methods incorporating some prior knowledge on plant performance function can also be utilised (Newton-like ES) (Moase, Manzie et al. 2010).

Moase, W. H., C. Manzie, et al. 2010. "Newton-like extremum-seeking for the control of thermoacoustic instability." Automatic Control, IEEE Transactions on **55**(9): 2094-2105.

sCO2 CBC steady-state plant performance function



Plant cost function

$$J = P_{net} - \alpha\,\Gamma\left(T_{t,in}, T_{\text{maximum}}\right) - \beta\,\Gamma\left(p_{t,in}, p_{\text{maximum}}\right)$$

Soft constraints introduced in performance metric

$$\Gamma(x,y) = \begin{cases} 0 & if \quad x < y \\ x - y & if \quad x > y \end{cases}$$

- Several optima exist depending on boundary conditions.
- Cost function curve is ASYMMETRIC, a constrained optimal control problem exists unlike conventional ESC cases.
- Gradient characteristics vary with different solar and ambient air temperature combinations

From **previous** proof-of-concept (Singh, Kearney et al. 2013) study with a fixed-controller gain in the PESC scheme, we learnt that:

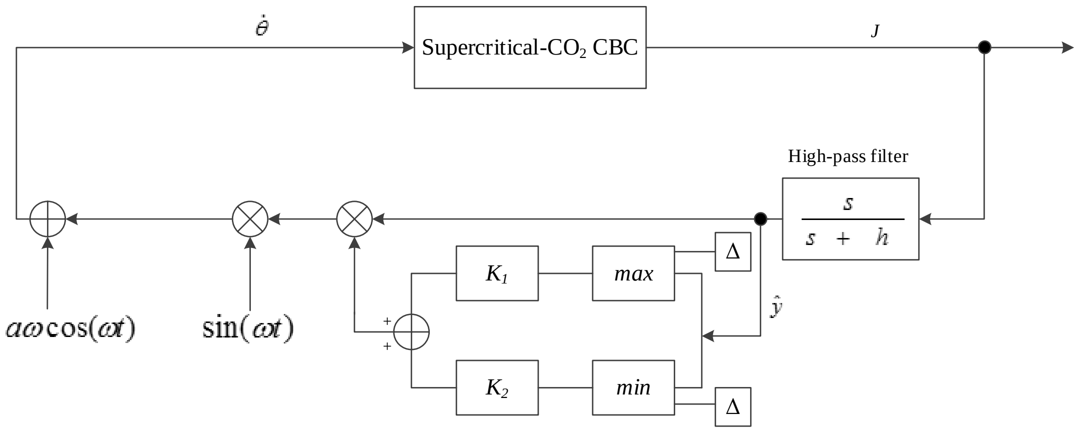
- A fixed controller gain (non-scheduled) needs to be small in order to guarantee closed loop stability.
- Small gain means that the convergence rate of the controller is slow when the gradients are not as steep on the other side of the optima.

Singh, R., Kearney, M. P., et al. 2013. "Extremum-seeking control of a supercritical carbon-dioxide closed Brayton cycle in a direct-heated solar thermal power plant." Energy **60**: 380-387.

Gain-scheduled Extremum-Seeking

Gain-Scheduled ES tuning rule

$$K(\hat{y}) = \begin{cases} K_1 & if \quad \hat{y} > \Delta \\ K_2 & if \quad \hat{y} < \Delta \end{cases}$$



Gain-Scheduled ES Simulation Parameters

Dither frequency, ω (rad/s)	0.0017
Gain, K_1	3
Gain, K_2	2
High pass filter cut-off frequency, h (rad/s)	0.001
Dither amplitude, a	10
Slack variable weights, α,β	0.5
Estimation error, Δ	0.15

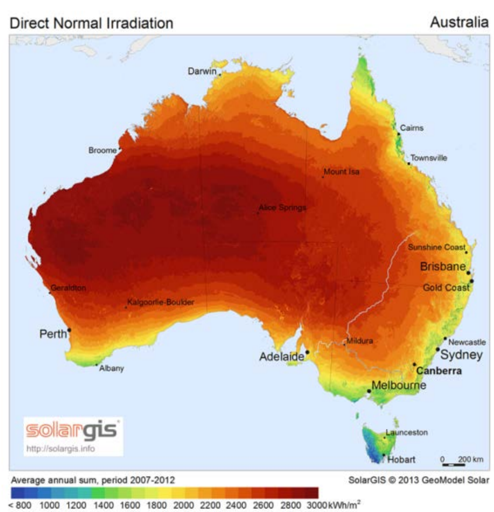
- **In this study,** improvement of ESC performance is investigated **through implementing a Gain-Scheduled ES tuning rule.**
- **Extra degree of freedom is introduced in tuning the ES**
- ES controller parameters remain unchanged on a day-to-day and seasonal basis

Gain-Scheduled ES simulation results compared with:

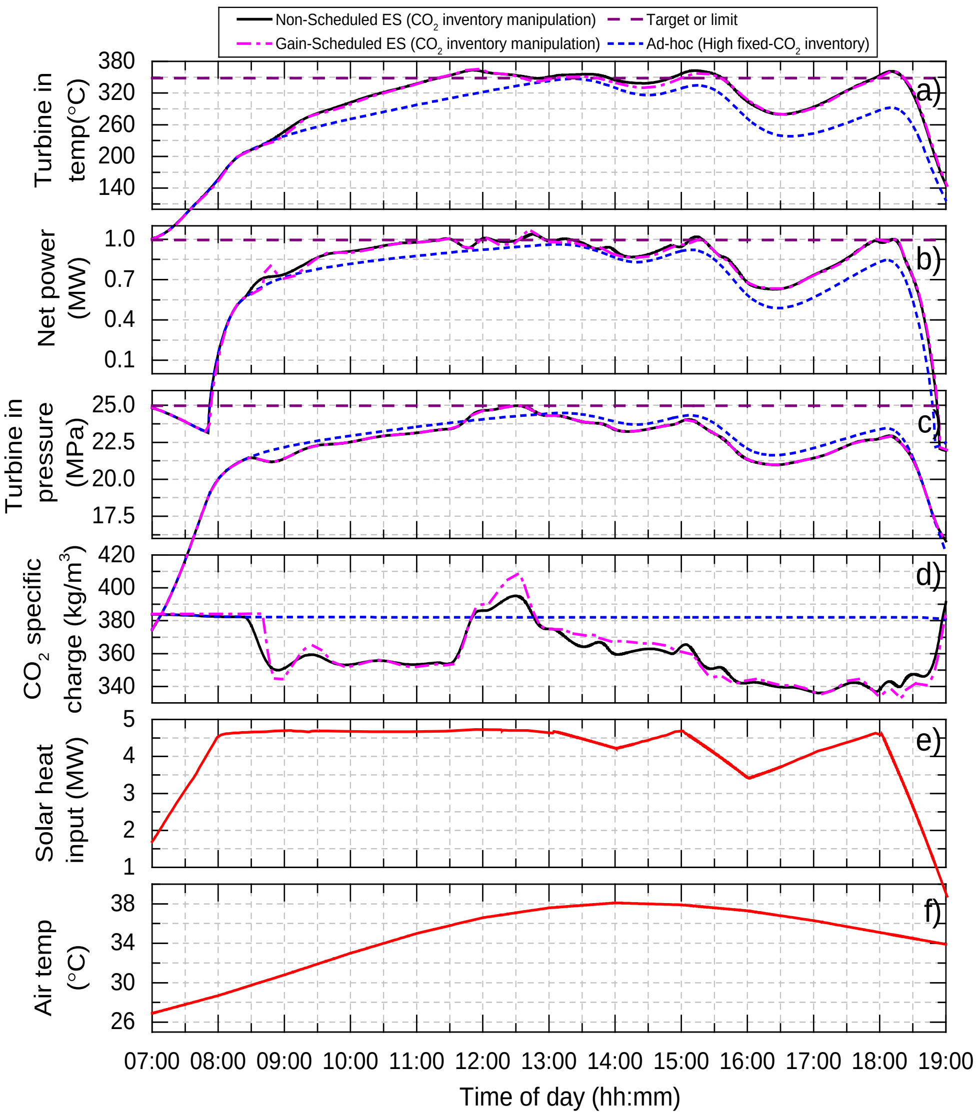
1. Non-scheduled ES approach, Gain $K=2$, $K=K_1=K_2$
2. Fixed-inventory (ad-hoc) approach
   - Initial charge determined previously through manual tuning to achieve sufficient performance and held constant

Key simulation conditions/simplifications

- No thermal storage
- Solar heat input and ambient air conditions at Longreach in Queensland, Australia
- Representative Summer and Winter day weather conditions with hypothetical heat input based on that from separate simulations from a parabolic trough field with a thermal-oil circuit
- Secondary controller assumption, maintaining above-critical compressor inlet temperature due to low average ambient air temperatures on Winter day
- Solar field defocussing above design solar heat input in Summer (secondary controller)
- CO2 inventory addition and removal conducted at compressor inlet

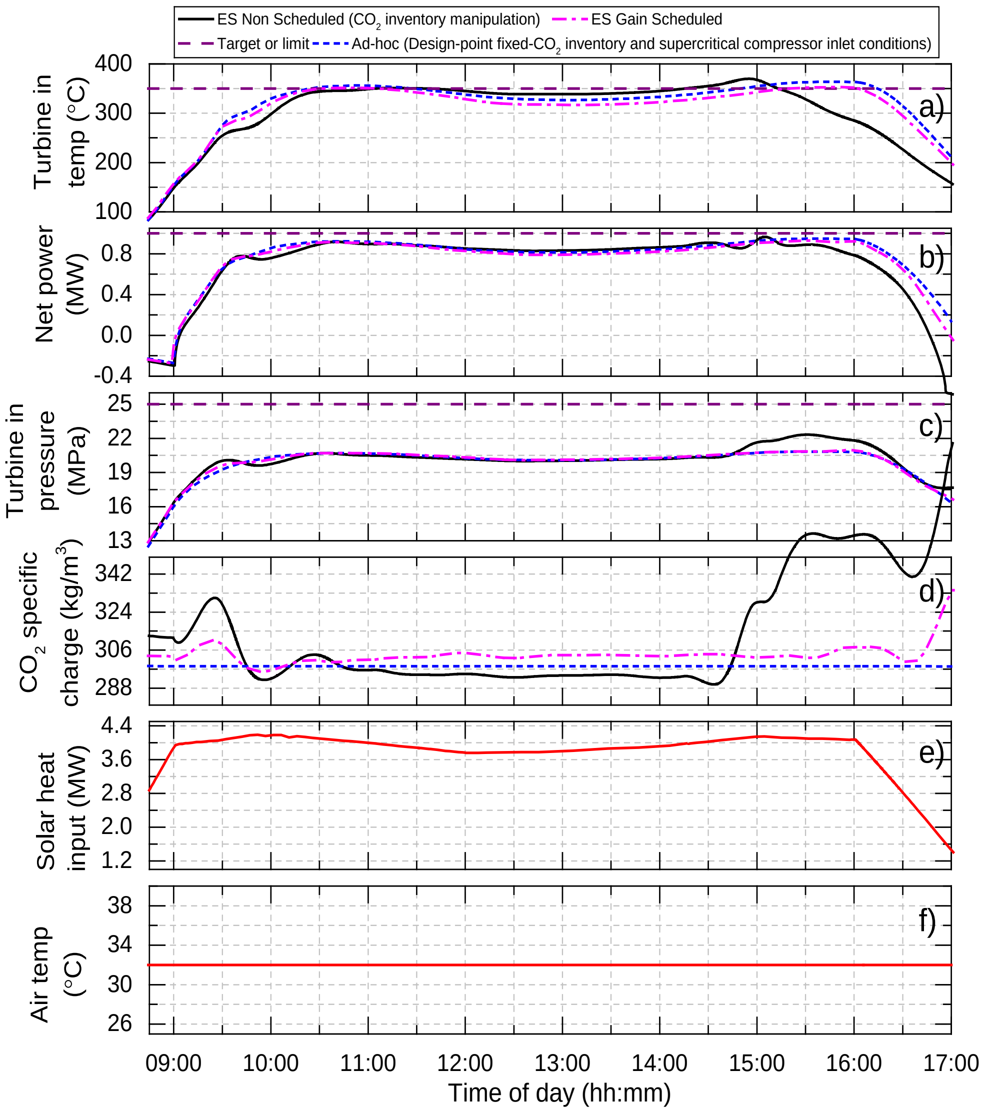


Summer day operation with defocusing (21-Dec)



- Gain-scheduled ES delivers average electrical energy generation of 8.6 MWh over the 10-hour normal solar insolation period (between 08:00 and 18:00).
- Non-scheduled approach delivers an average of 8.7 MWh delivered.
- Gain-scheduled approach maintains turbine inlet temperature closer to the target value of 350°C hence slightly lower power.
- An average of 7.9 MWh was generated using the fixed inventory approach (specific charge = 382kg/m^3).
- ES controller performance can be improved during low solar heat input periods
- Cost curves exhibit large plateaus at low solar heat input

Winter day operation (21-Jun)



- Extra power generated earlier and later into the day using gain-scheduled ES.
- Gain-scheduled ES scheme delivers average of 6.3 MWh compared to only 6.0 MWh delivered by the non-scheduled scheme.
- The fixed inventory approach (specific charge = 300 kg/m^3) in contrast delivers 6.4 MWh. However turbine inlet temperature limit is violated.
- Some performance degradation is observed between 12:00 and 14:00 with low solar heat input.
- Large plateau in the cost functions for low heat inputs contributes to this.

Conclusions

- Gain-scheduled ES rule has demonstrated increased overall sCO2 CBC net power output during winter while maintaining improved performance over the fixed-inventory approach during summer.

- Tuning using the gain-scheduled ES rule has shown to increase and mostly maintain turbine inlet temperatures close to maximum permissible limits across seasons.

- ES controller performance needs to be improved especially during dips in solar heat input for both summer and winter cases and will be investigated in future work.

- ES scheme delivers performance improvement across both extreme operating conditions, reduction in initial system calibration, and improved plant autonomy. However full benefits need to be ascertained using experimental work.

QUESTIONS

Thanks for your attention!

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