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Modelling Small-scale CHP Plant Under Closed Loop Control

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Background – UK Climate Change Levy

- A commodities tax introduced in April 2001
- Applicable to electricity, gas and other fuels (but not oil since this is already subject to excise duty)
- Payable by most (there are a few exceptions) non-domestic energy consumers
- Examples of current Levy rates: 0.15 p/kWh (natural gas); 0.43 p/kWh (electricity)

Background – CHP and the Levy

- Purpose of the Levy: to help secure the UK's CO_2 emissions reduction target (5% (Kyoto-binding); 12.5% targeted by between 2008 – 2012)
- Fuels used in "good quality" CHP will be exempt from the Levy
- UK CHP capacity target of 10 GWe by 2010 (about 15% of current capacity)

CHP Quality Indexing

- Quality indexing scheme operated by the CHPQA group at the UK's DEFRA
- QI thresholds set for different types of CHP installation
- A QI is calculated as a weighting of power and heat from CHP that is actually utilised
- Example, for small scale installations < 1 MWe…

Threshold: $\eta \geq 0.2$ AND $QI \geq 115$

Where: $QI = 230\eta + 125\phi$

($\eta =$ efficiency; $\phi =$ heat "efficiency")

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Modelling Equations – Gas and Work

$$\eta_{\text{indicated}} = 1 - r_c^{1-\gamma}$$

$$V_{\text{cyl}} = V \cdot V_{\text{disp}}$$

$$P_3 = \text{fnc}\left(v_{\text{cyl}}, T_{\text{ai}}, M_{\text{f}}, \eta_{\text{indicated}}, FLHV, W_{\text{brake}}\right)$$

$$P_2 = \max\left(P_3, P_{\text{crit}}\right)$$

$$M_{\text{g}} = \text{fnc}\left(A_{\text{throat}}, v_{\text{ai}}, T_{\text{ai}}, P_2, P_{\text{ai}}\right)$$

$$A_{\text{throat}} = \text{fnc}\left(IV_{\text{lift}}, IV_{\text{diam}}\right)$$

$$W_{\text{brake}} = \text{fnc}\left(M_g, \eta_{\text{indicated}}, \eta_{\text{mech}}, FLHV\right)$$

$$M_{\text{f}} = \text{fnc}\left(FAR, M_{\text{g}}\right)$$

(M_{g} is solved recursively)

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Modelling Equations – Heat Transfer

$$T_{\text{adiabatic}} = fnc\left(h_{\text{gas-chamber}}, FLHV, FAR\right)$$

($T_{\text{adiabatic}}$ implicit in $h_{\text{gas-chamber}}$ hence solve recursively)

$$T_{\text{gas-outlet}} = \text{fnc}\left(T_{\text{adiabatic}}, W_{\text{brake}}\right)$$

$$Q_{\text{HX}} = \text{fnc}\left(T_{\text{gas}}, T_{\text{coolant}}, E_{\text{HX}}\right)$$

$$Q_{\text{loss}} = \text{fnc}\left(T_{\text{coolant}}, T_{\text{ambient}}, E_{\text{loss}}\right)$$

Modelling - Uncertainties

- Inlet throat area fitted to mnfrs. data
- General form…

$$IV_{\text{lift}} = C_1 + C_2 V_{\text{disp}} + \ldots$$

$$C_3 V_{\text{disp}}^2 + C_4 r_c + \ldots$$

$$C_5 r_c^2 + C_6 r_c V_{\text{disp}} + \ldots$$

$$C_7 \left(r_c V_{\text{disp}} \right)^2$$

- Mechanical efficiency balanced from mnfrs. data
- Generally lower for smaller engines
- Typically, for naturally aspirated SI engines up to 250 kW…

$$0.6 \leq \eta_{\text{mech}} \leq 0.82$$

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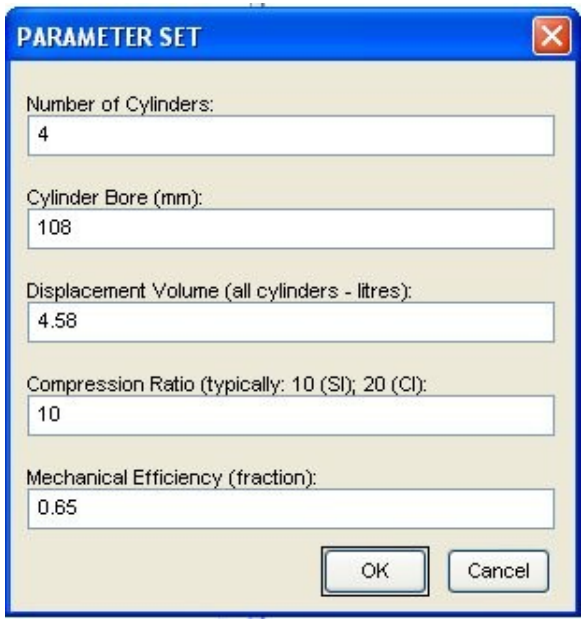
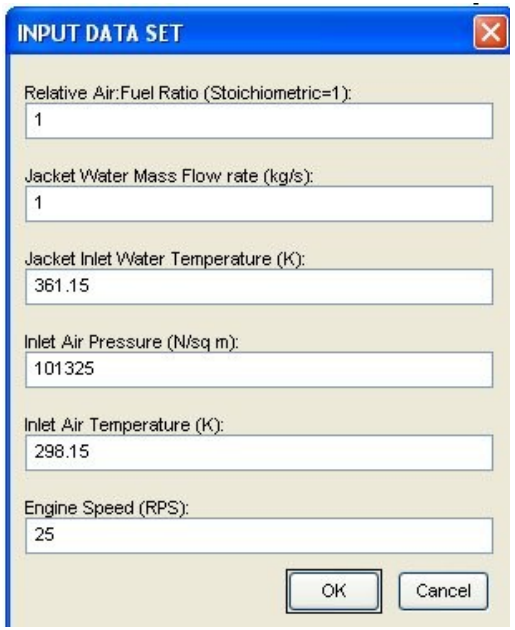
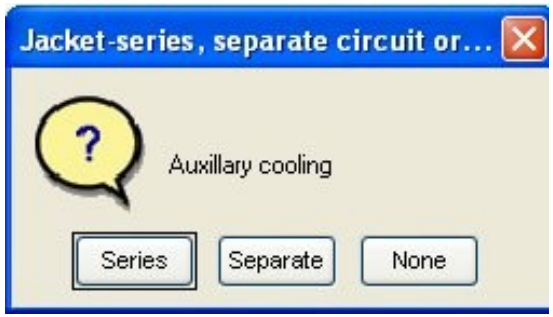
Matlab Function - ChpSim







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Manufacturers Reference Data

Manufacturer	Model	Brake Power (kW)	Fuel Use (kW)	Brake Efficiency	Displacement (Litre)	Compression Ratio
MAN Rollo	E0824E302	37	142	0.261	4.58	-
	E0826E302	70	210	0.333	6.873	-
	E2866E	95	271	0.351	11.97	-
	E2866E302	118	341	0.346	11.97	-
	E2876E302	130	376	0.346	12.82	-
	E2842E	177	490	0.361	21.94	-
	E2842E302	222	617	0.360	21.94	-
Perkins	3008SI	160	445	0.360	17.41	12
Waukesha	F11G	83.5	273	0.306	11.03	10
Caterpillar	G3304	61	185	0.330	6.994	10.5
	G3304	51	167	0.305	6.994	8
	G3306	91	266	0.342	10.49	10.5
	G3306	77	257	0.300	10.49	8
	G3406	138	407	0.339	14.6	10.3
	G3408	166	551	0.301	17.93	10
	G3412	244	758	0.322	26.9	10
Cummins	Onan LPG-2	5.8	20.8	0.279	0.928	9.5
	Onan LPG-3	9.7	30.7	0.316	1.391	9.5
	Onan LPG-4	13.2	43.6	0.303	1.855	9.5
	Ford LRG-4251	23.1	55.5	0.416	2.451	9.4
	Ford ESG-642	35.8	97.2	0.368	4.197	9.3
	Ford WSG-1068	70.9	195.3	0.363	6.77	9

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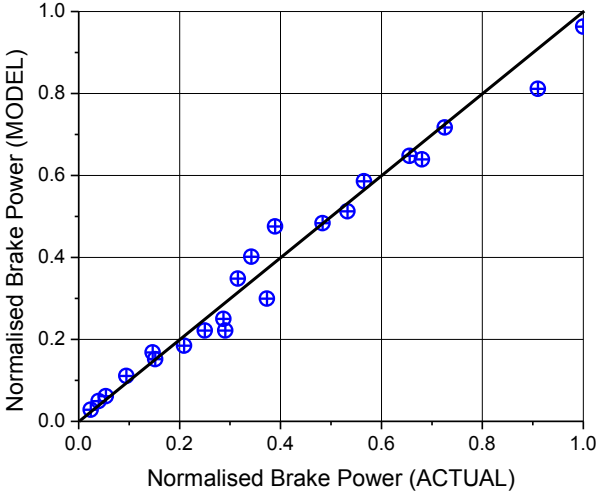
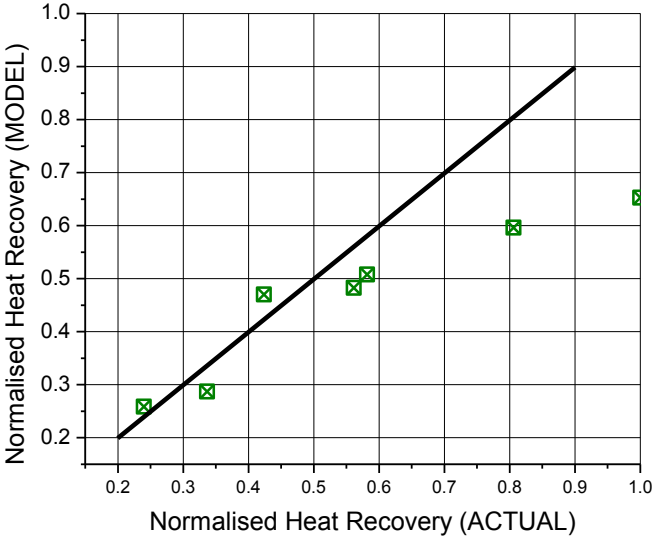
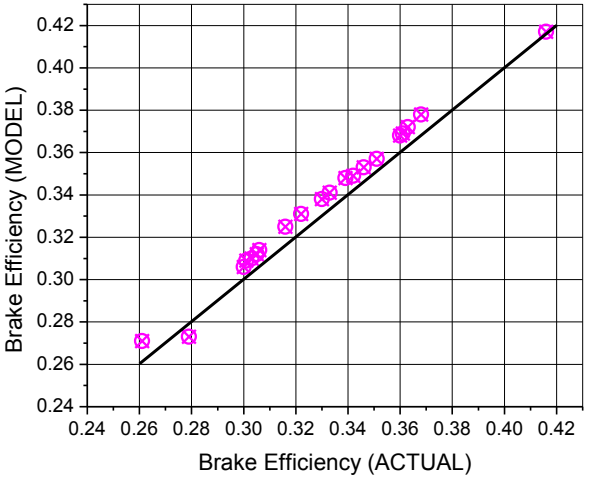
Correlation with Manufacturers Data







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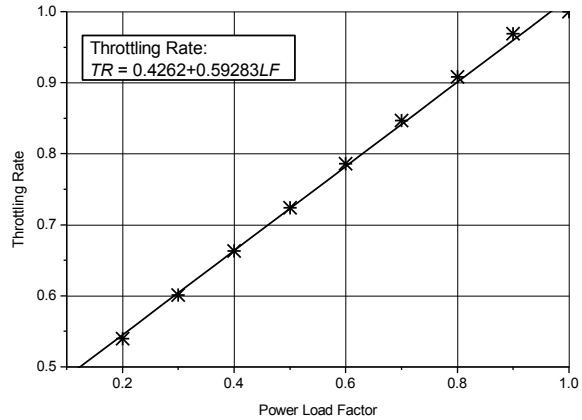
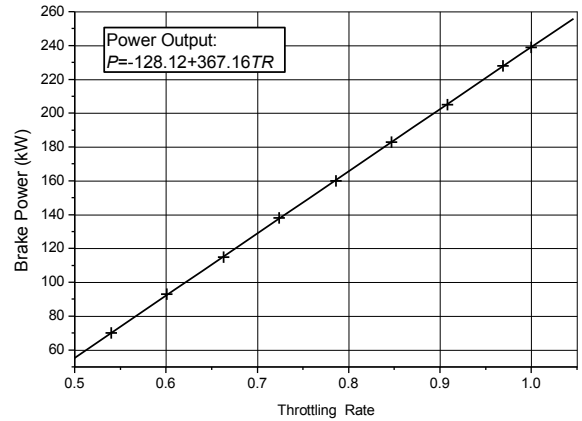
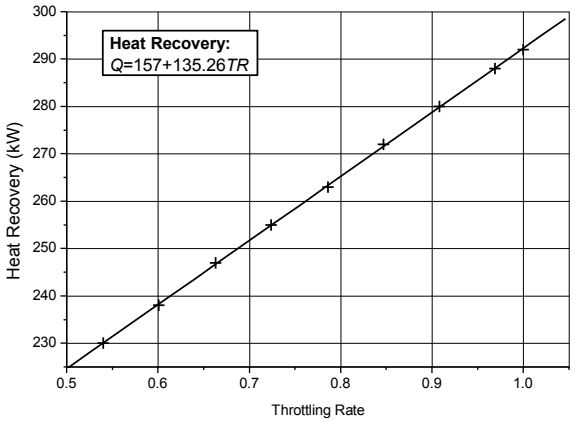
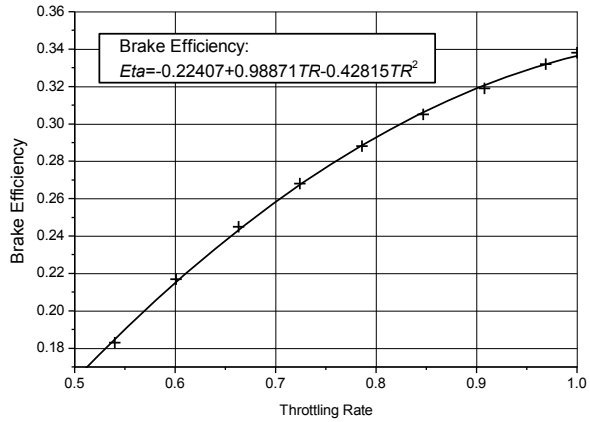
Parameter Extraction Using ChpSim









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Matlab Function ChpScheduler

- Reads hourly time series of heat & power demands
- Performs an hourly balance to give…
  - Module matching
  - Turndown
  - Energy balance
  - Machine utilisation
- Integrated annual energy balance includes *QI*

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Application Example: 700-household Village

- "Heat-rich" case
- Two scenarios…
  - existing case
  - 50% reduced heating to reflect a major insulation campaign

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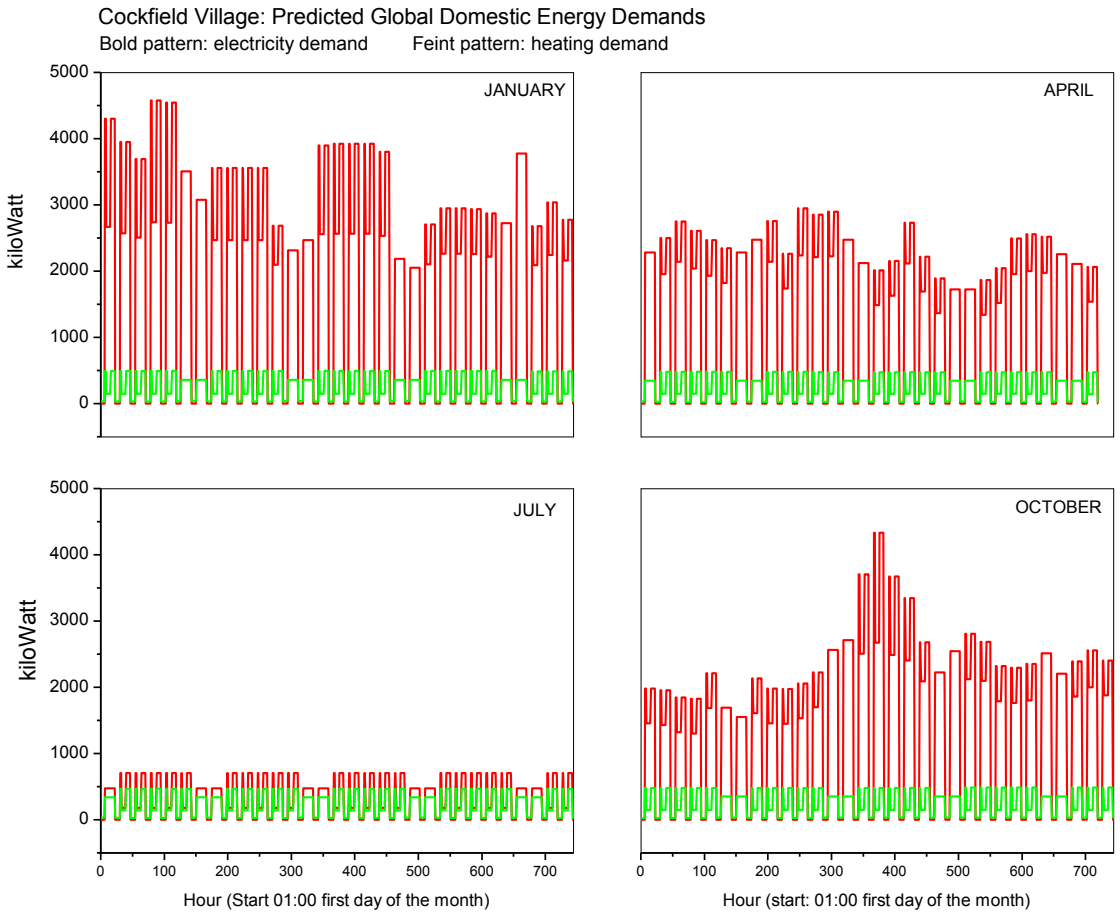
Simulated Village Energy Demands



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Application – Nominal Module Choice

- Naturally aspirated gas engine
- 8-cylinder in-line; 137 mm bore; 26.9 ltr.; r_c = 10; η_{mech} = 0.65; M_w = 5 kgs^{-1} (series cooled)
- Parameter extraction from *ChpSim*…

$$Q_{recovery} = 0.699 + 0.302\left(W / W_{rated}\right)$$

$$\eta = 0.0686 + 0.450\left(W / W_{rated}\right) - 0.182\left(W / W_{rated}\right)^2$$

- Simulated nominal capacities 239 kWe / 292 kWt

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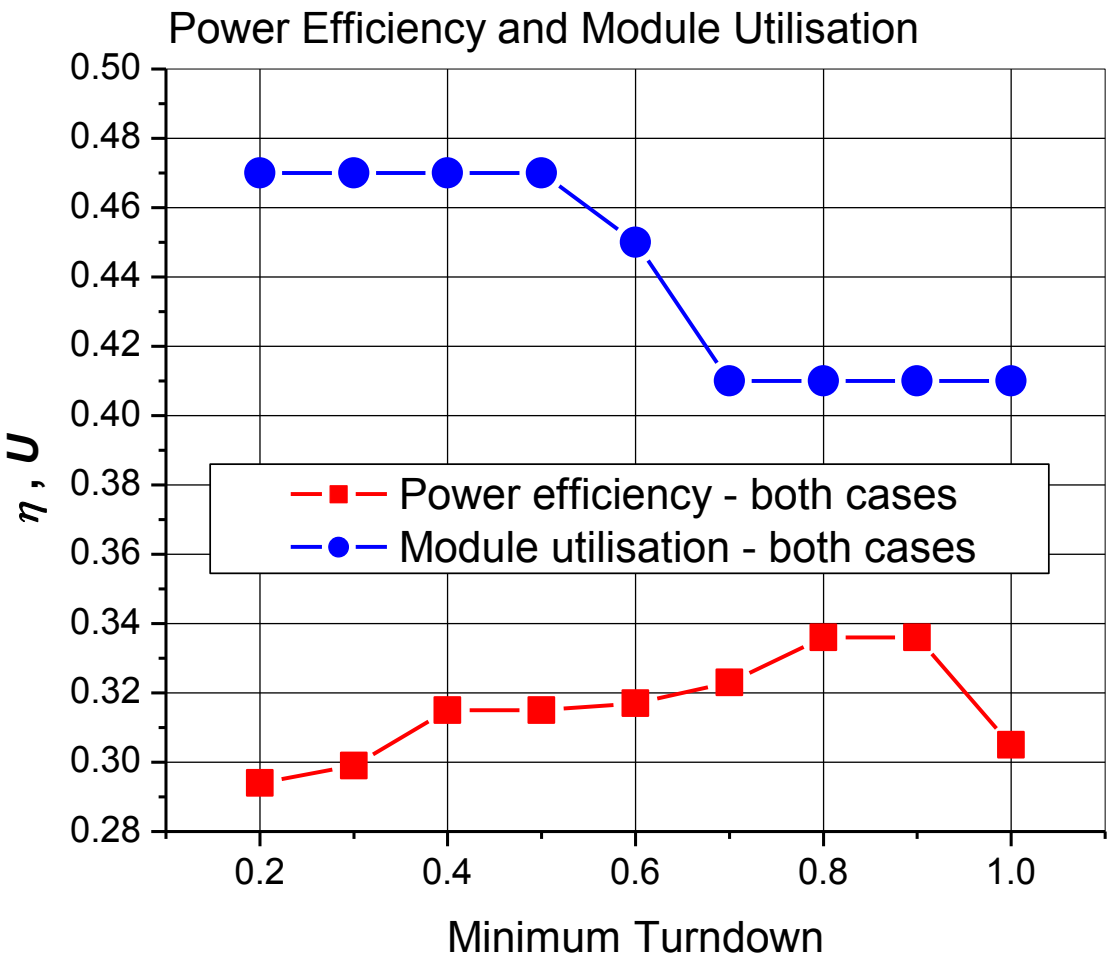
Results – Efficiency and Module Utilisation



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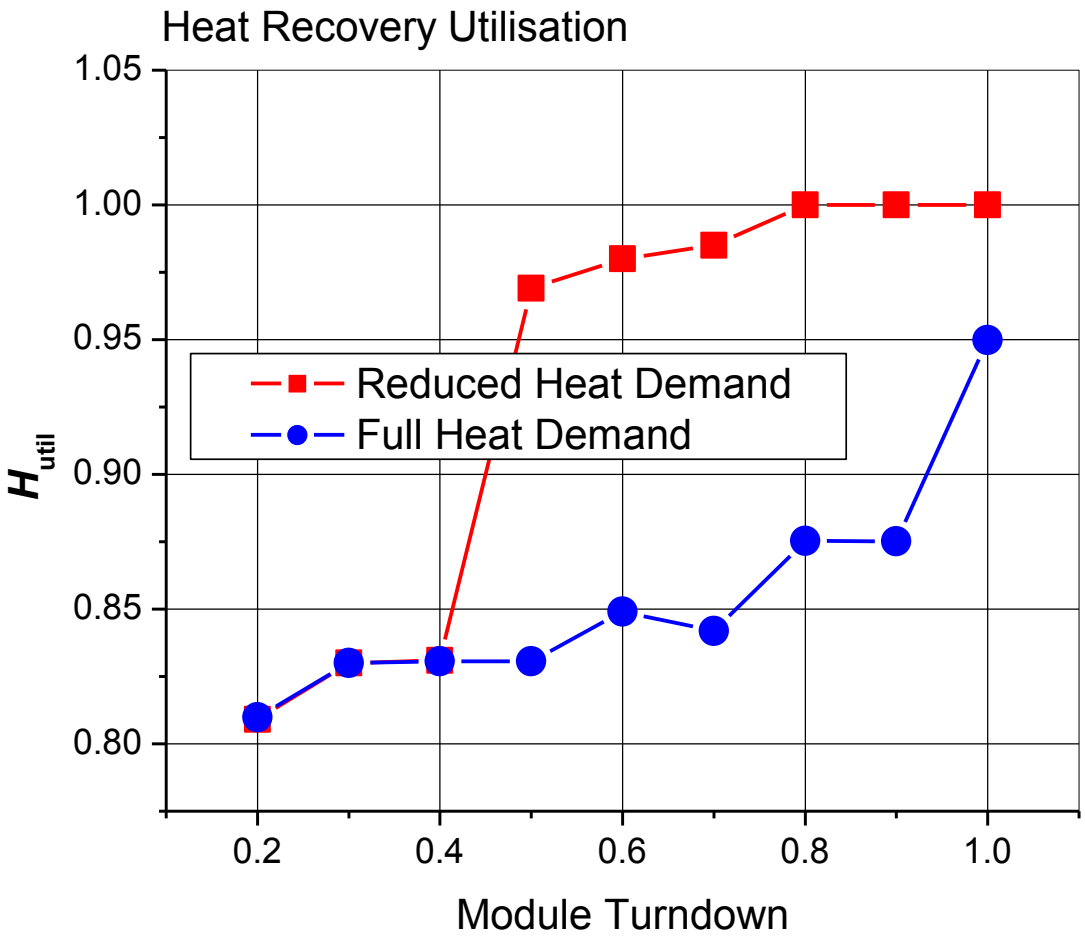
Results – Heat Recovery Utilisation



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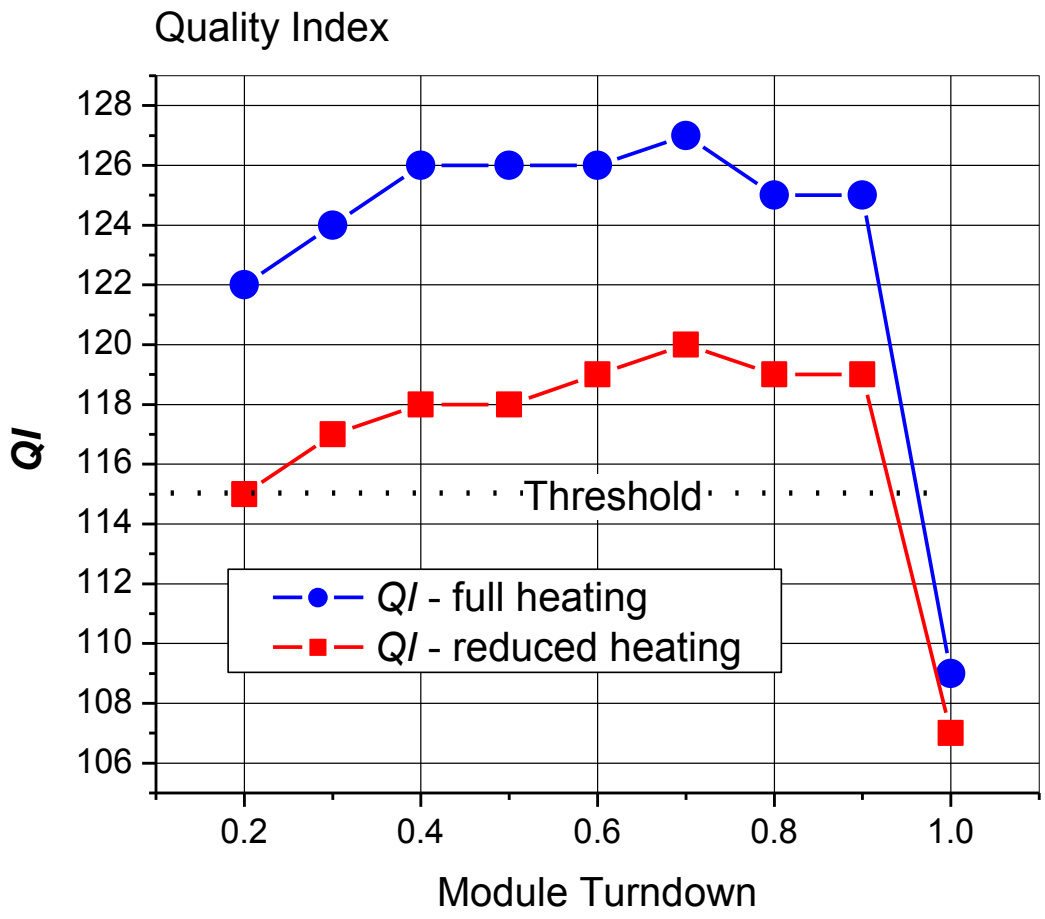
Results – Quality Index



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Conclusions and Further Work

- For maximised QI and η, a CHP module must be capable of turndown though this will reduce module utilisation
- The minimum turndown is shown here to maximise QI when set at 0.7 whereas for maximised η it should be 0.8 – 0.9
- For a "heat rich" application, heat recovery utilisation is maximised when no turndown is applied
- Further work is required to investigate short term module dynamics, smart control and thermal storage
- Further work is also needed to extend the range of model applicability to large turbo/super-charged engines and gas turbines

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