CSTB Workshop:
Matlab/Simulink Building and HVAC Simulation
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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)

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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")

Modelling Equations – Gas and Work

$$\eta_{\mathrm{indicated}} = 1 - r_{\mathrm{c}}^{1-\gamma}$$

$$\dot{V} \qquad \mathrm{V} \cdot V_{\mathrm{disp}}$$

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

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

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

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

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

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

(M_{g} is solved recursively)

Modelling Equations – Heat Transfer

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

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

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

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

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

Modelling - Uncertainties

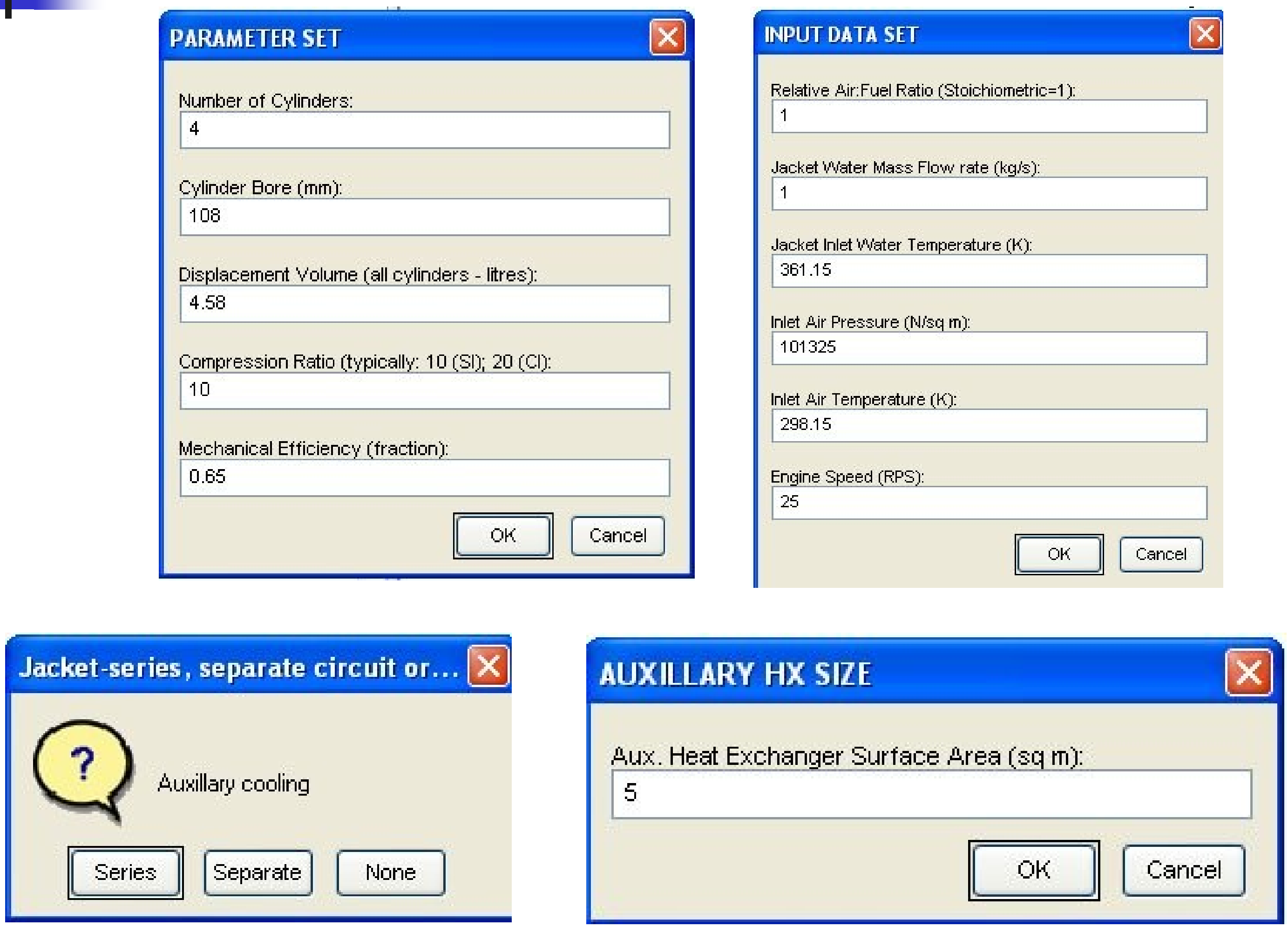
- Inlet throat area fitted to mnfrs. data
- General form…

$$IV_{\text{lift}} = C_1 + C_2 V_{\text{disp}} + \ldots$$
$$C_3 V_{\text{disp}}^2 + C_4 r_{\text{c}} + \ldots$$
$$C_5 r_{\text{c}}^2 + C_6 r_c V_{\text{disp}} + \ldots$$
$$C_7 \left(r_{\text{c}} V_{\text{disp}} \right)^2$$

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

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

Matlab Function - ChpSim



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	[illegible]

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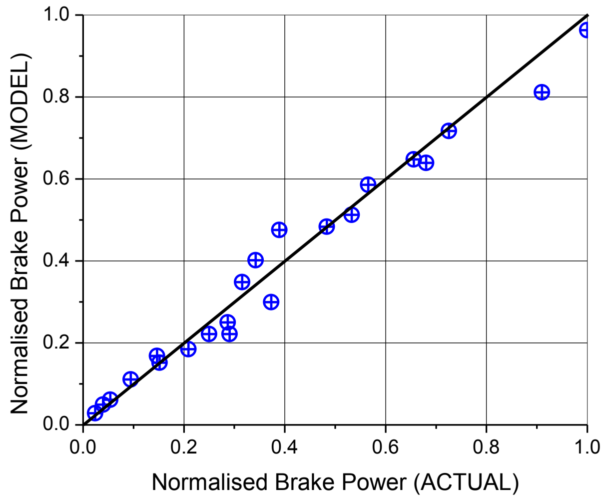
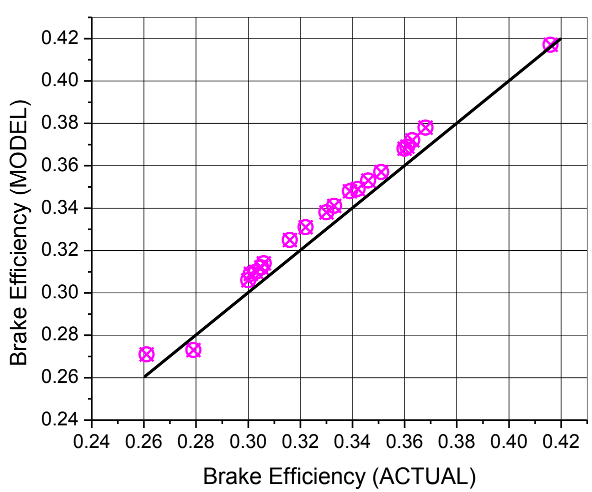
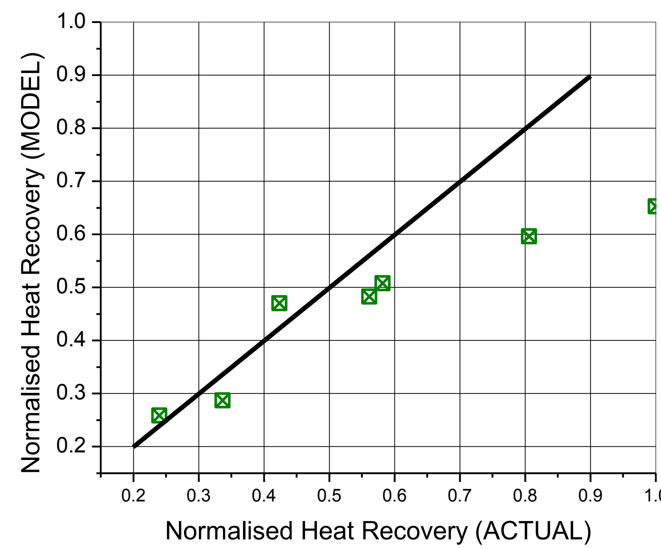
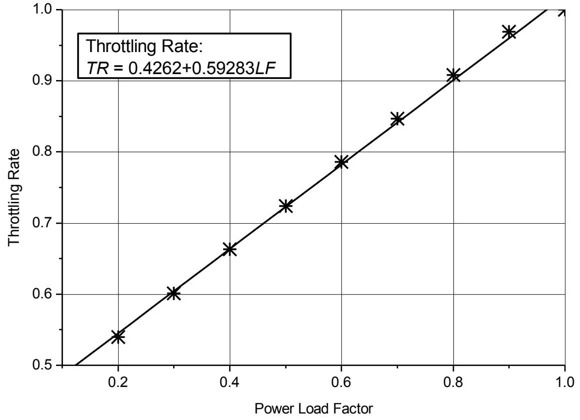
Correlation with Manufacturers Data

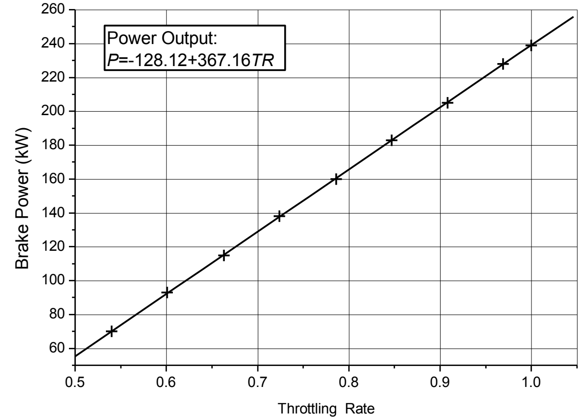


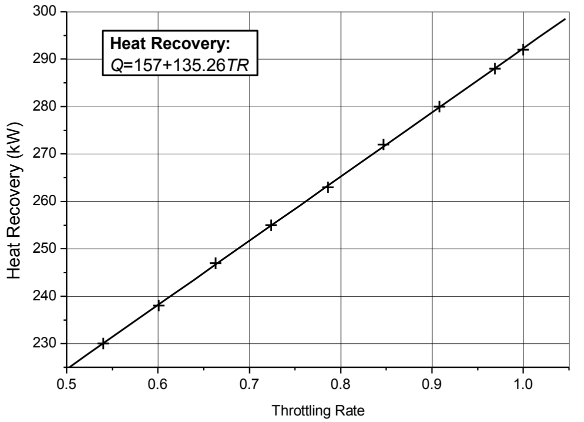


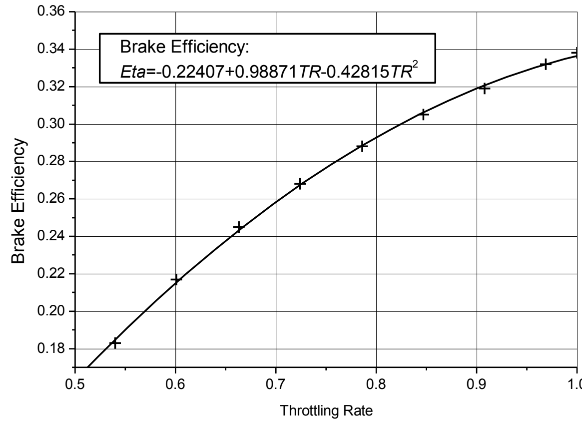


Parameter Extraction Using ChpSim



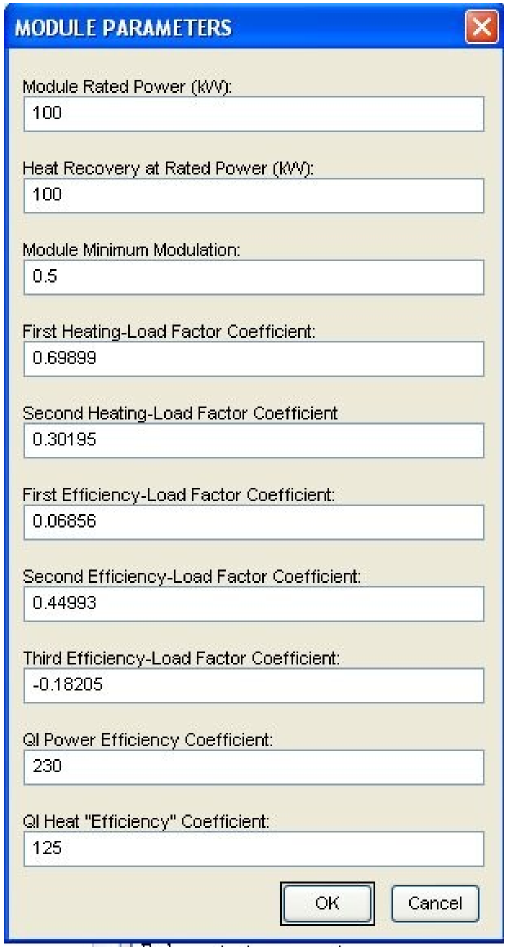






Matlab Function ChpScheduler

- 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*



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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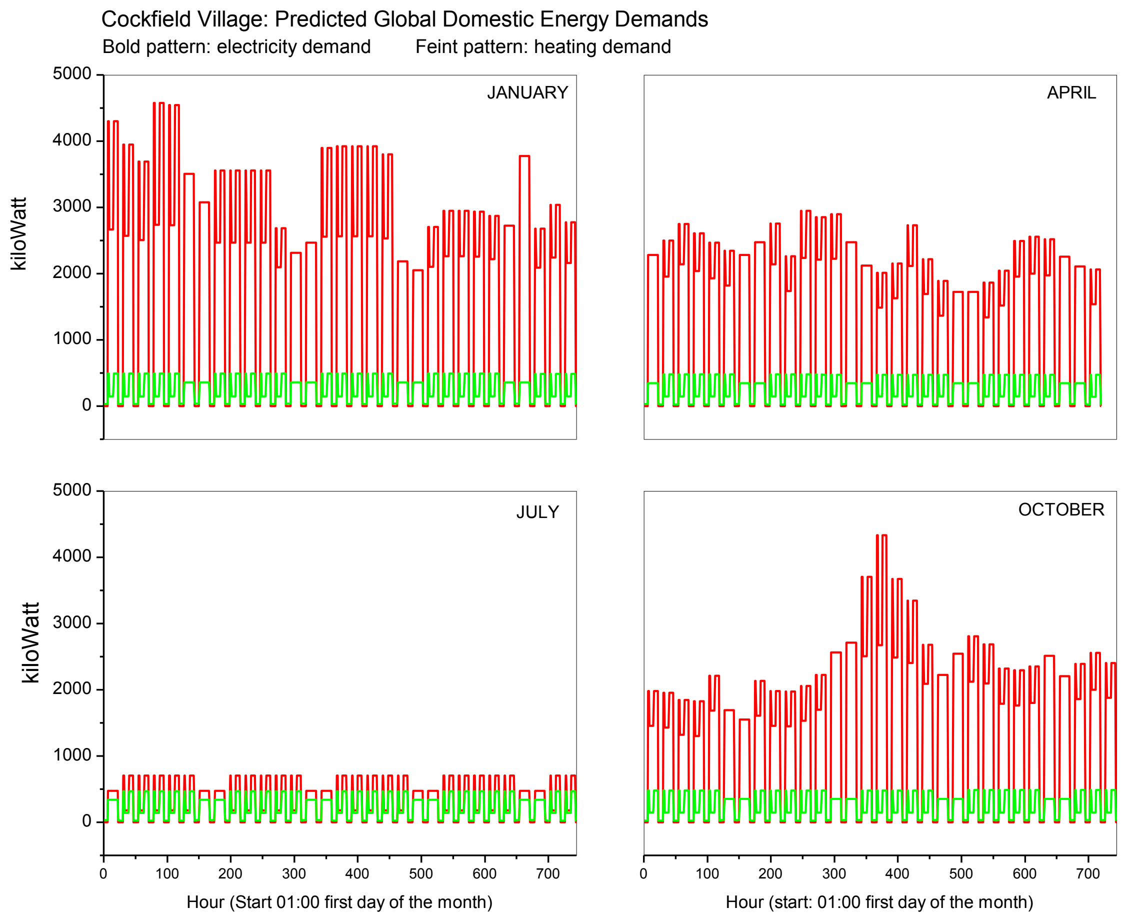
Simulated Village Energy Demands



Application – Nominal Module Choice

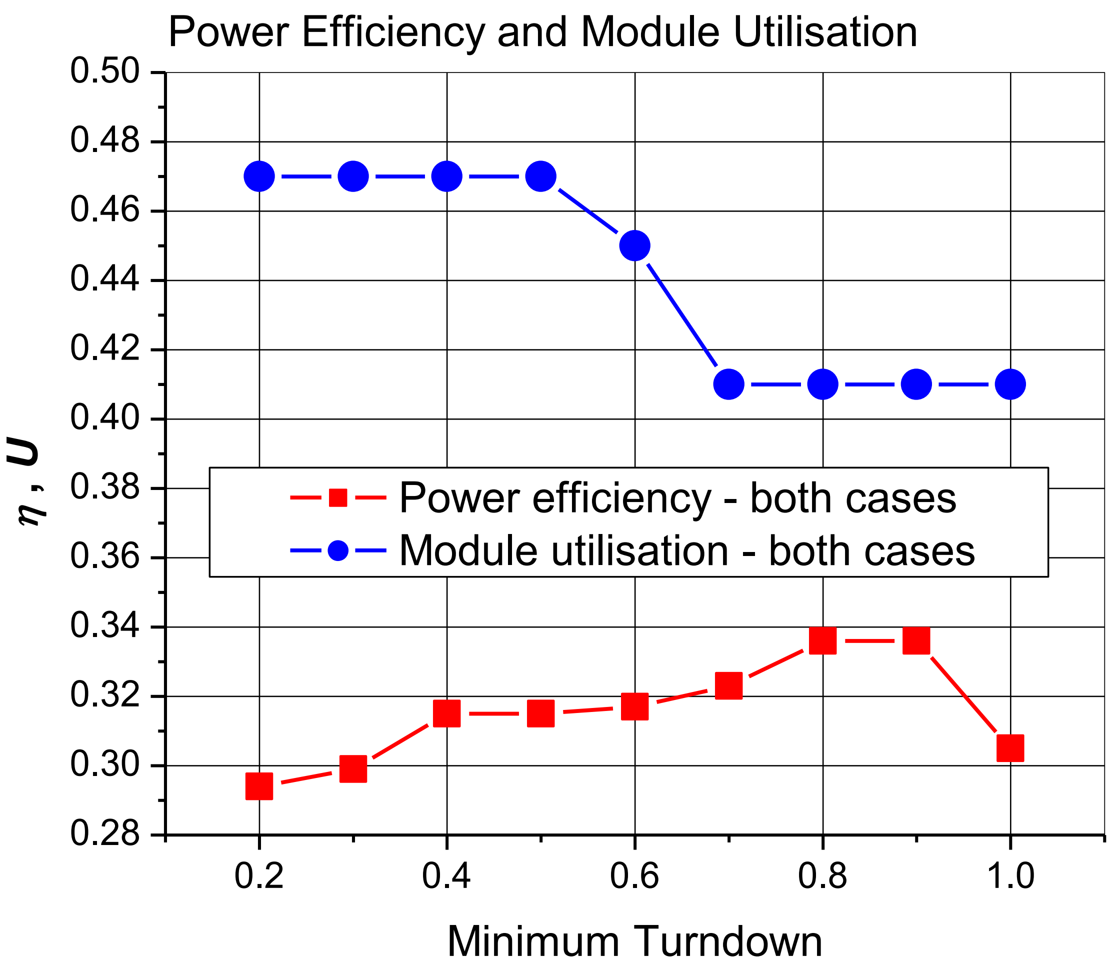
- Naturally aspirated gas engine
- 8-cylinder in-line; 137 mm bore; 26.9 ltr.; $r_c = 10$; $\eta_{mech} = 0.65$; $M_w = 5\ kgs^{-1}$ (series cooled)
- Parameter extraction from *ChpSim*…

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

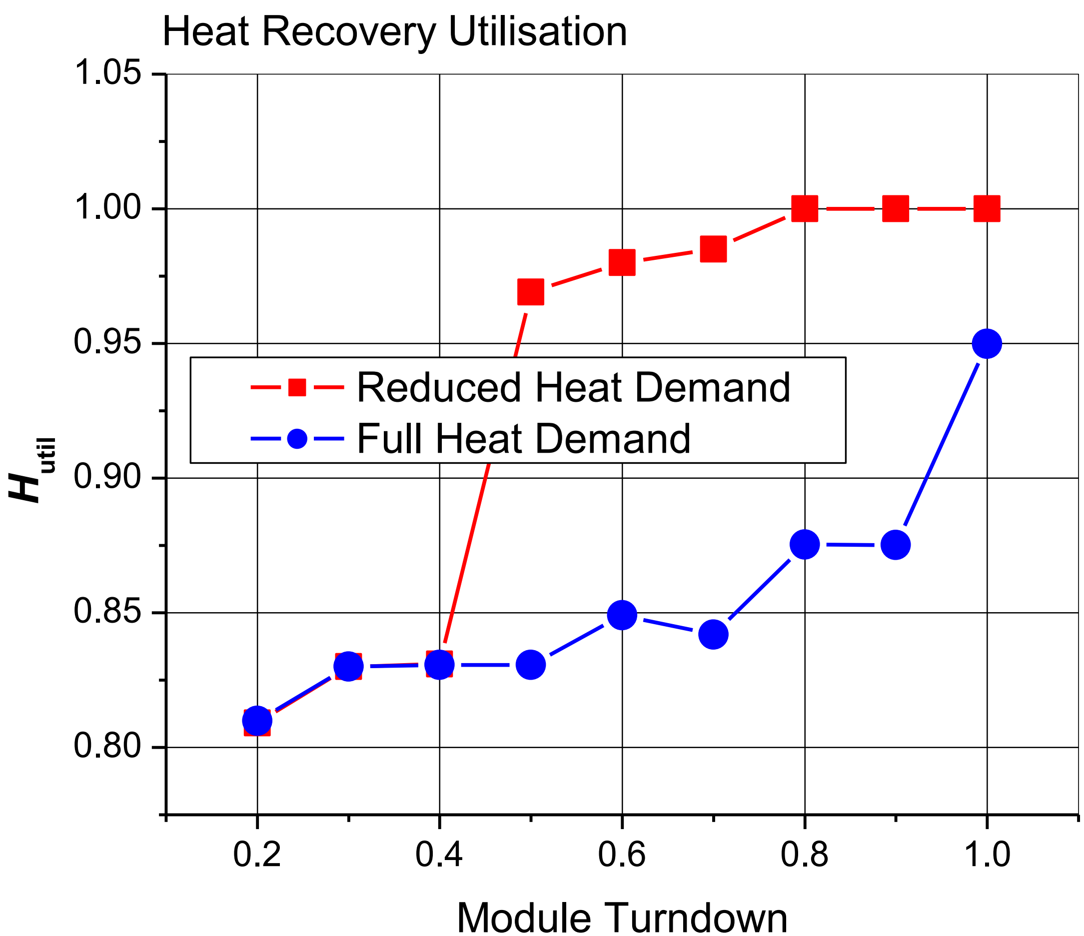
$$\eta = 0.0686 + 0.450\left(W / W_{rated}\right) - 0.182\left(W / W_{rated}\right)^2$$

- Simulated nominal capacities 239 kWe / 292 kWt

Results – Efficiency and Module Utilisation



Results – Heat Recovery Utilisation



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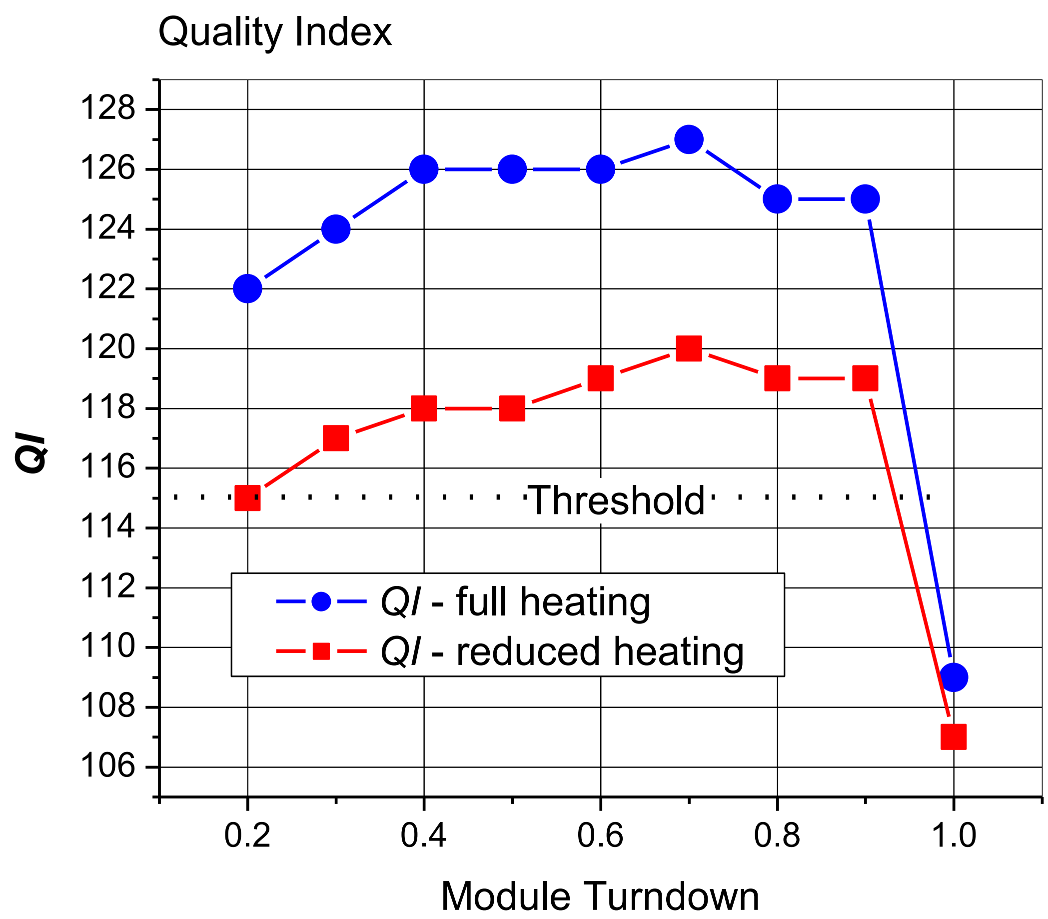
Results – Quality Index



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