

Northumbria Research Link

Citation: Underwood, Chris (2004) Modelling small-scale CHP plant under closed loop control. In: CSTB Workshop: Matlab/Simulink Building and HVAC Simulation, 14-15 October 2004, Paris.

URL:

This version was downloaded from Northumbria Research Link:
<http://nrl.northumbria.ac.uk/3387/>

Northumbria University has developed Northumbria Research Link (NRL) to enable users to access the University's research output. Copyright © and moral rights for items on NRL are retained by the individual author(s) and/or other copyright owners. Single copies of full items can be reproduced, displayed or performed, and given to third parties in any format or medium for personal research or study, educational, or not-for-profit purposes without prior permission or charge, provided the authors, title and full bibliographic details are given, as well as a hyperlink and/or URL to the original metadata page. The content must not be changed in any way. Full items must not be sold commercially in any format or medium without formal permission of the copyright holder. The full policy is available online: <http://nrl.northumbria.ac.uk/policies.html>

This document may differ from the final, published version of the research and has been made available online in accordance with publisher policies. To read and/or cite from the published version of the research, please visit the publisher's website (a subscription may be required.)

www.northumbria.ac.uk/nrl



**CSTB Workshop:
Matlab/Simulink Building and HVAC
Simulation
14-15 October 2004**



**Modelling Small-scale CHP Plant Under Closed
Loop Control**

C P Underwood

Northumbria University, United Kingdom



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 CO₂ 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: $QI = 230\eta + 125\phi$

(η = efficiency; ϕ = heat "efficiency")

Modelling Equations – Gas and Work

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

$$\dot{W}_{\text{indicated}} = \dot{V} \cdot V_{\text{disp}}$$

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

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

$$M_g = \text{fnc}(A_{\text{throat}}, v_{\text{ai}}, T_{\text{ai}}, P_2, P_{\text{ai}})$$

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

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

$$M_f = \text{fnc}(FAR, M_g)$$

(M_g is solved recursively)



Modelling Equations – Heat Transfer

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

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

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

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

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

Modelling - Uncertainties

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

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

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

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

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

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

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

Matlab Function - ChpSim

PARAMETER SET

Number of Cylinders:

Cylinder Bore (mm):

Displacement Volume (all cylinders - litres):

Compression Ratio (typically: 10 (SI), 20 (CI)):

Mechanical Efficiency (fraction):

INPUT DATA SET

Relative Air:Fuel Ratio (Stoichiometric=1):

Jacket Water Mass Flow rate (kg/s):

Jacket Inlet Water Temperature (K):

Inlet Air Pressure (N/sq m):

Inlet Air Temperature (K):

Engine Speed (RPS):

Jacket-series, separate circuit or...

 Auxiliary cooling

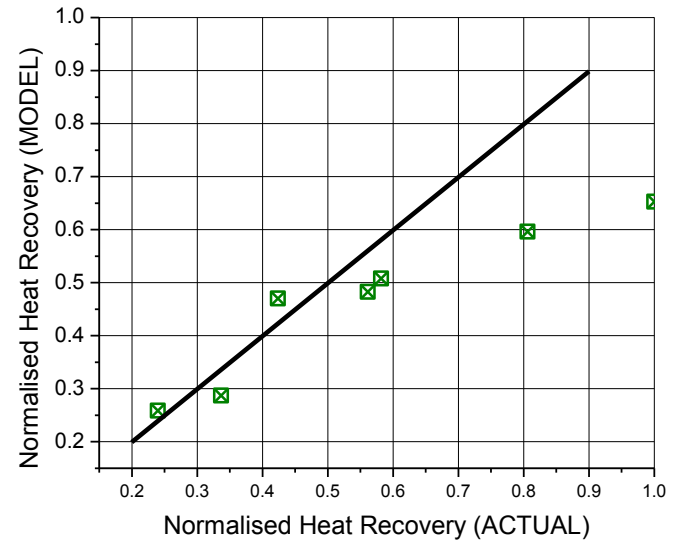
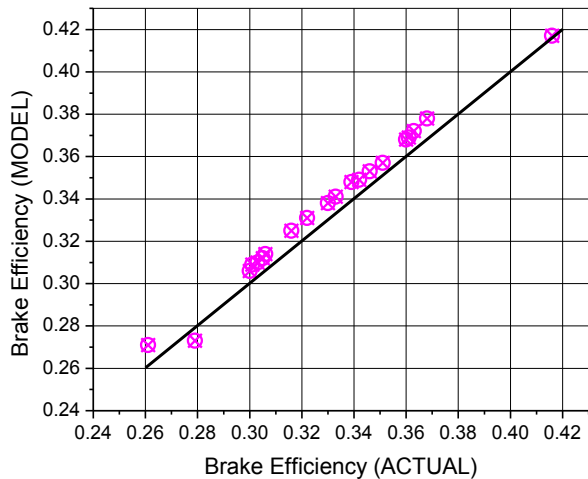
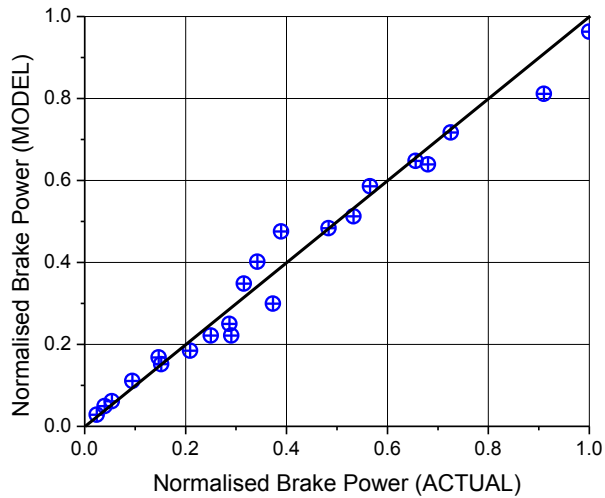
AUXILLARY HX SIZE

Aux. Heat Exchanger Surface Area (sq m):

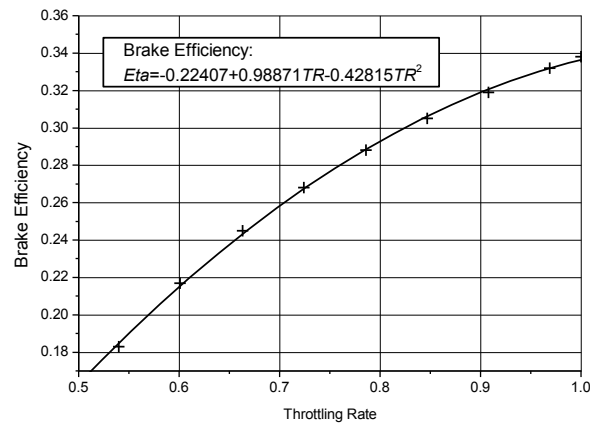
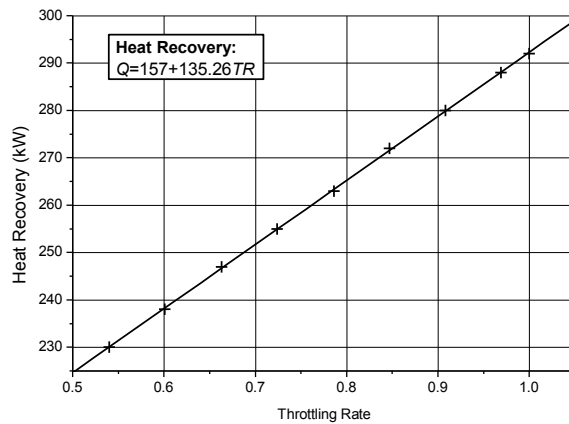
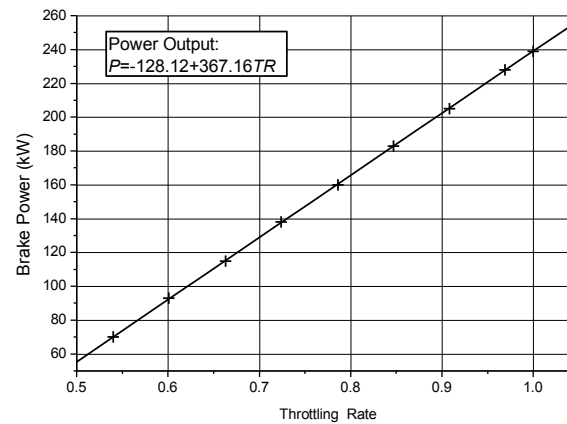
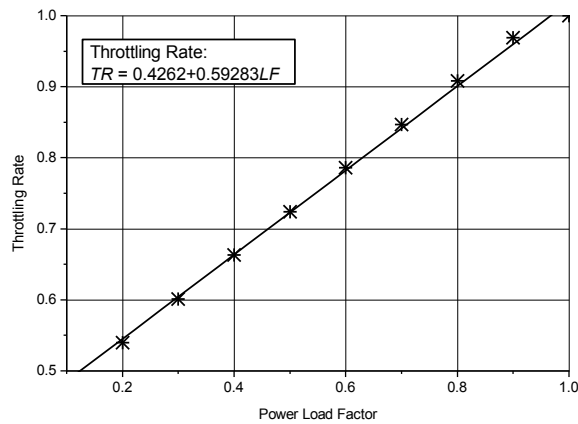
Manufacturers Reference Data

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	^

Correlation with Manufacturers Data

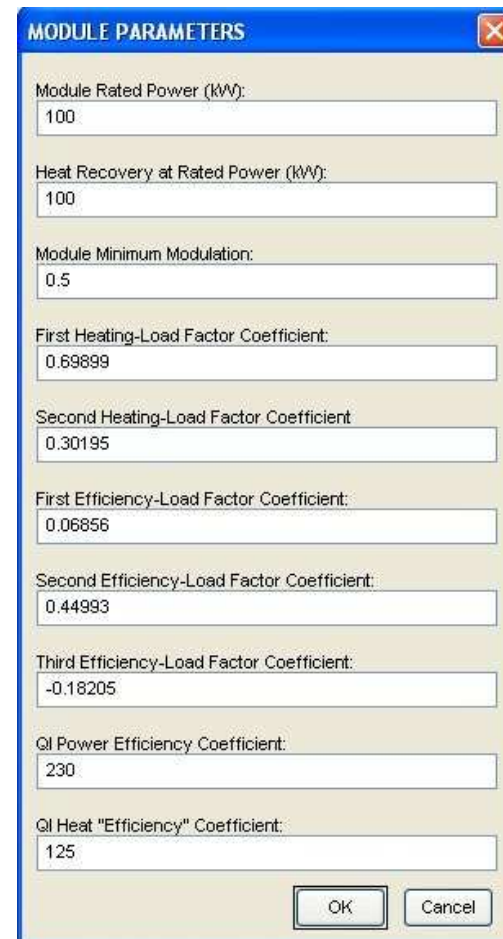


Parameter Extraction Using ChpSim



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



MODULE PARAMETERS

Module Rated Power (kW):
100

Heat Recovery at Rated Power (kW):
100

Module Minimum Modulation:
0.5

First Heating-Load Factor Coefficient:
0.69899

Second Heating-Load Factor Coefficient:
0.30195

First Efficiency-Load Factor Coefficient:
0.06856

Second Efficiency-Load Factor Coefficient:
0.44993

Third Efficiency-Load Factor Coefficient:
-0.18205

QI Power Efficiency Coefficient:
230

QI Heat "Efficiency" Coefficient:
125

OK Cancel

Application Example: 700-household Village



- “Heat-rich” case
- Two scenarios...
 - existing case
 - 50% reduced heating to reflect a major insulation campaign

Simulated Village Energy Demands

Cockfield Village: Predicted Global Domestic Energy Demands

Bold pattern: electricity demand Feint pattern: heating demand





Application – Nominal Module Choice

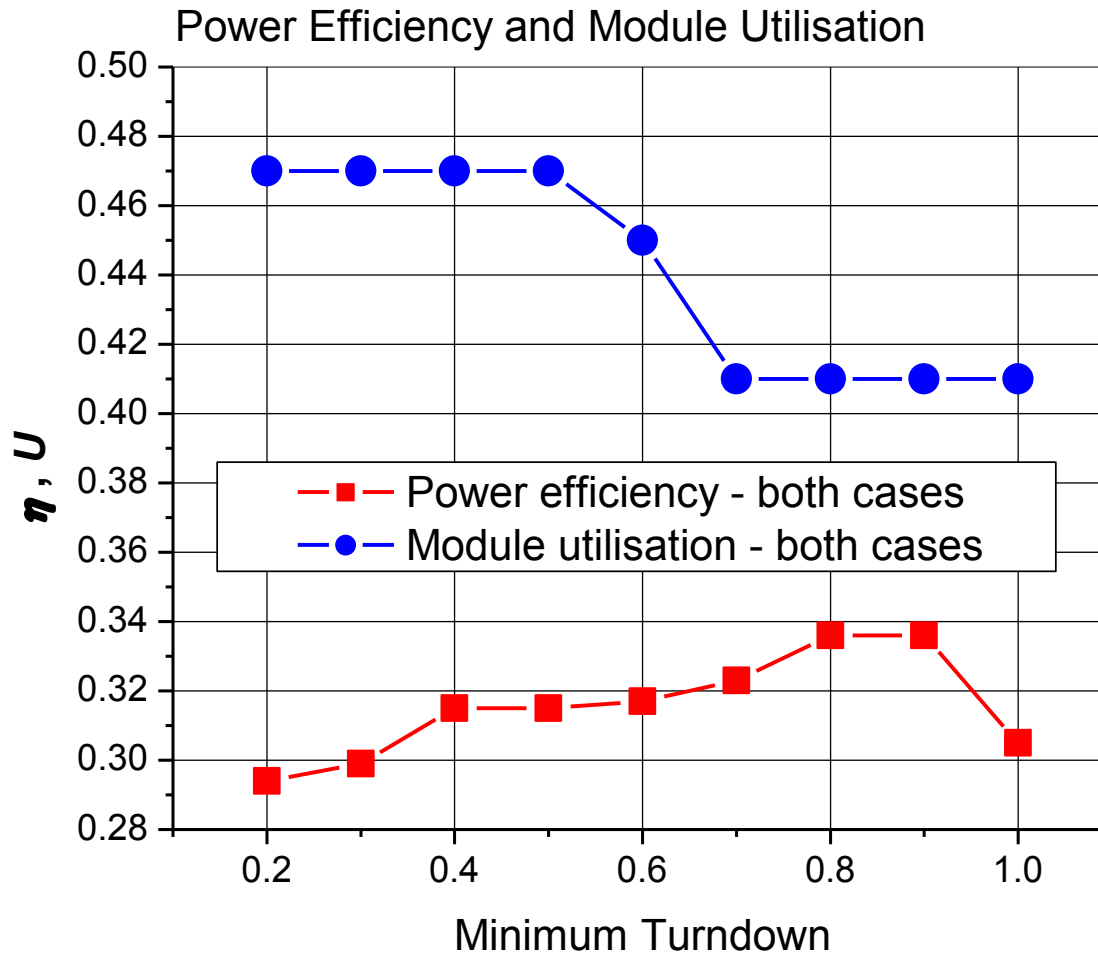
- Naturally aspirated gas engine
- 8-cylinder in-line; 137 mm bore; 26.9 ltr.; $r_c = 10$; $\eta_{\text{mech}} = 0.65$; $M_w = 5 \text{ kgs}^{-1}$ (series cooled)
- Parameter extraction from *ChpSim...*

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

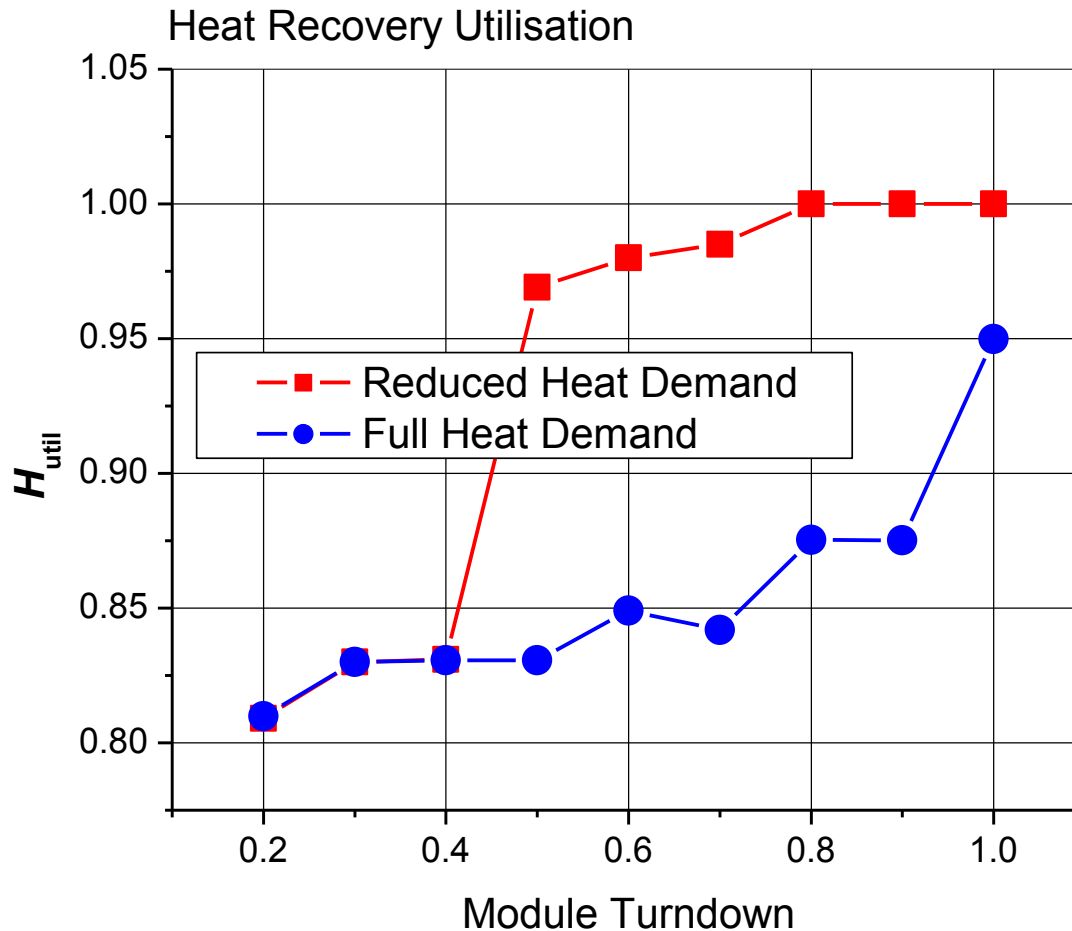
$$\eta = 0.0686 + 0.450 (W / W_{\text{rated}}) - 0.182 (W / W_{\text{rated}})^2$$

- Simulated nominal capacities 239 kWe / 292 kWt

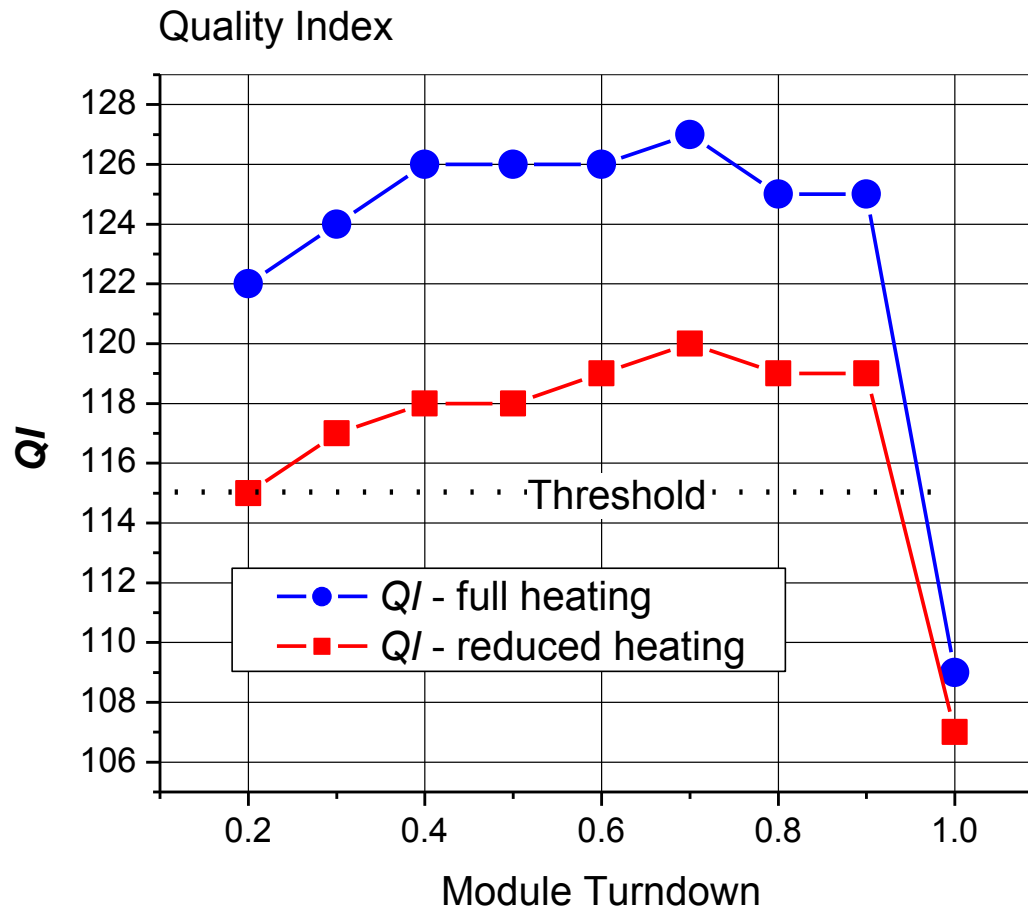
Results – Efficiency and Module Utilisation



Results – Heat Recovery Utilisation



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