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PROPOSED CHP UTILISATION MODEL FOR UK MARKET

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ABSTRACT: Industry recognizes that the shift in European Union (EU) subsidies towards green power and the need to cut carbon emissions drives the need for innovative and energy efficient saving solutions. One such approach which is now attracting the attention of industry is Combined Heat and Power (CHP). In this paper, the authors set out proposed CHP opportunities for a model specific to the UK market. We utilise linear programming to develop our model. The main advantage of the model is its easy-to-use functionalities which serve as a way potential CHP users may assess its viability. The development of the model forms part of research work sponsored by Red Engineering Design, a specialist mechanical and electrical systems and design firm based in Oxford, United Kingdom.

KEYWORDS: Combined Heat and Power, model, linear programming

INTRODUCTION

The main objective of this article is to report on a study conducted on behalf of Red Engineering, UK which aimed to evaluate the potential opportunities for Combined Heat and Power (CHP) in the United Kingdom (UK).

CHP is powered through the utilization of fossil fuels, primarily natural gas. As a technology, CHP is used to increase power generation efficiency by harnessing of waste heat energy. This waste heat energy comes from the generation of electricity. The waste is then used for either cooling or heating purposes, hence reducing the requirement for extra energy to be generated solely for either cooling or heating purposes. The main benefit of CHP is that it can process the conversion of nearly 90% of waste energy into energy which is to be used for cooling (or heating) and power generation purposes [1]. When connected to national energy grids, CHP offers the potential of selling back to utility companies any excess energy which is generated. This functionality creates the opportunity for additional generation of revenue to offset its initial capital cost which may be in some circles seen as high [2]. In effect, CHP delivers financial incentives when correctly implemented. The attributable benefits of CHP have driven its popularity among many member countries of the EU such as Denmark, Lithuania, Finland and the Netherlands which obtain over 30% of their energy from CHP [3, 4, 5, 6, 7]. Overall, based on a review of literature (see [1]), the main benefits CHP delivers includes a reduction in energy running and maintenance costs, a reduction in CO2 and green house emissions. CHP also delivers greater energy supply security [1].

METHODOLOGY

Scholarship [3,4,5,6,7,8] appears to suggest that CHP will deliver substantial benefits. Although this is the case, its widespread adoption does not appear to be straight forward. There are a number of challenges that CHP faces, includes its ability to match heating and electricity loads and difficulty projecting specific demands for heating. A review of the UK CHP market shows that there are a substantial number of companies that deal with CHP schemes (Table 1 and Table 2).

To help support these firms size CHP opportunities, feasibility and sizing models are employed. Compared to major CHP users such as the United States, we find a limited number of CHP sizing models that have been developed specific to the UK market. Example of some sizing models (both UK specific and non-specific), are shown in Table 3.

Table 1. Evaluation of Environmental and Energy Consultants and their use of CHP Technology (List Compiled from 2008 Consultancy Market Guide)

Company	Stance on CHP
AEA	AEA is one of the largest environmental consultancy firms in the UK. AEA is closely tied with the UK government in the development of CHP. AEA is the chief technical advisor to DEFRA on CHP and the leading provider of low carbon policy to the UK government.
AECOM	AECOM have undertaken many large scale power generation projects. Including a 7MW Biogas cogeneration project in New Zealand (AECOM, 2009). AECOM are also CHPA affiliated.
Atkins	Atkins Energy and Environmental sectors have assisted in consultancy elements of various CHP installations (Atkins, 2009) from small scale to larger district and community heating schemes.
Black & Veatch	Black & Veatch have undertaken multiple CHP feasibility studies, including many in their biomass services sector.
Entec UK	Entec specialise in renewable fuel CHP including biofuels and energy from waste schemes.
Enviros Consulting	Enviros Consulting specialises in the project management and dealing with legislation for renewable energy from waste schemes within the CHP industry.
ESD (Camco)	Camco have developed varying CHP projects including district heating, and a waste heat to power plant in China.
Mott MacDonald	Mott Macdonald have designed and developed multiple CHP projects from large power stations in Poland and China, to a biomass plant in Ireland.
Mouchel Group	Mouchel offer a project management service for power generation schemes including CHP.
MWH	MWH has developed a partnership with a renewable energy and waste management company operating throughout Europe. This has led to various projects including a biomass power station.
RPS Group	RPS Group as the largest environmental consultancy firm in the UK (ENDS, 2008) has a vast array of experience and projects within CHP. With expertise in micro-generation, district energy, biomass, energy from waste and industrial CHP schemes.
RSK Group	RSK Group provides an environmental impact assessment for CHP installations.
SLR Consulting	SLR Consulting have so far undertaken case studies on the feasibility of CHP, and have been stated that they intend to increase their development in this sector.
WSP Environmental & Energy	WSP's environmental sector provides consultancy on CHP including Biomass and Energy from Waste.

Table 2. Evaluation of Environmental and Energy Consultants and their use of CHP Technology (List Compiled from CHPA Membership List)

Company	Stance on CHP
Arup	Arup offer services including feasibility studies, engineering design, management of schemes, as well as strategic advice on CHPA accreditation and energy legislation.
AC Environmental Consulting	AC Environmental Consulting provides CHP support services including feasibility studies, CHPQA registration and maintenance.
Fontenergy	Fontenergy specialise in low carbon energy generation solutions. This is from the initial design to the management of the system. Their low carbon solutions include the use of CHP. In addition to this they have a joint venture with Lend Lease to install Biomass CHP for large developments or small industrial users within the UK.
BRE	BRE have extensive experience with CHP in the fields of energy efficiency, district heating and renewable. They provide consultancy including feasibility studies and option appraisals.
Delta Energy & Environment	Delta Energy & Environment specialise in decentralised energy technologies and provide financial analysis.
Future Green Solutions	Future Green Solutions are a sustainability research based company designed to aid in the education of new sustainable technologies.
Land and Marine	Land and Marine Project Engineering specialising in the design, project management and construction of industrial and commercial CHP.
Parsons Brinckerhoff	Parsons Brinckerhoff's energy services division has extensive experience into all aspects of CHP from micro generation to district energy. They offer advice on all elements of the CHP feasibility and implementation process.
Pöyry	Although Pöyry is a global consulting and engineering firm it has two main UK subsidiaries as Pöyry Energy Ltd and Pöyry Energy Consulting. Pöyry Energy Ltd has had involvement in over 5000MWe of CHP installation from small ICE's to large gas turbines as well as the use of biomass and wastes. Their consulting counterpart covers energy markets with again a focus on CHP.
PX Limited	Provide operations and maintenance support for power stations, including CHP.
Ramboll	The Danish roots of Ramboll have attributed to its strong CHP focus, with Denmark being the largest CHP user in Europe. Ramboll specialise in the field of district energy.
Thames Energy Ltd	Thames Energy offer a range of energy management services including feasibility studies into small scale CHP.
Urbed	Urban regeneration and development consultants. Offer feasibility studies and design for district energy schemes.

Table 3. UK Specific CHP feasibility and sizing models

Model	Use	Comments
Stilwell Calculator	Financial & Environmental Benefit Calculator	Simplest CHP benefit calculator available in UK. Its use is also free. However specifically designed for use with natural gas fired CHP plants.
CHP Sizer 2.0	Sizing, Financial & Environmental Benefit Calculator	Developed in conjunction with UK government. Limited as not functionality for CHP Quality Index (QI). Also complex in use as requires large data.
CHP Focus Evaluation Spreadsheet CHP-SIMP2-1	Basic Sizing and Financial Benefit Calculator	Developed in conjunction with UK government on simple excel spreadsheet. Limited as does not provide any indication for the environmental benefit or on the sensitivity of the results to energy prices.
ICHPA Evaluation Tool	Basic Sizing and Financial Benefit Calculator	Produced by the CHP associate in the Republic of Ireland. Major limitation is that this models does not account for sensitivity or environmental benefit. Also conducts calculations only in Euros which makes it applicable within the EU, but not within the UK where Euros are still not used.
EPA CHP Emissions Calculator	Environmental Benefit Calculator	Although widely used in the United States, it has not been used in the UK because majority if not all of its prime movers are specific to the United States market.

Our exploration of the various sizing and feasibility models shows that there is a clear potential for a model that adequately caters for various criteria for CHP. These criteria may includes (1) clarity with cost and maintenance break down and savings , (2) clarification with a realistic period of financial payback, clarity with CO2 savings, (3) incorporation of UK legislative framework, (4) sensitivity with UK tax and energy price and (5) a simple and user-friendly interface. Recognising these challenges, our objective has been to develop a model for CHP optimisation based primer mover recognition.

❖ PRELIMINARY RESULTS

We commenced the study by exploring the possibility of identifying specific prime movers that will be valuable for the development of a UK specific sizing and feasibility model (see Table 4.). We identified four parameters (Matching Heat and Electricity Demand, Maintenance Costs, Combined Heat and Power Quality Assurance (CHPQA) Requirements, Effect of size, CO2 Savings and Annual Savings on CHP installation capital cost), as being critical to the development of the feasibility mode.

Table 4. Summary of CHP prime movers

Prime Mover	Fuel	Power Output	Electrical Effic.	Total Effic.	Heat to Power Ratio	Thermal Output	Run Time	CHP Uses	Manufacturer
Spark Ignition Internal Combustion Engine	Natural Gas Biogas Recovered Gas	<4MWe	35%	80%	1:1 – 1:7:1	Max 11^c High Grade or Low Grade	85 – 92%	Small Scale	Alfagy Aircogen SAV Modules
Compression Ignition Internal Combustion Engine	Diesel Gas oil Heavy Oil	1- 1.5 MWe	35- 45%	72%	1:1 – 1.5:1, up to 2.5:1 with supplementary firing	Max 8^c High Grade or Low Grade		Small to Large Scale	Alfagy Aircogen SAV Modules Edina Yanmar
Stirling Engine (External Combustion Engine)	Gas Diesel Biomass Coal Waste	200 KWe	40%	95%	4:1- 8:1	High Grade 750^c	95%	Micro	Baxi Enegetix Whispergen
Gas Turbine	Natural Gas Biomas Recovered Gases Gas-Oil	50-250kWe 1MWe 200 MWe	20-35%	72%	1.6:1, up to 5:1 with supplementary firing	400^c – 500 High Grade		Micro, Small to large Scale	-
Steam Turbine	Coal Biofuel Gas Waste	>0.05 MWe	10%	84%	3:1- 10:1	Medium	99%	Large Scale	-
Combined Cycle	Natural Gas Biogas Recovered Gases Gas-Oil	>10 MWe	42%	74%	0.7:1 upwards				-
Fuel City	Polymer Electrolyte Fuel Cell	100W-50MW	Up to 65%	85%	0.5:1-2:1	120^c	-	Micro, Small & Large Scale	CFCL Ceres Power

Matching Heat and Electricity Demand: Sizing above base load provides a trade off from total energy efficiency and financial gain. There are two main conditions where sizing above base load can prove advantageous. Firstly the choice of prime mover and its heat to power ratio; this can be sized above the required electricity demand enabling additional electricity to be generated. This electricity can then be sold back to the grid to realise an additional income to offset the running costs of the facility. Common applications with consistent heating demands that are suitable for CHP consideration are shown in Table 5.

Table 5. Common CHP applications and heating demands (Adapted from Energy Institute. 2008)

Application	Reasoning
Swimming Pools and Leisure Centres	Consistent energy demand, potential for air conditioning
Hospitals	Consistent demand for ambient energy demand for hot water provision.
Hotels	Consistent demand for energy demand for hot water provision.
Residential Homes	Consistent demand for energy demand. Occupancy is continuous.
District Heating	Multiple organisations with varied energy requirements.
Community and Campus Based Heating: Universities, Schools, MOD Sites, Prisons	Substantially diverse and large energy demands, but may be seasonal due to less usage during vacation periods.
Industry	Substantial energy requirements to support industrial processes
Museums	Consistent and alternating energy demand, potential for air conditioning independent of hours of opening
Retail Stores and Shopping Centres	Consistent and alternating energy demand, potential for air conditioning independent of hours of opening
IT Facilities and Data Centres	Substantially diverse and large energy demands, high requirement for cooling
Waste Water Treatment Plants	Substantial energy requirements to support industrial processes

Maintenance Costs: To ensure efficiencies and maximise CO_2 savings, there is a requirement for high CHP maintenance. Such maintenance will ensure that cost savings are maximised and plat performance levels optimised. Maintenance costs are usually accounted for on two approaches which both includes standard and fixed yearly payments, or a 'pay-as-use' option. Table 6, shows estimated maintenance cost as calculated by the UK government.

Table 6. Maintenance Costs for CHP Prime Movers per kWh (DEFRA. 2008)

	4500 Operating hours / year	8000 Operating hours / year
Gas turbines	0.4 p/kWh	0.35 p/kWh
SIICE	0.7 p/kWh	0.6 p/kWh
CIICE	0.8 p/kWh	0.7 p/kWh
Steam turbines	Less than 0.05 p/kWh	Less than 0.05 p/kWh

CHPQA Requirements: CHPQA (Combined Heat and Power Quality Assurance), is a UK government initiative that is set to provide a practical means of determining 'good quality' CHP. According to Nock [1], Assessment for CHPQA includes calculations of Power Efficiency (*PE*) and Quality Index (*QI*). PE which articulates the efficiency of the prime mover generation is usually calculated in the form of Net Calorific Value (*NCV*) which is mathematically represented (PE_{Annual}), as

$$PE \geq 20\%\ GQCHP \qquad (1)$$

where

$$PE_{Annual} = \frac{\text{Electrical Output (MWe) x Operating Hours (h) x Availability (\%) x 0.01}}{\text{Fuel Input (NCV MWh) x Operating Hours (h) x Availability (\%) x 0.01}} \qquad (2)$$

On the other hand, the Quality Index (*QI*), which is obtained from power (η_{Power}) and heat efficiency (η_{Heat}) is represented as:

$$\eta_{Power} = \frac{\text{Total Power Output (MWhe)}}{\text{Total Fuel Input (MWh)}} \qquad (3)$$

and

$$H_{Heat} = \frac{\text{Qualifying Heat Output (MWhth)}}{\text{Total Fuel Input (MWh)}} \qquad (4)$$

At this stage, Qualifying Heat Output (MWhth) is seen as

$$\text{Qualifying Heat Output} = \text{Total Heat Output (MWhth)} - \text{Rejected Heat (MWhth)} \qquad (5)$$

and QI calculation is mathematically shown as

$$QI = (X \text{ x } \eta_{Power}) + (Y \text{ x } \eta_{Heat}) \qquad (6)$$

where *X* and *Y* weightings depend on CHP scheme size and fuel sources (Table 7).

Table 7. X & Y Weightings for CHPQA Quality Index Calculation (source UK government)

Fuel Type and Size	X Weighting	Y Weighting
Gas		
< 1MWe	249	115
1-10MWe	195	115
10-25MWe	191	115
25-50MWe	186	115
50-100MWe	179	115
100-200MWe	176	115
200-500MWe	173	115
>500MWe	172	115
Oil		
< 1MWe	249	115
1-25MWe	191	115
>25MWe	176	115
Coal		
< 1MWe	249	115
1-25MWe	191	115
>25MWe	176	115
Fuel Cell		
	180	120
By-Product Gas		
< 1MWe	294	120
1-25MWe	221	120
>25MWe	193	120

Fuel Type and Size	X Weighting	Y Weighting
Biogas		
< 1MWe	285	120
1-25MWe	251	120
>25MWe	193	120
Waste Gas		
< 1MWe	329	120
1-25MWe	299	120
>25MWe	193	120
Liquid Biofuel		
< 1MWe	275	120
1-25MWe	191	120
>25MWe	176	120
Liquid Waste		
< 1MWe	275	120
1-25MWe	260	120
>25MWe	176	120
Biomass or Soild Waste		
< 1MWe	370	120
1-25MWe	370	120
>25MWe	220	120
Wood Fuel		
< 1MWe	329	120
1-25MWe	315	120
>25MWe	220	120

Regression Equations: A total of 7 regression equations show the observation of the impact of *Size*, *CO_2 Savings* and *Annual Savings* on CHP installation capital cost [2],. The equations were developed from 'Estimate Equation' function of *EViews*, the econometrics package.

$$\text{Capital Cost} = 1342 \text{ x Size} \qquad (7)$$

$$\text{Capital Cost} = (1276.558 \text{ x Size}) + 221718 \qquad (8)$$

$$\text{Capital Cost} = (1185.064 \text{ x Size}) + (39.4 \text{ x } CO_2 \text{ Savings}) + 201950.2 \qquad (9)$$

$$\text{Capital Cost} = (1106.408 \text{ x Size}) + (-67.70185 \text{ x } CO_2 \text{ Savings}) + (5.089412 \text{ x Annual Savings}) - 89372.82 \qquad (10)$$

$$\text{Capital Cost} = (1342.561 \times \text{Size}) \tag{11}$$

$$\text{Capital Cost} = (1227.995 \times \text{Size}) + (46.43577 \times CO_2\ \text{Savings}) \tag{12}$$

$$\text{Capital Cost} = (1107.363 \times \text{Size}) + (-54.14 \times CO_2\ \text{Savings}) + (4.36 \times \text{Annual Savings}) \tag{13}$$

When applied to all the case study data each model gave the MSE as shown in Table 8.

Table 8. MSE model

	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6	Model 7
MSE	37334669	34627900	37447184	16691532	37358083	40402266	18920837

❖ FINAL RESULTS

The final results were obtained by observing how successfully CHP had delivered savings across 18 different case observations (Table 9).

Table 9. Case Study Data

Name	Size (kWe)	Cost (£)	Annual Savings (£)	CO_2 Savings (Tons CO_2)
Ards Leisure Centre	210	£143,100	£35,100	315
Blackpool Victoria Hospital	1,200	£1,500,000	n/a	1,700
Bonnyrigg Estate Edinburgh	330	£1,700,000	n/a	520
Charles Dickens Estate Portsmouth	520	£6,500,000	£61,800	420
ConocoPhillips Immingham	734,000	£350,000,000	n/a	3,000,000
Freeman Hospital	2,500	£3,690,000	£402,000	14,000
Heathrow Marriott	400	£180,000	£51,000	1,020
Hydebank Young Offenders Centre	210	£158,000	£44,000	316
Kingston Hospital	1,400	£2,900,000	£124,848	4,000
Lincoln Hospital	1,350	£1,400,000		4,000
Natural History Museum	1,800	£12,000,000	£500,000	1,800
Ormskirk Hospital	1,000	£5,300,000		4,000
Queens University Belfast	210	£149,400	£43,200	188
Southampton District Energy Scheme	5,700	£7,000,000	£350,000	11,000
Syngenta AgroChemicals	16,000	£10,600,000	£2,500,000	40,000
Telford Princess Royal Hospital	1,150	£1,400,000	£207,000	2,221
University of Southampton	1,400	£3,200,000	£200,000	2,000
Woking Park Leisure Centre	200	£1,046,774	£88,261	1,740

We initially set out to develop a simplified feasibility model. This model will have the ability to calculate basic CO_2 savings in that potential energy savings may be computed mathematically as follows

$$\text{Savings}_{Elec} = CHP_e\ (kWe) \times (\text{Site Electricity Tariff } (p/kWh) + CCL(p/kWh)) \tag{14}$$

$$\text{Savings}_{Heat} = CHP_{th}\ (kWth) \times (\text{Site Gas Tariff } (p/kWh) + (CCL(p/kWh) / \eta_{Boiler})) \tag{15}$$

where, CHP_{th} and CHP_e represent the CHP heat and electricity demand (in effect the prime movers).

We obtained both heat and electricity tariff information from the UK governments Office of National Statistics (ONS), and both data are representative of heat and electricity purchases p/kWh by UK manufacturers in 2008. Data on boiler efficiency (η_{Boiler}) which is also required to enable heat savings calculations was obtained from earlier work conducted by Sedbuk [9](2009). The savings is then represented mathematically as

$$\text{Net Annual Savings} = ((\text{Savings}_{Elec} + \text{Savings}_{Heat} - \text{Fuel Cost}) \times \text{Hours} \times 365 \times \text{Availability}) - \text{Annual Maintenance Costs} \tag{16}$$

While fuel cost which represents yearly operation cost multiplied by usage every 60 minutes are calculated (17), while the yearly CO_2 savings are calculated as (18):

$$\text{Fuel Cost} = ((CHP_e + CHP_{th}) \times \eta_{CHP}) \times \text{Fuel Cost } (p/kWh) \tag{17}$$

$$CO_2\ \text{Saving} = (\text{CHP Usable Heat} \times CO_2\ \text{Gas Constant}) + (\text{CHP Electricity} \times CO_2\ \text{Elec Constant}) - (\text{CHP Fuel Input} \times CO_2\ \text{Fuel Constant}) \tag{18}$$

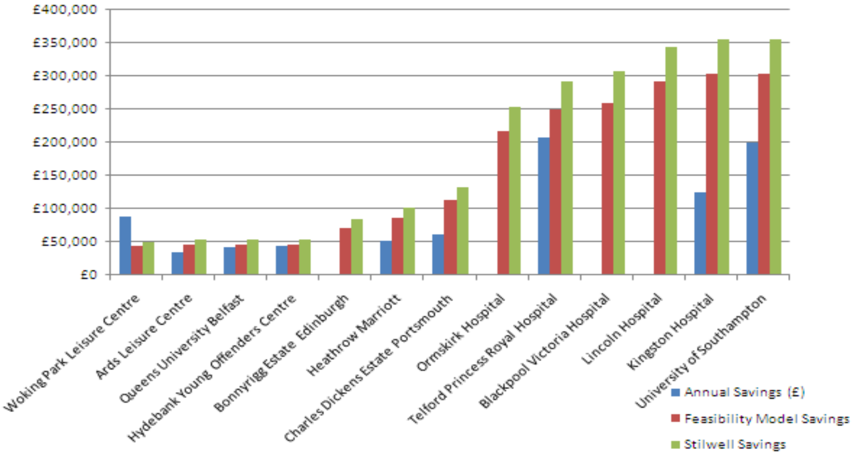

Figure 1. Comparison of actual and historical data (actual annual savings)

The model is validated by a comparison of historical data from the cases with the popular Stilwell Model. Out results (fig. 1) show that there are clear differences between the actual savings from the use of the Stilwell Model and our developed model.

We are of the opinion that these savings may be attributable to tradeoffs between CO_2 and financial savings.

CONCLUSION

The model we have developed demonstrates a significant potential to deliver increased precision and reality for CHP sizing and feasibility, especially when compared to the Stilwell model. It is however acknowledged by the authors that the CHP sizing model does have limitations which are mainly related to the data (primarily obtained from secondary sources), which have been employed as part of the sizing data.

REFERENCES

[1.] BROWN, A., MARYAN, P., RUDD, H. 2007. Renewable Heat and Heat from Combined Heat and Power Plants- Study and Analysis. AEA Technology. Version 1. pp.72.

[2.] NOCK, A., 2010. Evaluation of Opportunities for Combined Heat and Power. Unpublished MSc Thesis, University of Southampton, 2010.

[3.] MORTENSEN, H. and OVERGAARD, B., 1992. CHP development in Denmark: Role and results. Energy Policy, 20(12), 1198-1206.

[4.] LUND, H., SIUPSINSKAS, G. and MARTINAITIS, V., 2005. Implementation strategy for small CHP-plants in a competitive market: the case of Lithuania. Applied Energy, 82 (3), 214-227.

[5.] BJORKLUND, A., NIKLASSON, T. and WAHLEN, M. 2001. Biomass in Sweden: Biomass-fired CHP plant in Eskilstuna. Refocus, 2 (7), 14-18.

[6.] DANESTIG, M., GEBREMEHDIN, A. and KARLSSON, B. 2007. Stockholm CHP potential—An opportunity for CO2 reductions? Energy Policy, 35(9), pp. 4650-4660.

[7.] MEIJER, I., HEKKERT, M. and KOPPENJAN, J., 2007. How perceived uncertainties influence transitions; the case of micro-CHP in the Netherlands. Technological Forecasting and Social Change, 74(4), 519-537.

[8.] BABUS'HAQ, R., PROBERT, S., 1996. Combined heat-and-power implementation in the UK: Past, present and prospective developments. Applied Energy, 53, 47-76.

[9.] SEDBUK. Boiler Efficiency Database. Department for Environment and Rural Affairs. Sedbuk Website, 2009. Viewed at http://www.sedbuk.com on 01/09/2009.

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