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CHP and its role in efficient energy production: a feasibility assessment model

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Abstract

Purpose – The way and manner in which energy is produced is known to have a significant impact on emissions. For this reason, the UK government has sought to enhance the efficiency of energy production/conversion by focusing on a number of energy production approaches, including Combined Heat and Power (CHP). The purpose of this paper is to describe a practical approach for assessing the feasibility of CHP.

Design/methodology/approach – The authors provide an overview of Combined Heat and Power (CHP); describe a new and easy-to-implement feasibility and optimisation model to aid in the installation of CHP; and discuss the practical feasibility issues of CHP through an analysis of existing case studies using the proposed model. The modelling utilises regression models which are created using historical data obtained from public sources.

Findings – Compared against alternatives, the model is shown to be particularly useful, as its functionality is embedded in resource-intensive prime mover specifications obtained from seven real industrial cases.

Originality/value – The need for such a practical and easy-to-use model is driven by the existence of numerous models, which are mainly complex and not necessarily "user-friendly". The proposed model is set to provide a practical and user-friendly model for CHP appraisal that is easy to understand and assess in terms of prime movers such as capital cost, payback, annual financial and CO_2 savings.

Keywords Energy management, Energy sources, Energy technology, Modelling, Environment, Regression, Combined heat and power

Paper type Case study

1. Introduction

In the UK, over recent years, various bodies, institutions, government agencies, and scholars have sought to examine possible means of reducing the country's carbon emission footprint. One possible means of achieving this reduction identified in earlier research (Kelly and Pollitt, 2010; Psomopoulos *et al.*, 2010) involves the expansion of the use of combined heat and power (CHP).

CHP is an efficient means of heat and electric power generation, regarded by scholars (Fumo *et al.*, 2009) as providing a better chance of achieving lower emissions than comparative traditional energy systems. The basic precept of CHP is to recover energy generated from power and utilise it to generate heat. There are numerous advantages in the use of CHP; for example, it enhances the chances of achieving lower emissions than comparative traditional energy systems do (Fragaki and Andersen, 2011; Fumo *et al.*, 2009; Schmidt *et al.*, 2010; Toke and Fragaki, 2008). Another advantage is its ability to run

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independently from centralised grid systems, thus providing users with flexibility and supply security (Kelly and Pollitt, 2010).

CHP, which is also referred to as cogeneration, is known to offer a considerable number of environmental benefits in that it provides substantial energy savings against both conventional heat combustion generators and electricity power plants (Ren and Gao, 2010) through its ability to simultaneously produce heat and power near the site of consumption (Fumo *et al.*, 2009; Psomopoulos *et al.*, 2010). The environmental advantage in its utilisation comes from its ability to capture heat/energy which would have, in the case of standard combustion systems, been lost to the atmosphere (Mago *et al.*, 2009). In the case of CHP, however, exhaust heat is recovered and re-used, thus (according to Torchio *et al.*, 2009) delivering major climatic benefits through its ability to mitigate against the emission of pollutants such as CO_2, nitrogen oxide and sulphur dioxide. Through the capture and re-use of energy which would have dissipated into the atmosphere, CHP will utilise less fuel than equivalent combustion systems to produce comparable amounts of energy. It can thus be inferred/posited that as an enhanced and efficient means of energy production and generation, CHP can deliver critically important environmental benefits by reducing greenhouse gas emissions (Chicco and Mancarella, 2008). In light of the conclusions drawn from the United Nations Climate Change Conference held in Copenhagen in December 2009, the importance of CHP to the overall debate on the reduction of carbon emissions cannot be overemphasised.

Although CHP has attracted substantial research interest in the UK as a source of efficient energy (Blakemore *et al.*, 2001; Toke and Fragaki, 2008), and various models for efficient energy calculation do exist (Hashemi, 2009; Lahdelma and Hakonen, 2003), the majority of these models have limited application in a UK context because their modelling parameters are not specific to the UK market. Based on this, the objective of this study is threefold:

(1) to provide an overview of CHP;

(2) to describe a new and easy-to-implement feasibility and optimisation model to aid in the installation of CHP; and

(3) to discuss the practical feasibility issues of CHP through an analysis of existing case studies using the proposed model.

As a review of extant literature has shown, efforts to cut emissions have appeared to focus on two primary areas of interest; the first area focuses on energy demand and efficient utilisation, while the second focuses on efficient means of energy conversion. Being that the objective of this study is to develop a practical model for CHP appraisal, this study fits into the remit of the first area of interest by providing an understanding and assessment of CHP prime movers such as capital cost, payback, annual financial, and CO_2 savings. By no means should this endeavour be underestimated, as conveying a comprehensive understanding of CHP is extremely challenging due to its composition of a number of interfacing technological applications.

The rest of the paper is divided into four major sections. In Section 2, the application of CHP generation is undertaken. While Section 3 focuses on CHP sizing models, in the penultimate section of the paper, a number of industrial case studies against which the proposed model are to be validated and tested are presented. The final section of the paper concludes the paper.

2. Applications of CHP generation

2.1 CHP and the environment

In numerous works of scholarship (see Jacobsen and Zvingilaite, 2010; Streckienė *et al.*, 2009) and industry reports (see Shipley *et al.*, 2008), the utilisation of CHP has been shown to represent an effective means of not only enhancing energy efficiency, but also a means of improving environmental quality and – in the process – delivering substantial climatic benefits. For example, in the USA, Shipley *et al.* (2008) report that CHP has been able to deliver CO_2 reductions equivalent to 45 million cars being removed from the road. In the UK, such opportunities for CHP use remain vast. CO_2 emissions which are the primary man-made greenhouse gas that leads to global warming (Radhi, 2009) may, through CHP, be reduced by up to 57 per cent according to a report by the Electricity Association (2000). Many countries are now producing a significant proportion of their electricity requirements from CHP; King (2005) points out that Denmark meets about 50 per cent of its electricity requirements in this way.

With its origins in the industrial revolution, CHP or cogeneration is a technology that has been available for over a century. In situations where the demand for energy is steady, CHP, which involves the simultaneous production of heat and electricity, is regarded as an efficient means of power generation due to its ability to harness waste heat energy from electricity generation which is then utilised for heating (or cooling). According to the Energy Institute (2003), CHP can convert up to 90 per cent of energy into required power and heat, hence comparing very favourably with a conversion rate of about 45 per cent for standard power generation technologies. In fact, it might be noted that there are standard technologies available that convert more than 45 per cent of the fuel energy in electricity, e.g. CCGT-CHP plants with an electrical efficiency up to 55 per cent. Like standard generators, CHP generators transfer around 35 per cent of the fuel energy into electricity; however, unlike standard sources of power, CHP will harness the heat generated during conversion to achieve efficiency gains. In so doing, the need to source additional energy to be used specifically for either heating or cooling becomes negated. Table I presents an overview of possible uses of CHP.

2.2 Sizing categories

CHP can be split into three generic categories (large, small, and micro) depending on their power output. However, due to the lack of defined boundaries in size, CHP sizing is rarely discussed in precise sizing terms because of associated decision uncertainties. Unlike in European countries where CHP plants are not normally natural gas fired, in the UK CHP succeeds as a more efficient and successful form of power generation over more conventional approaches because of its use of fossil fuels (primarily natural gas), which has been linked to perceived technological, economic, political, and environmental advantages (Fumo *et al.*, 2009). Environmental advantages include, for example, the reduction of CO_2 emissions. Recognition of these advantages has meant that CHP has become popular in various European countries such as the Netherlands (Meijer *et al.*, 2007) and Denmark (Raven and Gregersen, 2007). In Denmark for example, over 40 per cent of its electricity is generated through CHP (Mignard *et al.*, 2007).

The choice of CHP prime mover (generator) greatly affects the performance of the installation. There are six major variations of CHP prime movers, an overview of which is given in Table II. A detailed description of each prime mover follows.

The internal combustion engine (ICE) is the most popular form of CHP prime mover. The ICE can be subdivided into two categories, spark ignition (SI) and compression

Industry	Utilisation
Swimming pools and leisure centres	Consistent heating demand for pool Consistent electricity demand for pumps Large demand for domestic hot water Prolonged opening hours Trigeneration potential with air conditioning
Hospitals	Consistent ambient heating demand 24 h operation High demand for domestic hot water
Hotels	Large heating demand Trigeneration potential with air conditioning in summer months Large demand for domestic hot water Leisure facilities, e.g. swimming pool
Residential homes	High demand for domestic hot water Large ambient heating demand for elderly residents Continuous occupancy
District heating	Opportunity for multiple organisations with varied heating and cooling profiles to even out demand Large scale domestic hot water Instantly available affordable heating
Community and campus-based heating: universities, schools, MOD sites, prisons	Potential for large diverse heating and cooling demand. Including laboratories, clean rooms, workshops, onsite accommodation High demand for domestic hot water Accommodation heating demand in mornings and evenings Office and teaching facility heating demands during the day
Industry	Heat-intensive industrial processes Large factory heating Potential for usage of hot water or steam
Museums	Consistent heating and humidity independent of opening hours Domestic hot water
Retail stores and shopping centres	Trigeneration potential for heating and cooling according to seasonality Extended operating hours
IT facilities and data centres	Large electrical and heating loads Consistent cooling demand for servers and data storage
Waste water treatment plants	Large heating and hot water demand for waste heat treatment Consistent heat and power demands

Table I. Popular possible application for CHP

ignition (CI). SI ignition is powered primarily by natural clean gaseous fuels providing a lower cost per kW in capital expenditure; however, its generating efficiency for electricity is relatively low at about 35 per cent. The second form of ICE used in CHP is the CI. The CI ignition is fuelled primarily by diesel but can run on gas-oil or have a duel fuel option. CI has greater electricity generation efficiency (35-45 per cent), than SI; however, it has a lower thermal output at around 85°C (compared to 110°C for SI).

The stirling engine is a form of external combustion engine, which has been shown to achieve relatively acceptable levels of electrical conversion efficiency. Stirling

Table II. Comparison of prime movers

Prime mover	Fuel	Power output	Electrical efficiency %	Total efficiency %	Heat-to-power ratio	Thermal output	Running time %	CHP uses	Manufacturers
Internal combustion engine	Spark ignition (natural gas, biogas, recovered gases)	< 4 MWe	35	80	1:1-1.7:1	Maximum 110°C high grade or low grade	85-92	Small scale	Alfagy, Aircogen, SAV Modules
	Compression ignition (diesel, gas-oil, heavy oil)	1-15 MWe	35-45	72	1:1-1.5:1, up to 2.5:1 with supplementary firing	Maximum 85°C high grade or low grade		Small to large scale	Alfagy, Aircogen, Edina, SAV Modules, Yanmar
External combustion engine	Gas, diesel, biomass, coal, waste	200 kWe	40	95	1:4-1:8	High grade 750°C	95	Micro	Baxi, Energetix, Whispergen
Gas turbine	Natural gas, biogas, recovered gases, gas-oil	50-250 kWe 1-200 MWe	20-35	72	1.6:1, up to 5:1 with supplementary firing	400-550°C high grade		Micro, small, and large scale	-
Steam turbine	Coal, biofuel, gas, waste	> 0.5 MWe	10	84	3:1-10:1	Medium	99	Large scale	-
Fuel cell	Polymer electrolyte fuel cell (PEFC), proton exchange membrane fuel cell (PEMFC), phosphoric acid fuel cells (PAFC), alkaline fuel cells (AFC), molten carbonate fuel cells (MCFC), solid oxide fuel cells (SOFC)	100 W-50 MW	Up to 65	85	0.5:1-2:1	120°C	-	Micro, small, and large scale	CFCL, Ceres Power

engines tend to be able to generate power output of up to 200 kWe. They also have low running costs (Harrison, 2002), making them ideal for micro CHP applications.

Gas turbines are capable of producing a power output from under 1 MWe to over 200 MWe. However, utilisation under 5 MWe is not seen as particularly cost effective. Research is, however, being undertaken in terms of micro-turbines (50-250 kWe), serving as a potential power source in micro-CHP units (De Paepe *et al.*, 2006). Gas turbines tend to produce electricity at comparably lower efficiencies of between 20 and 35 per cent compared to ICE. Although gas turbines are not particularly efficient, they do provide high-grade thermal energy at temperatures of 400-550°C. Gas turbines are, however, inherently reliable, thus minimising down time for maintenance, although they are they are considered more effective to a CHP application where intense heat is required. It is also recommended that they be run at full power for as long as possible to maximise efficiency.

Steam turbines offer a very simple and basic CHP capacity with a primary focus on heat generation rather than electricity. Steam turbines have a large capacity, leading to their popularity in countries such as the USA, and are a very popular means of CHP generation for large-scale systems. The fuel cell represents the latest breakthrough in CHP technology, and studies involving its use report impressive results. Companies such as the Australian power company Ceramic Fuel Cell Ltd (CFCL) have reported a 60 per cent electrical conversion capability and an efficiency rating of up to 85 per cent during testing (CFCL, 2009).

2.3 Financial benefits

Statistics shows that in the UK, one-third of power (electricity and gas) demand is from homes (DTI, 2001). With an ever-growing population (and associated demand for housing), in terms of financial benefits, when connected to the national grid CHP offers the possibility of selling excess electricity generated on site back to the electricity utilities companies (Marnay *et al.*, 2008). This can create further revenue to be offset against capital and operational costs. Based on this, CHP potentially can deliver a clear financial incentive if correctly implemented. Although CHP appears to have many advantages, it is important to point out that there are challenges associated with benefit realisation in the UK, where overall, CHP utilisation remains low (Hinnels, 2008; Toke and Fragaki, 2008) compared to other European countries. In response to its low adoption, the UK government has announced a target of 10 GW of CHP generation for 2010 (DEFRA, 2007). It, however, remains questionable whether this target will be achieved due to overall scepticism in the domestic UK market which is driven by an association of CHP with increases in household energy bills.

2.4 Legal framework

There is much research to suggest that the impact of global warming on the climate is as a result of man's activities (Romilly, 2005). Noting that in the UK, for example, the years between 1995 and 2006 ranked among the warmest years ever recorded (Bernstein, 2007), the government has attempted to manage the impact of global warming through legislation (Blakemore *et al.*, 2001). To meet CO_2 emissions reductions (see Table III), the UK government has, for example not only set a target 10 GWe of "good quality" CHP electricity generation to be achieved by 2010 (DEFRA, 2009), but also passed into law the 2008 Climate Change Act. The government also supports principle bodies such as the Combined Heat and Power Quality Assurance

(CHPQA) Programme. The CHPQA is the principle body for monitoring and determining what comprises "good quality" CHP.

In addition to legislation (a sample of government CHP legislation is identified in Table IV), another approach the government has adopted in its bid to achieve CO_2 emission reductions is by providing financial incentives to organisations adopting CHP. Such initiatives (although not comprehensive) include the offering of preferential business rates for CHP usage, and an Enhanced Capital Allowance Scheme which provides businesses with an opportunity to write-off their overall capital cost of the CHP installation against its taxable profits for the year of the capital outlay.

The government (sample government CHP legislation is identified in Table IV) has also made available energy saving grants to fund increases in energy-efficient technologies. Examples include the following:

- DTI's low-carbon building programme. These are grants for micro-generation including CHP. These grants are managed by the Energy Saving Trust.
- *E.On* community energy grants. This provides up to £30,000 to companies seeking to utilise CHP.
- Interest free energy efficiency loans. Managed by the Carbon Trust which provides grants up to £100,000 (£200,000 in northern Ireland).
- Bio Energy Capital Grants Scheme. This is organised by the National Lottery and so far has awarded seven grants of up to £500,000.

In addition to the various schemes and grants available (see Table III), the government continues to support the expansion of CHP through consideration of future proposals; one such proposal is feed-in tariffs which was proposed under the 2008 Energy Act as a means of promoting investment in small-scale low-carbon electricity generators (up to 5 MWe). Another scheme is the Renewable Heat Incentive which was implemented in April 2011.

3. Feasibility and sizing models

3.1 Existing models

There is a limited selection of CHP feasibility and sizing models available within the UK, compared with the likes of the USA. The USA has various software models available to aid with all steps of the CHP design process including sizing, financial benefit analysis, and environmental benefit analysis. These programmes range from automated excel spread sheets available as freeware to complete specialised CHP applications worth thousands of dollars. The Gulf Coast CHP Application Centre provides a complete listing of these CHP evaluation models. However, these models

Table III. Summary of key UK climate change targets

Sponsoring institution	Details	Target year
UK Government	UK Climate Change Act 2008, 80% reduction in CO_2 emissions by 2050	2050
UK Government	UK Budget 2009, 30% reduction in CO_2 emissions by 2020	2020
UK Government	UK Budget 2009, 15% of energy from renewables by 2020	2020
UK Government	UK Transition Plan 2009, 30% of electricity from renewables by 2020	2020

CHP incentives and legislation	Date introduced	Summary
Climate Change Levy (CCL)	2001-2023	Climate Change Levy (CCL) is a tax imposed by the UK Government on the supply of specified energy products that are used as sources of energy by commercial business. To receive exemption from this levy, a levy exemption certificate (LEC) is needed. LECs are available for users of efficient and environmentally friendly energy generation means. Current levy rates are £0.00470 per kWh for electricity and £0.00164 per kWh for gas. CHP receives total exemption
Climate change agreements (CCA)	2006 – Due for Extension until 2017	Agreements for large energy-intensive companies to receive 80% discount from CCL. The agreements allow an 80% reduction as long as key targets are met regarding a reduction in CO_2 emissions through other means and an increase in energy efficiency
EU Emissions Trading Scheme (EUETS)	2005-2012	European cap and trade system for CO_2 emissions allocations (EUAs). 20% less allocations than needed, therefore providing incentive for companies to reduce emissions or face fines for any shortfall in EUAs. EUAs can be traded over the duration of the year
Carbon reduction commitment (CRC)	2010	UK emissions trading scheme. Similar cap and trade system to EUETS; companies must purchase adequate allowances from government at £12 per tonnes of CO_2. The income generated by the scheme is redistributed at the end of the year between companies that have improved their emissions reductions
Renewables obligation (ROC)	2002	Electricity generated through renewable sources can receive a renewables obligation certificate (ROC). For biomass and waste CHP schemes the ROC value is £90 per MWh
Renewable Heat Incentive	April 2011	Still under construction, but designed to provide financial support to users of renewable heat
Feed-in tariffs (FIT's)	2010	Designed to promote investment into small- and micro-scale low carbon electricity generators. Value of the tariffs to be confirmed
Enhanced Capital Allowances	2001	Allows companies to write off capital cost against taxable profits
Business rates	2001	Exemption from business rates on CHP plant and machinery
VAT reduction	2005	5% VAT rate for domestic micro CHP units

Table IV. Summary of UK CHP incentives and legislation

(with the exception of pure environmental models) are only viable within the USA due to differences in the country's legislation and regulation of energy markets.

The investigation into the CHP feasibility and sizing models such as the Stilwell calculator, CHP Sizer 2.0, and the Irish Combined Heat and Power Association Evaluator shows that there is clear potential for a model that suitably combines all aspects of CHP feasibility and basic design.

From this research a basic set of specifications for a suitable model can be drawn up, summarised as:

- complete financial analysis with cost breakdown, annual savings and payback period;

- basic sizing dependent on heat and electricity profiles leading to choice of suitable prime mover and estimate of capital cost;
- indication of environmental benefit of CHP in terms of CO_2 savings;
- integration of UK legislation and incentives concerning CHP;
- sensitivity analysis regarding volatility of energy prices;
- simple interface and use of easily obtainable inputs; and
- use of simple techniques and easily available applications to ensure widespread use of the model.

The development of the models now commences by considering various parameters that may impact on CHP development and utilisation. These parameters may include:

- CHP development and utilisation may be dependent on the financial position of the sponsoring organisation, which means that there is a requirement to conduct a full investment appraisal before the decision to adopt CHP is made;
- understanding basic heat and electricity sizing. Such understanding will influence choice of suitable prime mover;
- full appreciation of CHP benefit in terms of CO_2 savings;
- an ability to integrate UK legislation and incentives concerning CHP;
- sensitivity analysis regarding volatility of energy prices; and
- this will also involve the development of a model, which has a simple interface.

Based on the above parameters that have been identified, the aim is to develop two CHP feasibility and sizing models based on multi-dimensional assessments (Wang *et al.*, 2008) which take into consideration all the parameters identified above. Linear programming is employed to undertake modelling. Existing research (Lahdelma and Hakonen, 2003) supports the conceptualisation of CHP optimisation as a linear programming problem.

3.2 The basic model

The first model is a "basic" model, which is designed to be used for calculating the annual saving achievable through CHP (over conventional separate power and heat generation). In addition to this basic capital cost and payback analysis, the model calculates basic CO_2 savings, and accounts for the effects of the European Union's Emissions Trading Scheme with respect to the maximum capital cost as well as providing a benchmark figure for capital cost based on previous case study data. The savings in electricity (E_S) and heat (H_S) can be expressed as:

$$E_S = CHP_e(\text{Site elecricity tariff}(\text{p/kWh}) + CCL(\text{p/kWh})) \quad (1)$$

and the savings in heat are calculated as:

$$H_S = CHP_{th}(\text{Site gas tariff}(\text{p/kWh}) + (CCL(\text{p/kWh})/\eta Boiler)) \quad (2)$$

In Equations (1) and (2), *CHPe* and *CHPth* represent the electricity and heat demand required from CHPs, respectively. The site electricity and gas tariff costs were obtained from the Office of National Statistics (BIS, 2009). The values used in this model are the 2008 average value for gas and electricity p/kWh purchased by a medium-sized manufacturing consumer. Climate Change Levy (CCL) rates are obtained from information provided by HM Customs (HMRC, 2005). Boiler efficiency (*ηBoiler*) is needed to calculate the heat savings and is the efficiency of any existing or upgrade boiler. This efficiency can range between 55 and 65 per cent for old boilers or up to 78-88 per cent for more modern boilers (Sedbuk, 2009). The net annual savings using the electricity and heat savings are calculated as:

$$\begin{aligned} Savings\eta = & ((Savings_{\text{Elec}} + Savings_{\text{Heat}} - \text{Fuel cost}) \times \text{Hours} \times 365 \\ & \times \text{Availability}) - \text{Annual maintenance costs} \end{aligned} \tag{3}$$

Fuel cost, on the other hand, is represented as:

$$\text{Fuel cost} = ((CHP_e + CHP_{th}) \times \eta_{\text{CHP}}), \text{Fuel cost}(\text{p/kWh}) \tag{4}$$

where *CHPe* and *CHPth* as earlier mentioned represent the electricity and heat demand required from CHP. In addition to calculating the annual savings and maximum possible capital cost the model also estimates the annual CO_2 savings as:

$$\begin{aligned} CO_2\,\text{Saving} = & (\text{CHP usable heat} \times CO_2\,\text{gas contant}) \\ & + (\text{CHP electricity} \times CO_2\,\text{Elec constant}) \\ & - (\text{CHP fuel input} \times CO_2\,\text{fuel constant}) \end{aligned} \tag{5}$$

These costs are calculated on an hourly basis. The annual maintenance cost is then offset against the annual savings to produce the net annual savings. The fuel used is an estimate obtained from the power and heat output. The value for net annual savings is then used with a user-defined payback period to calculate the maximum possible capital cost. If this cost of implementing a CHP scheme exceeds the maximum capital cost, then it is not considered economically viable. In addition to calculating the annual savings and maximum possible capital cost, the model also estimates the annual CO_2 savings. The CO_2 conversion factors (which are defined by current UK building regulations) are shown in Table V.

3.3 The advanced model

The advanced model builds on the basic model presented above, the major difference being that in the advanced model, the specifications incorporate varying prime mover specifications (see Table VI). The prime mover type, fuel type, and power-to-heat ratio

Fuel	CO_2 emissions factor ($kgCO_2$/kWh)
Natural gas	0.194
Biogas	0.025
Oil	0.265
Coal	0.291
Biomass	0.025
Grid displaced electricity	0.568

Table V. CO_2 conversion factors

Table VI.
Prime mover advanced inputs

Prime mover	Fuel type	Power-to-heat ratios
Spark ICE	Gas, biogas, waste gas, by-product gas	1:1-1:1.7 (intervals of 0.1)
Compression ICE	Gas, biogas, waste gas, by-product gas, oil, liquid biofuel, liquid waste	1:1-1:2.6 (intervals of 0.1)
Gas turbine	Gas, biogas, waste gas, by-product gas	1:1.6-1:5.0 (intervals of 0.2)
Steam turbine	Gas, biogas, waste gas, by-product gas, oil, liquid biofuel, liquid waste, biomass or solid waste, wood fuel, coal	1:3-1:10 (intervals of 0.5)
Stirling engine	Gas, biogas, waste gas, by-product gas, oil, liquid biofuel, liquid waste, biomass or solid waste, wood fuel, coal	1:4-1:8 (intervals of 0.2)
Fuel cell	Solid oxide fuel cell, molten carbonate fuel cell	1:0.5-1:2 (intervals of 0.1)

can be varied whereby the choice of prime mover determines the fuel and power-to-heat ratio.

The advanced model has the ability to optimise the prime mover size to maximise the financial benefits. To calculate this, the heat and electricity demand profiles need to be inputted. The profiles can be daily or annually and are estimated from a base load figure, a maximum figure, and a percentage above base load. The profile is modelled as one of two constant demands so the demand is either at the peak or at base load, whereby the percentage of time above base load is the sum of the above-base load demand in terms of time at peak demand rather than at base load (see Figure 1).

The proposed model aims to maximise the heat output through changing the electrical output, i.e. changing the size of the prime mover. Let C_h denote the size of the prime mover. For optimisation, a formula is proposed which seeks to ensure that C_e is maximised, subject to:

$$\alpha C_h + \beta C_e - \chi C_f \geqslant 0 \qquad (6)$$

$$\text{where} \quad \alpha = (\text{payback period})(\text{daily heat savings}) \qquad (7)$$

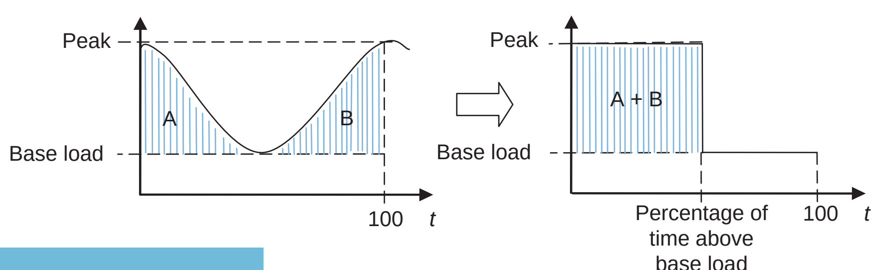

Figure 1.
Heat and electricity demand profiles

This constraint (6) enables the researchers to ensure that there is positive payback from electricity and heat (less fuel). Under these conditions, it is conceived that:

$$C_h = PC_e \quad (8)$$

$$C_f = (C_h + C_e)/\varepsilon \quad (9)$$

$$\text{while} \quad C_h \leqslant H_p \quad (10)$$

$$\text{and} \quad \omega_1\left(\frac{C_e}{C_f}\right) + \omega_2\left(\frac{C_h - C_r}{C_f}\right) \geqslant Q_t \quad (11)$$

$$\text{where } C_e \geqslant 0 \text{ and integer} \quad (12)$$

However, to be exempt from CCL levies, the CHPQA has determined that:

$$Q_t \leqslant QI \quad (13)$$

and:

$$QI = (\omega_1 \times \eta_H) + (\omega_1 \times \eta_P) \quad (14)$$

Nomenclature

Symbol	Meaning
α	Conversion constants for gas
β	Conversion constants for electricity
χ	Conversion constants for fuel
C_h	Amount of generated usable heat
C_e	Amount of generated electricity
C_f	Fuel input to CHP
C_r	Amount of rejected heat
ε	Efficiency rate of fuel
P	Heat rate power
ω_1	Weight of size source for CHP
ω_2	Weight of fuel source
η_P	Heat efficiency of power
η_H	Heat efficiency of heat
H_p	Optimum value of heat (pre-determined)
QI	Quality index

The weightings are designed such that they encourage the more environmentally beneficial but less economically advantageous schemes. The weights were reformed in 2007 and are valid for any new CHP scheme between 1 January 2007 and 1 January 2011 (Gearty, 2008). It is noted that the way in which the calculation of *QI* is done is intended for use when designing CHP installations. When concerning the calculation of

QI for existing CHP installations, adjustment factors must be used to allow for inaccuracies regarding the fuel input, power output and heat output when calculating η_{Power} and η_{Heat}. However, as this study is aimed as a feasibility study into the installation of new CHP schemes, accounting for inaccuracies in these inputs and outputs is deemed unnecessary. Additionally, the possibility of designing a scheme that is not likely to fully meet the CHPQA regulations is also ignored. Once the optimal value of the prime mover size is found, the basic model is then rerun to calculate annual savings when generating CHP with respect to the current costs of gas and electricity. The interface for the advanced model is shown (Figure 2).

By specifying the fuel input, the advanced model is able to recalculate the CO_2 savings, the annual savings and maximum capital cost. In addition to manually varying the gas, electricity, and fuel prices, the advanced model incorporates a minimum spark-gap calculator. This functionality is delivered using linear programming algorithms to calculate the maximum variation in electricity and gas prices, which is referred to as the minimum spark-gap ratio. To calculate the minimum spark-gap, the advanced model requires the user to input a minimum capital cost. The spark-gap calculator then employs the minimum capital cost along with the desired payback period to calculate the minimum possible annual savings and thus minimum possible spark gap for this CHP application. With natural gas-fuelled applications, the model also accounts for the varying fuel price.

In the case of the sustainable fuels where no definitive fuel price is known, the model requires users to estimate a fuel price as well as a minimum capital cost to calculate the minimum spark gap. Current gas and electricity prices yield a spark-gap ratio of 1:3.1; however, a 9 per cent increase in gas prices or an 8 per cent decrease in electricity prices will cause the spark gap to reduce to the *Ener.G* stated threshold of 2.8. To reduce the

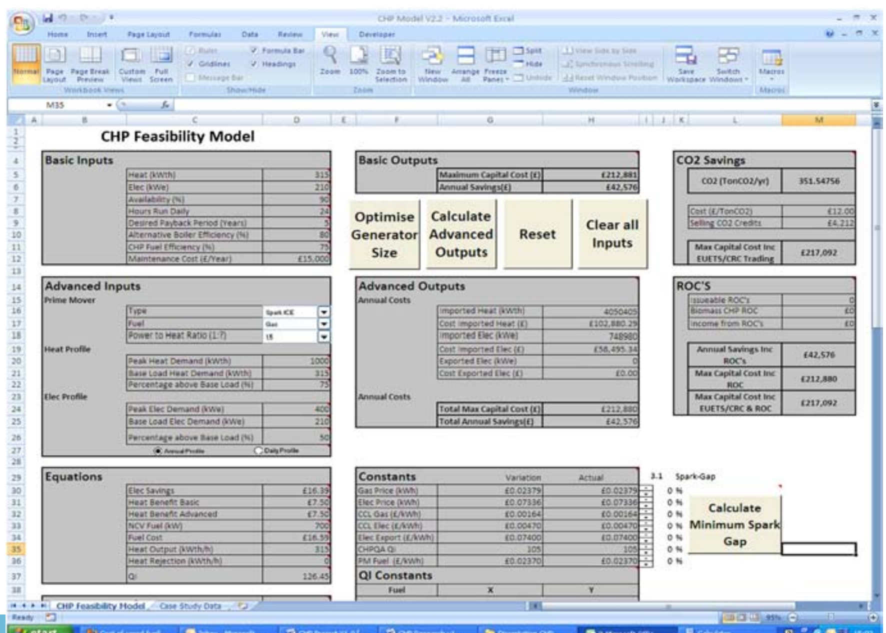

Figure 2.
A snapshot of the advanced model interface

sensitivity of a CHP installation to fluctuations in the gas and electricity markets, the use of a cheaper alternative fuel is advised; or it is advised to utilise dual fuel CHP prime movers.

4. Description of industrial cases

This section presents a number of industrial case studies on which the proposed model was validated and tested. These are selected from instances where CHP has been used successfully (and from where prime mover specifications are drawn), and include the following.

Southampton District Energy Scheme is the largest commercially developed district energy scheme in the UK. Covering a large shopping centre, a supermarket, a hospital, a university, council buildings, office blocks, a swimming pool complex, four hotels, and residential developments, the scheme (launched in 1986) is powered primarily by a 5.7 MWe CHP dual fuel generator and two 400 kWe gas powered generators. There are two additional satellite generators providing a total of 26,000 MWh of electrical energy per annum. The scheme cost around £7million to develop; it is run by Utilicom and Southampton City Council and realises a profit of between £10,000 and £15,000 per year, which is reinvested in further carbon-saving projects.

The ConocoPhillips Immingham CHP plant is an example of industrial use of CHP. The industrial sector of the CHP market accounts for over 80 per cent of CHP generated in the UK (BIS, 2009). With this sector, the ConocoPhillips Immingham CHP plant is the largest in the UK (and Europe). The £350 million project provides heat and power for both the Humber and Lindsay refineries with excess electricity exported back to the national grid. The plant currently delivers 70 per cent energy efficiencies, saving approximately three million tonnes of CO_2 per year.

Ards Leisure Centre near Belfast offers an excellent example of the use of CHP within a leisure centre. Prior to the installation of the CHP plant, the Centre's annual consumption for heat and electricity was 915 MWhth and 3,094 MWhe, respectively, amounting to total yearly running costs of £122,000. Following the installation of the CHP scheme, the Centre has been able to realise CO_2 savings of 315 tonnes and financial savings of £35,100 per year (DFPNI, 2009).

Woking Park Leisure Centre operates the UK's first fuel cell-powered CHP plant. The plant was procured at a cost of £1,046,774 (mainly through government grants), and forms part of Woking Borough Council's objective of reducing total CO_2 emissions by 80 per cent by 2090. As of 2003, the scheme was able to deliver an annual savings of £88,261 and 1,740 tonnes of CO_2 (Jones, 2003).

NHS Hospitals Trust may provide another popular application for CHP systems because of its demand for uninterrupted energy. Kingston Hospital NHS Trust is an example of a major CHP user. In 2007, the hospital upgraded its CHP. The system consists of a 1.4 MWe gas-fired CHP plant, in conjunction with two additional boilers and a 330 kW absorption chiller to provide the cooling element of the scheme. The scheme has been funded and maintained by Dalkia as part of a £2.9 million, 15-year private finance initiative project. The CHP plant has produced savings of £124,848 in energy costs so far (Lansdown and Dale-Jones, 2009).

The Natural History Museum and the Victoria and Albert Museum along with the energy services company Vital Energi Ltd have implemented a decentralised Trigeneration energy system for the two museums using CHP. The £12 million project is currently delivering energy efficiencies at about 44 per cent, respectively (LCCA, 2008), saving the National History Museum £500,000 per year in energy cost (Vital Energi, 2009).

There are 13 CHPQA-recognised university-based CHP schemes operating in the UK. One such case is the University of Southampton, where the CHP is utilised to provide the majority of the heating and electricity supply at the University's main Highfield campus. The £3.2 million trigeneration scheme incorporates two gas-fired 1,400 kWe generators providing 1,600 kWth heat output. It is estimated by the Higher Education Environmental Performance Improvement (HEEPI) (2007) that the scheme saves the University close to £200,000 per year on energy costs as well as reducing CO_2 emissions by up to 2,000 tonnes.

When dealing with the capital cost of the project, the existing model provides a maximum viable capital cost. This capital cost is calculated from the annual savings and the desired payback period. However, in order to offer a more accurate estimation for the capital cost a regression model created from past case study data has been investigated. The data on which this model is based have been compiled from extensive research into existing users of CHP in the UK. This includes the user case studies obtained from manufacturers', suppliers', and users' web sites. These data are shown in Table VII.

To cater for instances where it might prove difficult to estimate minimum cost, estimated capital cost profiles are provided in the advanced model. These estimated costs were developed via regression modelling based on data collected from a cross-selection of CHP cases. In order to create the regression model a suitable training data set had to be compiled.

The unavailability of size, capital cost, annual savings, and CO_2 savings data for CHP means that some data entries were incomplete; these incomplete entries were omitted during modelling. Following the removal of these entries, scatter plots of size vs capital cost, size vs annual savings, and size vs CO_2 savings were created, and from these clear linear trends were observed. Data entry yielding anomalous results was also excluded from the training data set. This left half of the initial data set to be used

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

Table VII.
Data collected from case studies

as the training data set. These data were then used to produce a regression model using EViews:

$$\begin{aligned}\text{Capital cost} = {} & (1,106.408\times\text{Size}) + (-67.70185\times CO_2\ \text{savings}) \\ & + (5.089412\times\text{Annual savings}) - 89,372.82\end{aligned} \quad (15)$$

Figure 3 shows a plot of the log of the actual capital cost against a log of the predicted capital cost. In this figure, a logarithmic value had to be used to cope with the capital costs ranging from hundreds of thousands to hundreds of millions of pounds sterling (£). These two plots can be seen to mirror each other very closely, clearly illustrating the validity of the model.

Validation of the model was conducted by comparing results obtained from the model against results from the Stilwell Model which is a popular CHP Calculator used in the UK (www.stilwellcalculator.com/). The results are shown in Figure 4. The Stilwell CHP Calculator is a popular and free application widely used in industry as a first-stage CHP assessor. The model is, however, limited in that it is tailored for use by professionals (client organisations, planners, architects, and engineers). For this reason, it requires not only expert understanding of CHP configuration, but also detailed appreciation of UK prime mover specifications.

The models show clear differences between predicted savings and the actual savings. Figure 5 shows that the developed model does closely map the actual values obtained from the case study data.

5. Conclusions

There is full recognition globally on the impact of carbon emissions on the environment. Recognition of this impact has been interpreted in various ways, leading to the development of an environmentally oriented sustainability agenda. The importance of studying CHP cannot be underestimated, as a clear relationship has been established between CHP initiatives, which have been shown to have lower CO_2 emissions than comparative traditional energy systems. The research topic is therefore important as it contributes to scholarship in this topical area, noting that in the UK, it was only in July 2009 that the government published its renewable energy strategy.

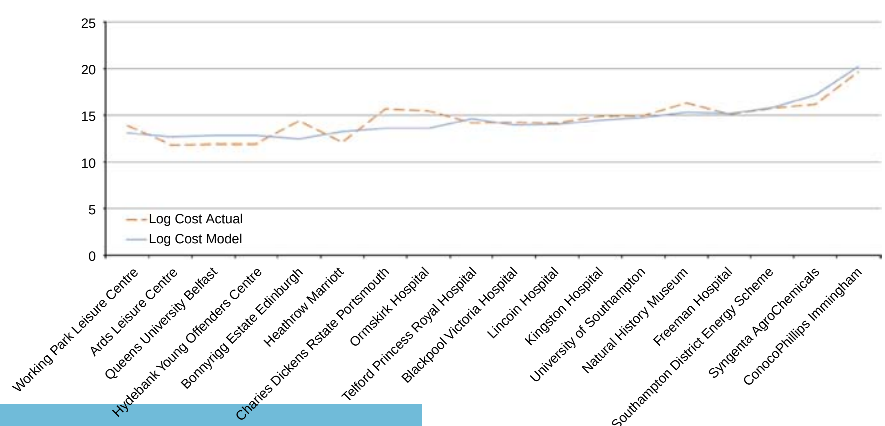

Figure 3.
Log actual vs log predicted capital cost

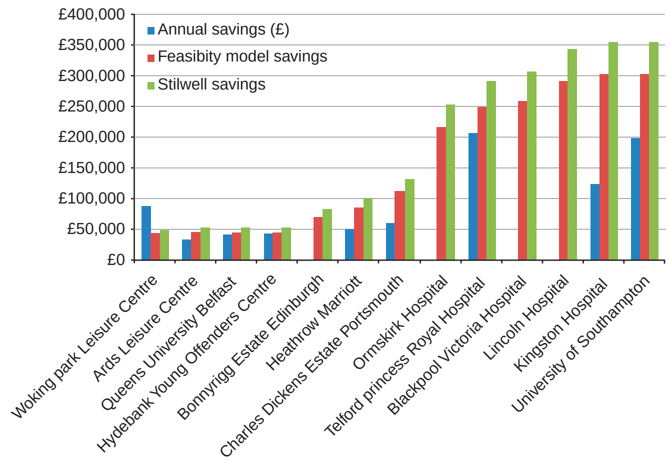

Figure 4.
Values from actual data and both models

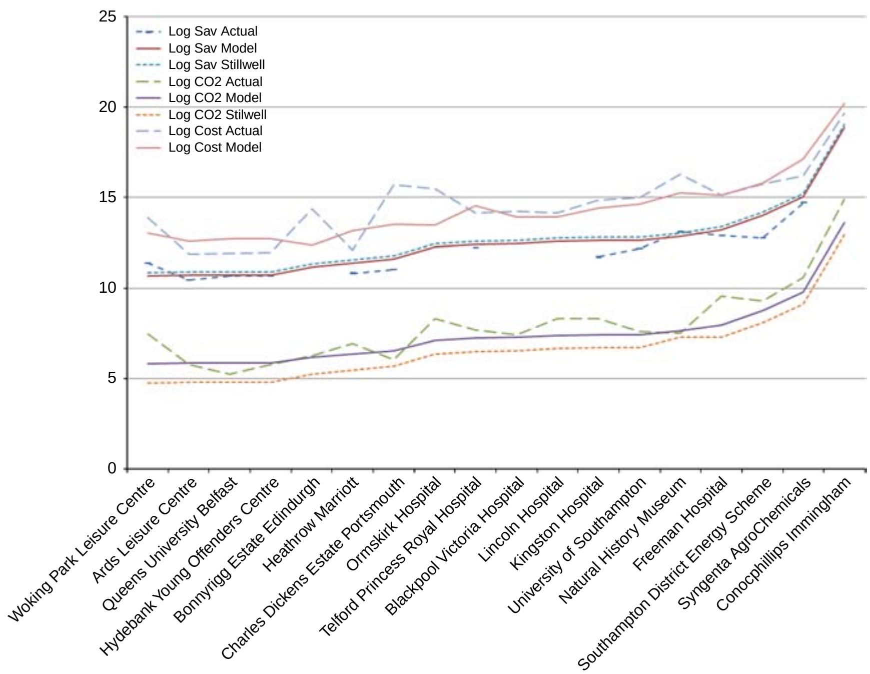

Figure 5.
Comparison of actual data

Overall, the objective of the study was to provide an overview of opportunities for CHP utilisation in the UK. This study also provides a simple model for assessing CHP feasibility. Although there are multiple CHP feasibility and sizing models available, most of these models prove complex and require vast quantities of input data, which are not always available. The model proposed in this study can be used for a first-stage appraisal by consultants in the industry to determine the financial and environmental benefits of CHP to an application. The applications available for such first-stage analysis are quite limited. The proposed model can be used easily and quickly. The results obtained from the case studies indicate that the model can be used as an alternative to the already popular Stilwell Model, and that it aims to provide increased versatility and accuracy.

It is the UK government's intention to champion the agenda on climate change and the reduction of CO_2 emissions. The intention is to achieve this objective by setting out a legal framework which binds numerous actors to the achievement of desired targets. This situation creates a substantial opportunity for the growth of the CHP market in the UK. Among the various initiatives being put forward by the UK government is the carbon reduction commitment of which consist of two aspects. The first relates to redesigning facilities that currently exist, thereby achieving desired energy savings through more efficient building insulation. The second strategy may involve an overall energy consumption level reduction. Due to the cost challenge involved in a redesign effort, it appears more likely that the UK government will continue to push for legislation that supports overall energy consumption reduction. CHP has the competency to support such legislation, and it can be confirmed from the case studies reviewed as part of this research that CHP has the ability to deliver measurable environmental (and financial) benefits. The major drawback with a CHP initiative is that it requires substantial financial outlays, especially at the initial stages (inception and deployment). For some companies, committing to initial investment cost might be difficult, particularly when the expected payback period appears "long".

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