

Development of a Combined Heat and Power Sizing Model for Higher Education Buildings in the United Kingdom

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Abstract

The four Higher Education Funding Councils in the United Kingdom want all universities to reduce CO₂ emissions by 34% by 2020 compared to a 2005 base. Universities that have installed Combined Heat and Power (CHP) technology are making good moves towards achieving their CO₂ reduction target. For a CHP project to be successful, a detailed technical, economic and environmental assessment is required. Generally, this assessment is carried out using a computer-based model. Currently available CHP models have limitations in terms of flexibility, accuracy, reliability and complexity and their use could result in an under sized or oversized CHP scheme that could lead to a complete failure of the project. Therefore, there is an urgent need of a robust and user-friendly model, which integrates multiple features that are missing in the currently available models.

This paper presents the development of a spreadsheet based CHP sizing model for a single or multiple university buildings. The major strengths of the model are its simplicity, flexibility of data entry, selection of multiple electrical and thermal demands, an in-built real database for a range of CHP sizes, multiple control strategies, multiple investment routes and their life cycle cash flow analysis, and the potential for detailed sensitivity analysis of payback period using the Monto Carlo Simulation technique. The model, which we call the London South Bank University (LSBU) CHP model, has been tested with three other CHP models for different control modes for the same building and the comparisons are discussed.

Keywords: Combined Heat and Power, CHP, CO₂ emissions, building energy modelling, university estate

29 1. Introduction

30 Depletion of fossil fuels and their associated environmental impacts have forced the modern world to
31 promote clean and efficient technologies [1]. Energy intensive sectors have set their carbon reduction
32 targets. The Higher Education Sector of United Kingdom plays a central role in contributing to the
33 national economic growth. In 2010, the four Higher Education Funding Councils (HEFC) for the United
34 Kingdom required all higher education institutions (HEI) to set a carbon reduction target from a 2005/6
35 baseline of 34% by 2020 for direct fuel (Scope 1) and electricity consumption (Scope 2) carbon emissions
36 [2]. Universities in the UK have developed Carbon Reduction Plans (CRP) that describe energy
37 efficiency measures and clean energy technologies. One such clean technology is Combined Heat and
38 Power (CHP). The UK's Higher Education (HE) sector offers strong potential for CHP technology. A
39 number of universities have installed CHP technology in the last decade and have successfully reduced
40 their carbon emissions. Towards the end of 2011, 49 out of 161 universities had installed CHP systems.
41 This number increased to 60 in 2014/15 showing universities increased confidence in this technology [3].
42 Owing to this increased number of CHP installations in the HE sector, energy generation from CHP
43 systems during 2014-15 increased by 50% compared to 2008-09. In 2014-15, CHP systems supplied 13%
44 of the total energy demand of the UK's HE university sector compared to 9.91% in 2010-11 [4].

45 CHP is the simultaneous generation of usable heat and power (usually electricity) in a single process with
46 an overall efficiency of typically up to 80% [5-6] as shown in Figure 1. Electricity is generated on or
47 close to the end user's site, allowing capturing and using the resulting waste heat for site applications [7].
48 On the other hand, centralised power generation plant in the UK has an average delivered efficiency of
49 only around 40% with modern combined cycle gas turbine stations achieve a delivered efficiency of about
50 45-50%. The remainder of energy in the fuel dissipates in the form of heat via power station's exhaust
51 gases, cooling towers and from the electricity transmission and distribution systems.

52 CHP schemes are assessed through the CHP Quality Assurance programme (CHPQA). The CHPQA
53 offers a Quality Index (QI) scale, which provides a means of assessing the quality of CHP Schemes. CHP
54 schemes having QI greater than 105 are eligible for benefits such as Climate Change Levy (CCL)
55 exemption [8].

56 The feasibility of a CHP for a single or multiple buildings depends on numerous technical and financial
57 factors. The most important aspect of CHP decision making is a modelling based technical, economic and
58 environmental evaluation [9]. This type of evaluation is performed using a computer-based CHP sizing
59 model. A model with limited features could result in an under sized or oversized CHP scheme that could
60 lead to a complete failure of the project.

61 Existing CHP models differ in structure, characteristics, input assumptions, and the level of detail they
62 include. It is therefore difficult to obtain similar results from different models for the same input data.

Hinojosa et al. [9] compared four different models that include the SEA/RENUE¹ model, CHP Sizer, Ready Reckoner and Energy Pro-3. They found a number of limitations in all four models. They particularly highlighted the need for data transparency and recommended that a custom-built spreadsheet is more flexible and transparent. The Northeast Combined Heat and Power Application Centre [10] investigated the potential for CHP for an industrial facility and a school by comparing results from four CHP models available in USA. They found large differences in the payback period for both facilities.

Nock et al. [11] compared different CHP models in the UK market and concluded that there is a clear potential for a model that adequately caters for various criteria for CHP. Williams et al. [12] developed a computer model to aid in the sizing of CHP plant for buildings with limited known information. This tool can only be used for a basic assessment and does not offer a detailed technical, economic and environmental analysis. Elkarim [13] developed an electricity led model for sizing a CHP for the Dublin City University based on minimum monthly (rather than hourly) electricity consumption.

Ren et al. [1] developed a mixed integer non-linear programming model for the optimal sizing of a CHP system for a proto-typical residential building in Japan. User input energy load profiles are required, and there is no option to test different operating strategies. Teymouri et al. [14] extended the model for the geography of Iran, but the main limitations are that it only considers a heat led strategy and can be used only for residential buildings.

Maidment and Tozer [15] developed a spreadsheet model for a supermarket, but it only considers full load CHP, and not a heat led or electrical led strategy. In addition, it does not offer a life cycle analysis of energy and carbon savings. Gvozdenac et al. [16] developed a spreadsheet model to assess the potential for CHP for the commercial sector in Thailand. This CHP model offers only a single operating strategy, (i.e. electricity and heat led) which mainly depends on the variation of the electricity and gas tariffs.

It is extremely important to understand the desired characteristics of a CHP sizing model for performing an evaluation. During site visits to universities and through attendance and discussion at the London Energy Managers Group [17] meetings, one of the authors (KA) identified that a CHP model is required specifically for the HE sector buildings comprising of the following features:

- a) simple, easy and reliable tool;
- b) Ability to assess multiple operating strategies (heat-led, electricity-led and heat- and electricity-led) and time periods (24 hour or 17 hour);
- c) ability to calculate an optimum size;

¹ SEA Renue is an independent social enterprise and environmental trust with the experience, expertise and commitment to create strategies and deliver solutions that measurably reduce carbon footprints, creating a sustainable and equitable future for all.

- d) Ability to generate hourly thermal and electricity load profiles for different building types based on monthly or annual consumption use data, or no use data (new building)
- e) Ability to model multiple buildings;
- f) Ability to enter different costs (electricity, fuel, Carbon Reduction commitment (CRC), Value added tax (VAT), incentives such as Feed-in tariff (FiT), and Renewable Obligation Certificate (ROC), renewable heat incentive (RHI) and electricity and heat export tariff rates);
- g) Ability to provide life cycle cash flows for capital investment, discount energy purchase and Energy Service Company (ESCO) contract options;
- h) Ability to undertake sensitivity analysis of payback period; and
- i) Option to display results in graphical form.

Keeping these aforementioned desired characteristics in mind, three currently, available CHP models in the UK market were reviewed. These three CHP models are.

- DECC CHP assessment tool [18]
- Engine Room [19]
- CHP Sizer [20]

Major features and limitations of these models are summarised below in Table 1.

The literature review and features comparison of currently available CHP models points to an urgent need for a user-friendly reliable CHP sizing model that evaluates CHP options. Such a tool needs to be easy to use, but with a full range of characteristics as discussed above. To fill this gap, a new CHP sizing model called the “London South Bank University (LSBU) CHP model” was developed which integrates all the desired features that are missing in the other available CHP models and are desired for a reliable and robust evaluation of CHP’s economic and environmental assessment. The details of LSBU CHP model are discussed in Section 2.

2. LSBU CHP model

This section describes the development of LSBU CHP model in detail. The development of the model is fully described in Amber (2010) [21]. It is a spreadsheet-based model developed in Microsoft Excel ®. The model comprises the following worksheets as shown in Fig. 2. The function of each worksheet is explained in detail below.

2.1 Database Sheet

The database sheet contains data for a wide range of different parameters including Higher Education Environmental Performance Improvement (HEEPI) energy performance benchmarks, bank holidays, monthly heating degree-days¹, half-hourly, daily and monthly benchmarks for electricity and fuel consumption for different types of HE campus buildings.

2.2 Data Input Sheet

The data input sheet has five sections and requires user to enter information about the building, plant room, switch room, fuel consumption and electricity consumption. It allows users to enter information about the building (e.g. building type, building area, building sensitivity, region, its charity status, CRC status). It also allows the user to enter information about the building's plant room and switch room and actual electricity and fuel consumption data (e.g., annual, monthly or half-hourly, whichever is available) and fuel prices.

2.2.1 Generation of hourly energy consumption profiles

Based on the data and information entered, the LSBU CHP model generates real or estimated hourly electricity, fuel and thermal demand profiles. If users enter no data, the CHP model estimates annual consumption based on HEEPI benchmarks for selected building type. It then converts this annual kWh figure into monthly figures using the Degree Day (DD) method and then further converts the monthly consumption figures into daily and then hourly consumption profiles based on the profile of a similar building type. Fig. 3 shows the process how the model develops hourly electricity or thermal profiles.

Data for two fuel meters may be entered and the model aggregates it to establish an hourly fuel profile. Fuel used for catering or in laboratories is deducted and the model develops hourly thermal demand profiles using Eq. (1).

$$T_h = F_h \times \eta_{boiler} \quad \text{Eq. (1)}$$

¹ Degree-day (DD) is a measurement designed to measure the demand for energy needed to heat a building. DD is derived from measurements of outside air temperature. The heating or cooling requirements for a given building at a specific location are considered directly proportional to the number of DD at that location.

144 *Where;*

145 T_h *is hourly thermal demand*

146 F_h *is hourly fuel consumption in kWh*

147 η_{boiler} *is boiler efficiency*

148 Users have the option to enter data for a maximum of four low voltage supplies, and can provide tariff
149 information. The model develops an aggregated electricity demand profile if multiple LV supplies are
150 connected to the same bus bar. Otherwise, the model only considers data for LV supply having highest
151 electricity consumption. The model then calculates CO₂ emissions for the final sets of both electricity and
152 fuel consumption data using the carbon factors from its database sheet.

153 **2.2.2 Calculations of different energy costs**

154 The model calculates energy cost and CRC cost for the final sets of both electricity and fuel consumption
155 data selected by the CHP model. Once the CHP model has established hourly electricity and thermal load
156 profiles, it calculates electricity consumption for the day and night period for each single day of the year.

157 Annual energy cost (C_{ENERGY}) includes all costs relevant to the purchased gas and electricity and is given
158 by Eq. 2

$$159 \quad C_{ENERGY} = C_E + C_F + C_{CCL} + C_{VAT} \quad \text{Eq. (2)}$$

160 *Where*

161 C_E *is the annual cost of annual electricity consumption*

162 C_F *is the annual cost of fuel purchased*

163 C_{CCL} *is the annual Climate Change Levy tax amount for electricity and fuel*

164 C_{VAT} *is the annual amount of value added tax paid on electricity and fuel*

165 All these costs are explained briefly one by one as below;

166 • **Annual electricity cost, C_E**

167 Annual electricity cost is the cost of grid electricity purchased and is calculated as follows:

$$168 \quad C_E = (E_{de} \times e_{de}) + (E_{ne} \times e_{ne}) \quad \text{Eq. (3)}$$

169 *Where;*

170 E_{de} & E_{ne} *are annual electricity consumption (kWh) during day and night periods*

171 e_{de} & e_{ne} *are electricity unit prices for day and night time electricity (in £/kWh)*

172 • **Annual fuel cost, C_F**

This is the cost against the annual gas purchased, which is consumed in boilers and CHP plant. It is calculated as follow in Eq. (4);

$$C_F = (F \times g) \quad \text{Eq. (4)}$$

Where;

F is annual fuel consumption (kWh)

g is fuel unit prices (in £/kWh)

- **Annual climate change levy charge tax for electricity and fuel, C_{CCL}**

The Climate Change Levy (CCL) is a tax on the use of energy in industry, commerce and the public sector. Buildings with charity status are exempted from CCL charges. The model reads the information entered by the user in Section-A of the data input sheet regarding the buildings charity status and makes appropriate calculations. The CCL tax on gas and electricity usage is calculated as shown in Eq. (5).

$$C_{CCL} = (E \times \gamma_e \times e_{ccl}) + (F \times \gamma_f \times f_{ccl}) \quad \text{Eq. (5)}$$

Where;

E is annual electricity consumption in kWh

F is annual fuel consumption (kWh)

γ_e is percentage of annual electricity consumption exempted from CCL tax

γ_f is percentage of annual fuel consumption exempted from CCL tax

e_{ccl} is the CCL rate for electricity (in £/kWh)

f_{ccl} is the CCL rate for fuel (in £/kWh)

- **Annual VAT tax charges for electricity and fuel, C_{VAT}**

This is the tax paid on the purchase of electricity and fuel. It is at a rate of 20%, or 5% for eligible institutions such as charities. The model calculates the VAT charges for electricity and fuel as shown in Eq. (6).

$$C_{VAT} = (C_E + C_{ccl}^e) \times x_{vat}^e + (C_F + C_{ccl}^f) \times x_{vat}^f \quad \text{Eq. (6)}$$

Where;

C_E is annual cost of electricity purchased (£)

C_F is annual cost of fuel purchased (£)

C_{ccl}^e is annual cost of CCL charges paid for electricity purchased (£)

202 C_{ccl}^f is annual cost of CCL charges paid for fuel purchased (£)

203 x_{vat}^e is the VAT rate for electricity (%)

204 x_{vat}^f is the VAT rate for fuel (%)

205

206 • **Annual CRC charges for electricity and fuel, C_{crc}**

207 These are the charges applied to each emitted tonne of CO₂ (t/CO₂) from electricity and fuel
208 consumption. These are calculated as shown in Eq. (7).

209
$$C_{CRC} = \left\{ (E \times y_{co2}^e) + (F \times y_{co2}^f) \right\} \times Z \quad \text{Eq. (7)}$$

210 Where;

211 E is annual electricity consumption in (kWh)

212 F is annual fuel consumption (kWh)

213 y_{co2}^e is carbon emission factor of grid electricity (tonnes of CO₂ /kWh)

214 y_{co2}^f is carbon emission factor of grid fuel (tonnes of CO₂ /kWh)

215 Z is the cost of one CRC allowance (£)

216 • **Baseline carbon dioxide emissions (tonnes of CO₂)**

217 The CHP model calculates the baseline carbon dioxide emissions by using Eq. (8).

218
$$CO2_{baseline} = \left\{ (E \times y_{co2}^e) + (F \times y_{co2}^f) \right\} \quad \text{Eq. (8)}$$

219 Where;

220 y_{co2}^e is carbon emission factor for grid electricity (tonnes of CO₂ /kWh)

221 y_{co2}^f is carbon emission factor for fuel (tonnes of CO₂ /kWh)

222 **2.3 Buildings Selection Sheet**

223 Users can select electrical and thermal connections to CHP for up to 30 buildings.

224 **2.4 CHP Sizing Sheet**

225 The CHP Sizing Sheet is used to test a range of CHP sizes and types. It offers scenarios such as exporting
226 excess electricity and heat and selecting either 17 or 24 hour running. The CHP model tests three different
227 control strategies as follows: (a) heat led with zero heat rejection and excess electricity; (b) electricity led
228 with excess heat generation and heat; and (c) electricity led with minimum heat rejection and no excess
229 electricity.

Fig. 4 shows the flow chart of electricity and heat led CHP control strategy with no excess heat and electricity generation.

Fig. 5 shows the flow chart of the heat led control strategy of the CHP.

Fig. 6 shows the flow chart of electricity led control strategy of CHP.

The model calls the relevant data from the database sheet for the selected CHP size (i.e. the CHP electrical output, thermal output, fuel input, Operating and maintenance (O&M) cost at 50%, 75% and 100% load, CHP's parasitic load, CHP cost, depreciation cost and replacement cost, values of power and thermal efficiency coefficients for the calculation of a quality index). The user can also enter the rate for the feed in tariff (FiT), ROC, RHI, export tariff for electricity and heat and penalty charges for excess heat rejection if any. The model then summarises the technical, financial and environmental results of three control strategies into a table allowing users to identify an optimum control strategy. Users then test different sizes of CHP until they have identified the optimum size and control strategy for their site.

2.5 CHP Cost Sheet

Users can enter different costs in the CHP Cost Sheet with VAT rates or they could request CHP model to estimate these costs for them. The model estimates different elements of capital costs as a percentage of CHP cost such as CHP cost, Infrastructure cost, Government fee, Project management cost and Project contingencies. The model reads the CHP size and type selected by the users in the "size your CHP" sheet and calls upon the corresponding costs from the database sheet. The Project level contingency should range from a minimum of 7%, for a project with very low risk, to 30% for a project with very high risk [22]. The model assumes project contingency of 7%.

2.6 Life Cycle Analysis (LCA) Sheet

Table 2 presents details of three financing options that have been integrated into LSBU CHP model and allow users to test different financing options for their CHP scheme.

2.7 Sensitivity Analysis Sheet

The CHP model investigates the effect on the payback period of the project of variation in electricity and fuel prices in a range from -10% to +40%. Fig. 7 shows the graphical output.

The CHP model uses Monte Carlo simulation to see how variation in a number of parameters such as fuel price, electricity price, FiT could affect the payback period of the optimum size selected. The data on the left hand side of Fig.8 are the minimum and maximum limits between which a parameter such fuel price could vary.

In the example given, the analysis suggests that the payback period is highly likely to be in the range of seven to nine years. The cumulative probability curve suggests that there is a 70% probability that the payback period will be less than 10 years.

The model runs 10,000 iterations based on randomly selected values of parameters within the range prescribed. (In the example given, from a reduction in price of 10% to an increase in price of 50%). It presents the results as a histogram and cumulative frequency plot of the payback period (as shown on the right side of Fig. 8). Statistical data including measures of central tendency spread and shape for the payback period probability distribution. Data is also produced on the correlation and the strength of the correlation between input parameters and the payback period, as shown in Figure 9.

This comprehensive sensitivity analysis should be extremely helpful in investment decision making. A future implication of this method is that it may be used to calculate an investment risk premium, for example, related to the standard deviation of the observed values of payback period. It is important to mention here that none of the existing models reviewed in this work have this feature.

2.8 CHP Results in graphical form

This sheet generates the following results for the optimum size of CHP in the form of graphical displays. A dashboard displays results parameters including the following:

- *Quality Index of CHP;*
- *Annual running hours of CHP;*
- *CO₂ savings (%);*
- *Excess heat generated by CHP (%);*
- *Increase in fuel consumption post CHP installation (%);*
- *Decrease in grid electricity demand post CHP installation (%);*
- *Payback period of CHP project; and*
- *Internal rate of return, (%).*

Fig. 10 shows a snapshot of the Results sheet.

The model generates the following graphs for the optimum size of CHP, i.e. for Pre and Post CHP installation.

- a) Fuel Consumption
- b) Thermal demand
- c) Electricity consumption
- d) CO₂ emissions saving

These are shown in Fig. 11, Fig.12, Fig. 13 and Fig. 14 respectively.

The CHP model also allows users to check the CHP operation on any selected day of the year. Users can select a date from a drop down list. The CHP model reads this date and calls upon the corresponding hourly thermal and electrical demand and CHP generation profiles on that selected day. Fig. 15 shows the CHP's daily operation.

2.9 Comparison of features of LSBU CHP model with different CHP models

297 Finally, a comparison of different desirable features of CHP models has been presented in Table 3. It is
298 apparent that the LSBU CHP model integrates all the desired features that are essential for a detailed
299 evaluation of CHP's economic and environmental feasibility.

3. Testing and comparison of results of CHP models

The LSBU CHP model was tested on Floyer House, Queen Mary University of London hall of residence, as shown in Fig.16. The results obtained from the CHP model have been compared with results obtained from CHP Sizer, Engine Room, and the DECC CHP tool for the same building.

The 151-room building, which is occupied throughout the year, was built in the 1960s and its gross internal (GIA) area is 4,691.71m². It is a naturally ventilated building with no cooling plant installed. Electricity to the building is supplied through a single low voltage supply, which is installed near the plant room in the basement. The plant room is located in the basement and comprises of 7x100kW gas fired space heating ‘Hamworthy’ boilers and two gas fired hot water heaters. All boilers is more than 15 years old. This building is a part of the CRC scheme. The tariff for electricity during both the day and the night is 9.75p/kWh. The gas tariff is 4p/kWh.

3.1 CHP sizing for Floyer House and comparison of CHP model results

Hourly electricity and thermal demand profiles of Floyer house are presented in Fig.17 and Fig.18 respectively.

Heat led, electricity led, and electricity and heat led control strategies were tested and the results were compared. Table 5 summarises the main information assumed for each of these approaches. Each model has a different number and variety of inputs, with the DECC CHP tool having the smallest requirement for data inputs and the LSBU CHP model have the most extensive requirement for data inputs. The principal the features and inputs for each model are summarised in Table 4.

After entering the demand profiles and other parameters, results for three different control strategies (i.e. heat led, electricity led and heat and electricity led) were obtained in all the applications. The results are discussed below and shown in Tables 5, 6 and 7.

3.1.1 Heat led control strategy

The DECC CHP tool does not allow users to select different operating strategies, but it is clear from the magnitude of the CHP selected and thermal demand of the building that the model assumes heat led control strategy. The results obtained from the DECC CHP tool are highly unrealistic as it finds a 500kWe CHP as an optimum size of CHP that is nearly four times bigger than the CHP size obtained from the Engine Room and LSBU CHP model. Because this CHP tool accepts only the monthly profile figures as input and does not show its assumptions, the results obtained from this tool are questionable. Table 5 presents the results for the heat led control strategy.

In terms of recommended CHP size, the results obtained by the Engine Room and the LSBU CHP models are similar (i.e. 90kWe). However in terms of running hours of CHP, net savings and CO₂ savings, the

Engine Room model shows lower values compared to our model. This may be because of the fact that Engine Room model only reads average hourly electricity and thermal values instead of considering a full year complete set of half-hourly values for electricity and thermal demands. In addition, the capital cost estimated by the Engine Room is lower than the figure, which was estimated by the LSBU CHP Model. This difference explains the lower figures in payback period, NPV and IRR. On the other hand, CHP Sizer finds 50kWe as the optimum CHP size and gives much lower values for NPV, IRR and CO₂ savings than Engine Room and the LSBU CHP Model. This was mainly because the CHP unit selected by the programme was of small size and this affected the calculations over the 15-year analysis period.

While comparing the Engine Room and the LSBU CHP model results, lower running-hours were obtained by the Engine Room model i.e. 6,715 compared to 8,635 running hours obtained by the LSBU CHP model. This mainly resulted because only monthly average values for electricity and thermal profiles were used in the Engine Room model. This highlights the importance of using complete sets of real half-hourly profiles for both electricity and thermal demands.

3.1.2 Electricity led control strategy

Table 6 presents the results for the electricity led control strategy. It can be seen that the DECC CHP tool does not allow this option, therefore it was not possible to estimate an electricity led control strategy in this software. In this case, CHP Sizer found 50kW CHP as the optimum size of CHP. This is mainly because CHP Sizer does not have a real CHP database and the next CHP in its listing is 100kW which is definitely too big a size when compared to the hourly electricity load profile. The capital cost estimated by the CHP Sizer i.e. £44k is out date as the current cost of a 50kWe CHP is £105,000. The Engine Room model also found 50kWe CHP as the optimum size of CHP compared to 70kWe CHP suggested by the LSBU CHP model. This difference is mainly because only monthly average values for electricity hourly profiles were used in the Engine Room model. Again, this highlights the importance of using complete sets of half-hourly profiles for both electricity and thermal demands. It can be seen that the LSBU CHP model is giving the highest values in terms of IRR and CO₂ savings. In this scenario, the units were operating at part load most of the time, and the models did not allow power export. The smaller unit size, using the average hourly profiles and the out-dated capital cost figures are still the main factors for the differences in results.

3.1.3 Electricity and heat led control strategy

Table 7 presents the results for the electricity and heat led control strategy. The DECC CHP tool and CHP Sizer do not offer this type of load strategy. Engine Room identifies a 50kWe CHP as an optimum size of CHP for this building whereas the LSBU CHP model identified a 70kWe as an optimum size. It can be seen that the LSBU CHP model is giving the highest values in terms of NPV, IRR and CO₂ savings. The smaller unit size and use of average hourly profiles in Engine Room are major factors for the differences in results.

3.2 Discussion on the comparison of CHP models

The detailed feasibility study of CHP applications involves many different variables, which makes it a complex process. Understanding the difficulty of the feasibility and modelling of the system is essential. A case study was undertaken for a radiator heated student residence hall and results from three different CHP models (i.e. DECC CHP tool, Engine Room and CHP Sizer 2) were compared with the results obtained from the LSBU CHP model.

The DECC CHP tool is a basic CHP sizing tool and is the least transparent application among all of the applications studied in this research. It does not offer any control strategies (i.e. heat led or electricity led). It does not allow half-hourly or hourly electricity and thermal profiles to be entered. It sizes the CHP based on monthly electricity and thermal data entered. It does not contain a real database of CHP units and therefore results from this tool must be validated against other CHP models available in the market before making any decision on investment.

CHP Sizer is a straightforward tool, only valid for four types of buildings, which allows undertaking feasibility studies in as few as five steps. It is intended to give only a first order indication of feasibility and offers two control strategies, i.e. heat led and electricity led. It does not contain a real database of CHP units and the costs estimated by this model are out-dated as of 2013. It does not take into account the CRC costs and Quality Index features. Further to the above, it does not allow testing a CHP for a multiple set of buildings.

The Engine Room model is relatively flexible, comprehensive and easy to use, but the user interface is still modest. The Engine Room model has a good potential to be expanded, and already includes several features of other models. Currently it does not allow entering hourly electricity and thermal profiles for a full year. Instead, it allows entering average hourly profiles for each month. Due to this factor, it may not identify the most suitable CHP size (as we have witnessed in Tables 7 and 8). Further to above, it does not allow testing a CHP for a multiple set of buildings.

The following is a summary list of important features that are not included in the CHP models (i.e. the CHP models studied in this research) and this includes;

- a) Not allowing a full year set of both half hourly or hourly electricity and thermal profiles to be entered
- b) Not allowing a full year set of both half hourly or hourly electricity and thermal profiles of multiple electricity and fuel meters to be entered
- c) Not allowing a full year set of both half hourly or hourly electricity and thermal profiles for multiple buildings to be entered
- d) Not incorporating a comprehensive cash flow over the life period of the proposed CHP system
- e) Not including a comprehensive sensitivity analysis, which is highly important for investment risk analysis.

The results of the comparison between different CHP models and the deficiencies discovered in these models help to further justify the development of the CHP model as part of this research.

To validate the CHP model's ability to undertake economic and environmental evaluation of the CHP system, a case study was undertaken for a radiator heated student residence hall. A similar set of input data was entered in the four models that include the DECC CHP tool, Engine Room, CHP Sizer 2 and the LSBU CHP model. Results were obtained for three different types of control strategies including heat led, electricity led and heat and electricity led.

For the heat led strategy, it was found that Engine Room and the LSBU CHP model identified a similar size of CHP as the optimum size, i.e. 90kW whereas CHP Sizer identified 50kWe as the optimum size for this control strategy. For the electricity led strategy, the LSBU CHP model identified 70kW as the optimum size of CHP whereas CHP Sizer and Engine Room identified 50kWe as the optimum size of CHP. For heat and electricity led strategies, the LSBU CHP model identified 70kWe as the optimum size of CHP whereas Engine Room identified 50kWe. CHP Sizer and DECC CHP tool were unable to provide results under this third type of control strategy.

The DECC CHP tool is the most basic type model among the four models compared and lacks in a variety of features. In addition to the above, it does not offer any of the three control strategies studied. Its results are very different from those of the other three models. Therefore, results from this CHP model are highly questionable.

CHP Sizer 2 is a good CHP model and offers basic features, which are required for the economic and environmental evaluation of a CHP system. However, it offers only two control strategies, i.e. a heat led and electricity led strategy. Further to this, it does not include CRC costs and Quality Index features. It also does not have a real database of CHP units, which makes its results questionable as most of the cost figures used by this application are out dated and need to be updated. The CHP Sizer cannot offer testing of CHP for a multiple set of buildings.

The Engine Room model is relatively flexible, comprehensive and easy to follow, but the user interface is still modest. The Engine Room model has a good potential to be expanded, and already includes several features of other models. Currently it does not allow hourly electricity and thermal profiles for a full year to be entered. Instead, it allows average hourly profiles for each month to be entered. Due to this, it may not identify the optimum size of CHP. Engine Room cannot be used for a multiple set of buildings.

LSBU model has a real database of different sizes and types of CHP plants and possesses some unique features that are missing from other models, such as its ability to consider multiple buildings for CHP evaluation. This model considers each cost that should be taken into account while undertaking a life cycle evaluation of CHP and thus makes the cost analysis more realistic and reliable. Its comprehensive sensitivity analysis of payback period is another distinguishing feature that enables the higher authorities

in making an appropriate investment decision. It is certainly a transparent tool in which user can modify different inputs as required.

4. Conclusions

Carbon reduction targets set by Higher Education Funding Councils (HEFCs) for the United Kingdom are the major drivers in the HE sector to improve its energy and carbon performance. Other drivers include government policies and rising energy costs. Combined Heat and Power (CHP) is a cost effective technology, which could help the HE sector of the United Kingdom to achieve its carbon reduction targets. The HE sector's energy intensive buildings such as medical, chemical and engineering laboratories and radiator heated student residence halls offer strong opportunity for CHP due to their high electricity and thermal demands.

To be successful, a CHP must be properly sized according to the building(s) electrical and thermal demands using a reliable CHP sizing model/tool. The desired characteristics of a CHP model were identified through discussion with Energy Managers and through attending meetings with the LUEG whereas a critical review of the limitations of existing models led to a specification for an improved CHP sizing model dedicated for the university sector. Therefore, a new CHP model was developed specifically for UK's university sector buildings. The developed CHP model (known as LSBU CHP model) offers a variety of options for developing real or estimated half-hourly thermal and electrical demand profiles. A unique feature of the CHP model is that it allows users to model CHP for multiple buildings. It provides a life cycle analysis (LCA) of cumulative cash flow for three different types of financing options and provides important financial parameters such as payback period, net present value (NPV) and internal rate of return (IRR) thus making it easier for users to identify a feasible investment route. Further, by using the Monte Carlo simulation technique, it provides a detailed sensitivity analysis for the payback period of the project and helps in identifying the more significant financial parameters affecting the project's economics. The chain of algorithms developed to predict hourly electricity and thermal profiles from annual, monthly or daily or from the complete absence of data is another unique feature of this model.

The CHP potential for a test building was analysed using four different CHP models, i.e. the LSBU model and three publicly available models, and the results were compared for three different types of control strategies. A direct comparison was difficult as publicly available models were using out of date cost data and only offered limited modelling features. In addition to this, it was not possible to compare certain features such as mixed control strategy, multiple buildings scenarios and financial sensitivity analysis as these features were missing from the publicly available models. The results obtained from four models clearly showed that the LSBU model offers most reliable results.

Overall, this study has made good use of various data sources that have become available electronically in recent years. In this sense, the LSBU CHP model is very much a product of the present information age and has used data that would have been difficult, if not impossible, to collate even a few years ago. The

energy managers of the UK universities can use this model to evaluate CHP's technical, economic and environmental feasibility for their campus building (s).

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Acronyms

BMS	Building Management System
CCL	Climate Change Levy
CHP	Combined Heat and Power
CHPA	Combined Heat and Power Association
CHPQA	Combined Heat and Power Quality Assurance
CIBSE	Chartered Institute of Building Services Engineers
CRC	Carbon Reduction Commitment
DECC	Department of Energy and Climate Change
DEP	Discount Energy Purchase
ESCO	Energy Services Company
FiT	Feed in Tariff
HDD	Heating Degree Day
HE	Higher Education
HEEPI	Higher Education Environmental Performance Improvement
HEFC	Higher Education Funding Council
HELP	Hourly Electricity Consumption Profile

501	HESA	Higher Education Statistics Agency
502	HH	Half Hourly
503	HMRC	HM Revenue and Customs
504	IRR	Internal Rate of Return
505	kW	Kilowatts
506	kWh	Kilo Watts Hour
507	LCA	Life Cycle Analysis
508	LSBU	London South Bank University
509	NPV	Net Present Value
510	O & M	Operations and Maintenance
511	QI	Quality Index
512	QMUL	Queen Mary University of London
513	RHI	Renewable Heat Incentive
514	ROC	Renewable Obligation Certificate
515	UK	United Kingdom
516	USCHPA	United States Clean Heat and Power Association
517	WACC	Weighted Average Cost of Capital