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Life Cycle Cost and Carbon Appraisal for a Prefabricated Residential Development in London

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ABSTRACT: This paper provides an overview of the opportunities for renewable energy generation and low-carbon solutions in a prefabricated residential development (which includes some commercial space) in London. Its objective is to identify the optimum design of mechanical and electrical (M&E) plant and energy solution configurations. As well as technical appraisals and assessments of compliance with planning policies, a broad comparison of the capital cost and life cycle cost (LCC) of different options is carried out. To assess the costs, specifically the energy costs, and the carbon implications of various design scenarios, this study has reviewed the capital costs as well as the operational costs (cost in use) of applying various renewable and low carbon energy technologies to different primary heating strategies, over a 30-year life cycle. This is the same period included within the operational model. Accordingly, scenarios involving the use of electricity, gas and air source heat pumps (ASHPs) were examined and compared. The results suggest that ASHPs have the lowest energy and carbon emissions but high LCC, while the gas plant option has the lowest capital and maintenance costs.

KEYWORDS: Energy, Life Cycle Cost, Low Carbon Technologies

1. INTRODUCTION

1.1. Background

Energy use in buildings – to provide a comfortable and healthy indoor environment for occupants – currently accounts for over 40% of the total primary energy consumption in the US and EU, and is causing substantial CO_2 emissions [1,2]. In the UK, direct greenhouse gas (GHG) emissions from buildings were 88 $MtCO_{2e}$ in 2018, accounting for 22% of total UK GHG emissions [3]. The Climate Change Act commits the UK government, by law, to develop policies on the path to a 100% reduction in GHG emissions, compared to the 1990 levels, by 2050 [4].

Although energy for space heating and cooling within buildings is the most significant contributor to UK emissions, the overall demand for space heating is falling as a result of increasing fabric efficiency. Despite a growing number of households in the UK, the overall heat energy consumption for non-domestic buildings had fallen by 18% in 2015 compared with 1990 levels [5]. However, gas is still the primary source of heating, with around 85% of UK households and 65% of non-domestic buildings using natural gas for heating [6]. This is incompatible with the UK's long-term decarbonisation plan, and it is necessary to implement other low-carbon heating options by the 2030s to meet the net-zero emissions target by 2050 [7].

The dominant housing type in several countries, including the UK, is stand-alone, single-family dwellings. The average floor-area of stand-alone dwellings has been increasing faster than the average floor-area of flats (or apartments) in England. Considering the form factor, and that in England over a third of new dwellings are stand-alone houses, increasing insulation to meet building regulation requirements will not be enough to reach the UK zero-carbon target. Therefore, considering clean and green sources of energy is essential [8,9].

With various forms of heat generation technology available, as well as heat delivery and energy efficiency options, there is much incentive for the installation and use of green and clean technologies within the UK building stock. However, most building developers still see investment in energy efficiency as a risk rather than a productive realignment, mainly due to cost uncertainty and lack of expertise [10].

In the UK, the government's report *Construction 2025 – Industrial Strategy* [11], launched in July 2013, set a number of challenging carbon and cost objectives, such as:

- 33% reduction in the initial costs of construction and the whole-life costs of built assets
- 50% reduction in GHG emissions in the built environment.

A review of UK construction labour models suggested that promoting the concept of 'factory sharing' and building offsite could accelerate the pace at which the UK's construction carbon and cost targets could be met, and also solve the 'lack of expertise' issue [12].

1.2. Aims and objectives

This paper provides an analysis of the opportunities for low carbon solutions and renewable energy generation in a mid-rise residential development (which includes some communal spaces), in London. The assessment was carried out to assist an offsite construction developer in making an informed decision on the optimum design of mechanical and electrical (M&E) plant and energy solution configurations to meet the government cost and carbon reduction targets. As well as technical appraisals and conformance with planning policies, this decision will also be based on the broader consideration of capital and life cycle costs (LCC). The analysis had the following objectives:

- to identify the solutions which are most likely to result in the lowest cost energy bills for the occupants in prefabricated residential developments
- to understand the capital costs of achieving the lowest energy costs for occupants
- to help in achieving the financial, sustainability and operational benefits derived from following the principles of industry best practice life cycle analysis (LCA) throughout the design development.

2. METHODOLOGY

To assess the costs, specifically, the energy costs and the carbon implications of various design scenarios, the capital costs as well as the operational costs (cost in use) of applying various renewable and low carbon energy technologies to different primary heating strategies were examined for a 30-year life cycle period. Eight scenarios were examined and compared. The full list of all the explored scenarios is outlined in Table 1. The key considerations for selecting or discounting various options were technical applicability and policy and planning requirements, as well as capital costs and LCC. All scenarios were compliant with the prevailing Part L UK thermal building regulations.

2.1. Selection of the options

The primary plant, listed in Table 1, is the incoming gas and electricity supplies that the building management (BM) purchases directly from the grid to provide energy for space heating, hot water and electricity in the apartments and communal spaces. The selection of an air source heat pump (ASHP) and the supplementary plant options was based on the developer's budget and the amount of risk they were willing to take. ASHP, combined heat and power plant (CHP) and solar technologies were considered by the developer to be low risk, and, compared to other options, such as, for example, hydrogen boilers or ground source heat pump (GSHP), are commonly used in residential buildings.

Table 1: The selected Part L compliant scenarios which have been reviewed as part of the energy and LCC appraisal.

Primary Heating Plants		Supplementary Plant Installation
Scenario 1	Central Gas Boiler	SHW
Scenario 2		Communal PV
Scenario 3		CHP + communal PV
Scenario 4	Electric Heating and Hot Water	SHW
Scenario 5		Communal PV
Scenario 6	Central Air to Water Heat Pump (ASHP)	No Supplementary plant
Scenario 7		SHW
Scenario 8		Communal PV

Primary heating plants:

1. A central gas boiler for providing heating and hot water to the apartments and communal spaces was assessed as the baseline model. As mentioned before, gas is still the main source of heating and, therefore, it is important to compare it with other options. A set of 3 x 300kW (available manufacturer size) high-efficiency gas-fired boilers were assumed to provide a total heat and hot water capacity of 743kW. The proposed boilers would be served by the incoming gas supply.
2. Central electric hot water generation (a central electric immersion hot water cylinder) and local electric heating within apartments (2kW – 3kW electric panel heaters installed within each apartment) were assessed. This solution required an improvement in the building fabric, glazing and air tightness to achieve building regulations approval. Currently, the CO_2 intensity of electricity (0.2556 $kgCO_{2e}$) is significantly higher than that of gas (0.1838 $kgCO_{2e}$), but green renewable power supply has reduced the CO_2 intensity of electricity significantly over recent years [13].
3. A central ASHP was assessed. As well as the UK government's plan to fund and implement more ASHP installations, this system would benefit from providing cooling in the future under future climate change conditions, thereby reducing the risk of overheating [3,14]. This option involved proposed heat pumps with a total heat and hot water capacity of 743kW, assumed to be located on the roof of the building, to serve the underfloor heating and domestic hot water services within the apartments and communal spaces.

Supplementary plant installation:

1. Solar thermal hot water (SHW) collectors were assessed. Based on the current concept design 200kW appeared to be a reasonable allowance for SHW panels.
2. Solar photovoltaic (PV) panels to serve landlord supplies directly were assessed. A configuration of 384 panels to provide 96kWp was considered by the project's M&E engineers.
3. PV panels to serve residential areas were assessed. Each apartment would be provided with a dedicated solar PV panel (77 panels in total) rated up to 260W.
4. A CHP was assessed. A 50kWth CHP plant was assumed to be installed within the communal plant room to provide a proportion of the total building heating and domestic hot water load. This option assumed that electricity would be generated simultaneously and delivered into the communal areas' low voltage distribution network.

It is noteworthy to mention that all the recommended technologies currently benefit from the UK government's Renewable Heat Incentive (RHI) and Feed-in-Tariff (FIT). However, as the rates are changing and FIT scheme was closed to new applicants from 1 April 2019, these are not considered in this LCC assessment [14].

2.2. Case study

The calculations in this report were based on the generic drawings (Fig. 1) provided by the development's architect. The generic scheme consists of 77 residential units and approximately 2308m^2 of flexible communal floor areas. In order to (i) develop the optimum baseline energy strategy, (ii) establish where the main energy uses are and (iii) minimise the energy demand, an assessment of a typical two-bedroom, 85 m^2 floor area, top-floor apartment was undertaken. The selected apartment is highlighted in Figure 1. This is typically the worst-case apartment, based on the high percentage of exposed thermal elements (i.e. roof and walls on two sides).

The proposed construction measures, applied to the residential building for the selected scenarios, are presented in Table 2. The values represent a cross-laminated timber (CLT) offsite construction method applied to the new development to meet UK building regulations for new residential buildings [15]. As can be seen in Table 2, the electric scenarios required fabric and glazing improvement to meet the UK building regulations minimum requirements.

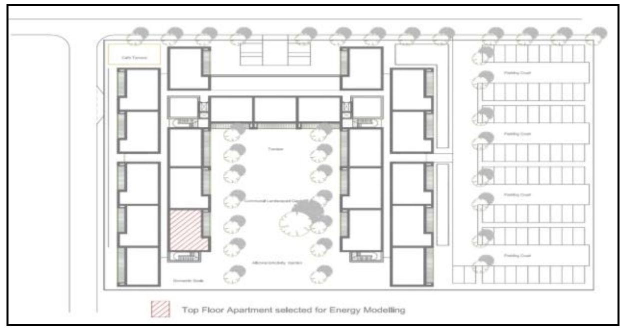

Figure 1: General drawing and selected apartment for the energy analysis.

Table 2: Comparison between the fabric thermal properties (U values) for different scenarios.

Proposed Fabric	Gas Boiler and ASHP Scenarios U values	Electric Heating Scenarios U values
External Wall	0.15 W/m^{2}K	0.15 W/m^{2}K
Party Walls	0.18 W/m^{2}K	0.18 W/m^{2}K
Roof	0.13 W/m^{2}K	0.11 W/m^{2}K
Ground Floor	0.13 W/m^{2}K	0.13 W/m^{2}K
Windows	1.00 W/m^{2}K	0.85 W/m^{2}K

British Standard BS 8544:2013 guidance has been used to carry out LCC assessment (construction, operation, maintenance and replacement costs) of the development [16]. To estimate annual energy costs, energy consumption generated from the Standard Assessment Procedure (SAP-2012) [17] was used for the apartments and the dynamic thermal analysis simulation software *DesignBuilder* was used for the communal areas.

3. RESULTS AND DISCUSSION

In respect of building operation and life cycle replacement, consideration was given to use, maintainability, replacement frequencies and sustainability of building components. Also, possible changes to reduce costs, or to improve sustainability or ease of operational efficiency were identified. The following elements were considered under the 30-year LCC analysis:

- capital costs
- utility costs
- maintenance costs
- replacement costs.

3.1. Capital costs of M&E plants and energy solutions

The construction costs of M&E plant and energy solutions for this research were provided by the project's quantity surveyor. The capital costs presented include component costs and a budget allowance for boiler rooms, including all plant, boiler-room pipework, insulation and valves, ancillary equipment, flue and controls. These allowances are based on high-level, Stage 1 cost-planning data [18], and the costs have not been broken down in detail.

3.2. Apartment energy costs

The energy costs borne by each apartment would include:

- energy costs for energy consumed in the apartment
- communal area energy costs proportioned across 77 apartments.

Therefore, the total costs of heat to the apartment plus the contribution to the communal area energy costs is defined by:

$$\text{Apartment's consumption} + \frac{\text{Communal areas} - \text{Commercial space}}{77}$$

3.2.1. Apartment consumption

This is the cost of energy use for space heating, hot water and electricity within the apartment. Where heat consumption in the apartment is mentioned in this paper, it covers both space heating and hot water consumption. 'Regulated energy consumption' refers to space heating, hot water and electricity for lighting, ventilation, fan and pumps.

The use and management of each apartment by the occupants would ultimately determine the actual consumption experienced by each occupant. However, the calculation methodology includes a standard provision for the occupiers' use of small power devices and typical household electrical appliances. This is known as 'unregulated energy' and is common for all the scenarios.

It has also been assumed that each apartment would be metered directly:

- for electricity by the electricity supplier at the standard single rate of £0.15 p/kWh, and
- for heating and hot water through the heat interface unit smart meter by the BM at the standard single rate of £0.04 p/kWh.

3.2.2. Proportional communal energy costs

This is the cost each apartment would pay to cover the energy costs (heating, hot water and electricity) within the communal spaces (excluding commercial spaces). This cost would cover the losses in the heating distribution and savings from renewable energy technologies.

3.2.3. Apartment energy costs summary

The scenarios have been assessed in terms of their ability to deliver the lowest cost energy to the occupants of the apartment.

In order to simplify the comparison of the solutions, the results showing one apartment's energy expenditures are set out (see Figures 2 and 3). The minus costs in red represent the additional PV electricity generation which would be utilised in commercial areas. The costs are presented from cumulative lowest to highest energy costs. The unregulated energy would be constant for every scenario.

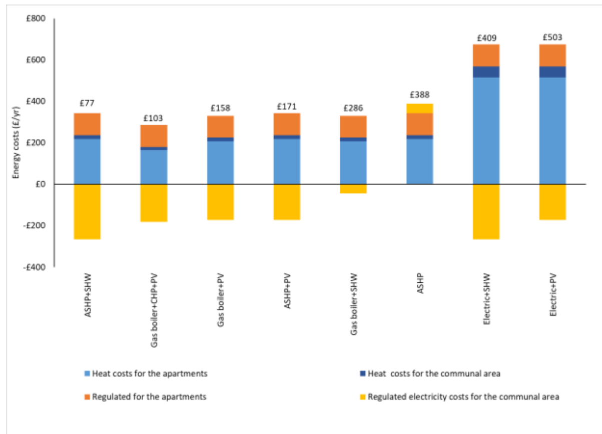

Figure 2: Apartment energy costs including heat and regulated electricity only

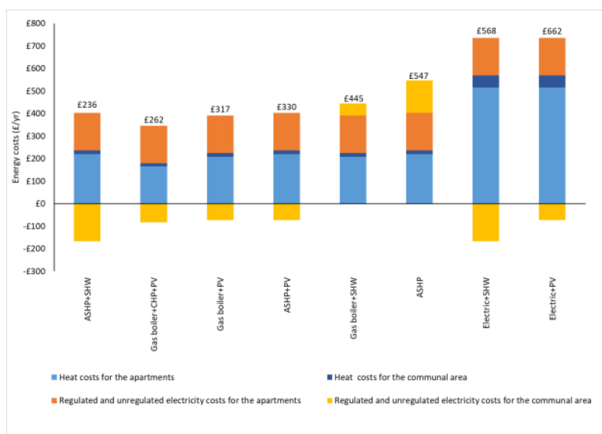

Figure 3: Apartment energy cost including heat, regulated and unregulated electricity

3.3. CO_2 emissions

The annual carbon dioxide emissions for the entire building were established, based on the primary energy use within the building (apartments and communal spaces) and the corresponding carbon dioxide emission factors for the various energy strategy scenarios. Figure 4 presents a comparison of the annual carbon dioxide emissions based on the regulated energy use.

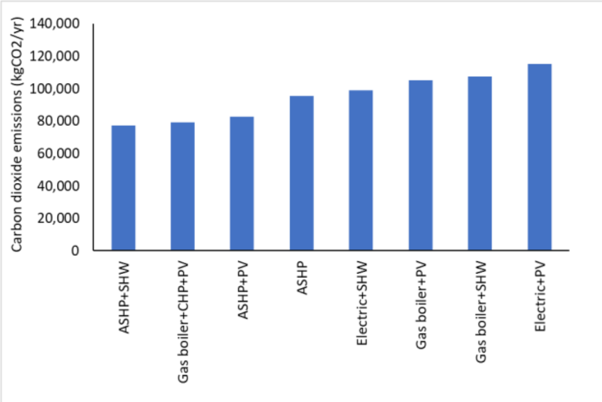

Figure 4: Annual CO_2 emissions based on regulated energy for the entire development (residential and communal areas).

3.4. Maintenance costs

For the majority of the M&E services installations, a similar level of inspection and maintenance regimes would be required. However, different renewable technologies and low carbon options have varying maintenance requirements. Information on the maintenance requirements was obtained from Royal Institute of Chartered Surveyors (RICS) *New Rules of Measurement* (NRM) 3 [19] and Chartered Institution of Building Services Engineers (CIBSE) *Guide M* [20]. The maintenance costs included in this analysis and obtained from various manufacturers are:

- statutory and operational costs suggested by the manufacturers and CIBSE *Guide M* and NRM 3
- replacement of minor components advised by the manufacturers
- cleaning.

It should be mentioned that the repair costs that may be required over the assumed 30-year analysis period have not been included for any of the systems.

3.5. Replacement costs

Replacement costs are estimated using the net present value (NPV) of the original capital cost estimate, based on the industry-standard approach. A discount rate of 3.5% has been applied for the NPV estimates.

The service life expectancies are estimated using the published data such as CIBSE, Building Cost Information Services (BCIS) and manufacturers' product and warranty data. However, these assumptions are sensitive to practical operational considerations, in particular the use and location of the facility, occupancy patterns and varying intensity. Some of the components' life expectancies are presented in Table 3.

Table 3: Life expectancy of M&E components

Components	Life expectancies
Boiler	20
CHP	20
SHW	20
PV	20
Electric Heating/Radiators	20
Underfloor Heating	20
ASHP	15
MVHR Units	15
pumps	10

3.6. Life cycle costs summary

A comparison of the elemental capital and LCC for different options over a 30-year period, based on NPV, is summarised in Figure 5.

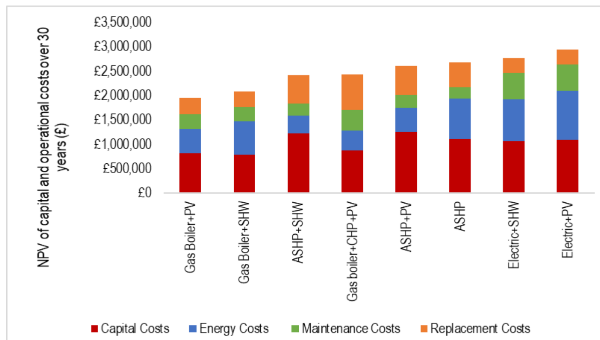

Figure 5: Net present value of net capital and life cycle costs over 30 years for the entire development.

The LCC summary combines the totals of the capital costs, energy costs, maintenance costs and replacement costs.

The 30-year analysis is set to reflect the same period included within the operational model. These costs are shown with the exclusion of government incentives (i.e. RHI & FIT) as these change every year.

4. SUMMARY AND CONCLUSION

This paper's approach was to take a realistic view of a building's operation and life cycle replacement, taking account of use, maintainability, replacement frequencies, and sustainability of M&E components. It aimed to identify possible changes to reduce in-use costs or to improve sustainability or increase operational efficiency.

Accordingly, the LCC and operational carbon emissions of eight scenarios were evaluated. As presented in Figure 4, Scenario 2 (gas boilers with PV technologies) has the lowest LCC and a relatively low energy cost. This strategy is simple to operate and has a reasonably long-life expectancy (resulting in lower LCC). However, ASHP and SHW scenario has the lowest energy costs. The ASHP solutions (Scenarios 6, 7 and 8) have higher capital and replacement costs. However, they have the lowest carbon emissions. At present, the simplest of all solutions, electric heating, requires a higher investment in the building fabric. However, the SAP2012, which was used for the analysis, uses the outdated high CO_2 intensity factor and maybe exaggerating the heat demand, which results in higher predicted energy costs. A high-quality building fabric (which the CLT process enables) may make electrical heating viable in the future, and the electric heating options would be worth investigating as part of an offsite construction and CLT test programme.

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