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Energy performance analysis and assessment of retrofit renewable energy technology for a university building

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Abstract. The climate change phenomenon is an ever-growing emergency driven by the emission of harmful anthropogenic gases from fossil fuel consumption. Its potential consequences, such as extreme weather and irreversible environmental impacts, have made it a focal point for political acts, targets, and regulations on a national and global scale. The operation of commercial buildings, in addition to the generation of the energy to which they consume, are identified as some of the highest contributing areas to these emissions. For university buildings, it is imperative that energy consumption is understood and addressed in order to protect the environment, reduce operational costs, meet government grant allocations, and continue to offer educational services to their students. This paper conducts an energy performance analysis of the Henry Cotton Building, part of Liverpool John Moores University. The current energy consumption data is investigated using the techniques of energy benchmarking, Cumulative Sum of Differences and fabric assessment. The results indicated that both electricity and gas consumption sit within average recommended levels for similar buildings and could both be improved towards 'good' industry practice. Predicted consumptions were found to be similar to actual, highlighting no significant performance issues and indicating no improvement. The fabric conditions were found to deviate significantly from modern industry standards. The study concludes with a review of potential renewable energy technology alternatives, to improve energy sustainability in the building by generation substitution. The analytic hierarchy process was utilised to compare the various solutions against each other and multiple criteria that impact successful implementation. The results identified solar as the most viable (score 78.5), followed by wind (score 66), geothermal (score 60) and biomass (score 50.5).

Keywords: Buildings, energy performance, sustainability, Analytic Hierarchy Process, renewable energy

1. Introduction

1.1 General background

Climate change is a growing global emergency with the potential for significant detrimental impacts across the triple bottom line of sustainability. Change is accelerating irreversible environmental degradation, amplifying extreme weather risk, causing economic disruption and eliminating sources of food and safe water. The proven cause of this phenomenon's acceleration is a proportional increase to the levels of atmospheric greenhouse gas (GHGs) accumulation, emitted from the consumption of fossil fuels.

Globally, the in-use operational stage of buildings accounts for approximately 27% of these anthropogenic gas emissions, and 30% of total energy consumption (Delmastro, 2022). The use of non-renewable fossil fuels produces a dominant 84% of this energy supply, generating 75% of GHGs (Ritchie et al, 2022). This global trend correlates with that of the UK, where the interrelating sectors of energy supply (from non-renewable sources) and consumption for non-domestic purposes are two of the highest emitting sectors (Shepheard, 2020).

Emphasised by new government acts, targets, and legislations, in alignment with United Nations Sustainable Development Goals, there is global priority for change. In June 2019 the UK parliament passed legislation to target emissions reduced by 100% from 1990 levels, resulting in a net zero balance with atmospheric removal. Provisional figures for 2021 state a 47.3% total reduction, however, this is not on track to meet the target (O'Sullivan, 2022).

The significant contribution of the non-domestic buildings sector presents an opportunity for improvement towards more sustainable developments. For educational buildings, reducing energy consumption rates and resultant emissions, in addition to preserving the natural environment, can present an economical opportunity of reduced lifetime operational costs and eligibility for government grant allocations (Altan, 2014). In addition higher educational buildings have high energy demands which could be due to variable behavioral change and occupant education on smart building systems

(Backlund et al, 2023)

1.2 Assessment purpose

The purpose of this study is to undertake an energy performance analysis of the case study building from the collected performance data for electricity and gas consumption. This process is carried out using three analysis techniques: energy benchmarking, Cumulative Sum of Differences (CUSUM), and a fabric assessment.

Following the analysis, potential renewable energy technologies are identified and reviewed in regard to viability for implementation in order to improve sustainable performance in the aim of net-zero achievement. This process utilises an adapted Analytic Hierarchy Process (AHP), in assessing options in relation to key selection criteria.

1.3 Case study overview

Figure 1: Henry Cotton Building (HCB) aerial photograph (Digimap, 2022 – adapter by the authors)

The Henry Cotton Building (HCB) is a 1989 non-domestic property and part of the Liverpool John Moors University (LJMU) city campus, located on Webster Street, Liverpool. The structure comprises of four floors, with rooms dedicated to lecture theatres, research laboratories, IT computing suites, study rooms and staff offices and is bordered to the southern perimeter by adjacent multi-storey buildings. There is no surrounding available land in the vicinity, or locally to any other campus buildings. The key building details identified from site walkover and desktop studies are summarised in Table 1.

Table 1: Summary of HCB elements and details

Building element/ system	*Summary of details*
General	Four floors (including ground) $7743m^2$ useable floor space Internal finishes show damage & wear/tear in high traffic areas such as corridors
Walls	External walls masonry brick / blockwork - No thermal wall insulation Internal blockwork or plasterboard partitioning
Windows	Mixture of old-style double glazing and single glazing Some cannot be opened
Roof	External slate tiled roof, pitched to all sides – no insulation, some visible damage and overgrown vegetation. Internal suspended ceiling tiles - typically plasterboard on a metal frame, with gap to structural ceiling for wiring, services, lighting, acoustic installation
Floor	Concrete slab to ground floor labs (structural materials & hydraulic labs) Vinyl flooring to corridors & restroom facilities Standard carpet tiles for classrooms & offices
Heating	Gas fired boiler - main heating fuel natural gas, with 83% efficiency Intermittent operation in winter – typical design comfort temp of 18 degrees with internal radiators
Ventilation	Electricity - mixed-mode mechanical cooling ventilation Natural in classrooms, mechanical assisted in labs
Lighting	Occupancy sensor and manual lighting system

2. Energy performance analysis

2.1 Existing energy consumption

The HCB currently consumes natural gas for heating and electricity for ventilation and operational power supply requirements, with no renewable energy technology implemented. Consumption data was obtained from the 2021/22 and 2020/21 periods, for electricity and gas respectively, as was most current 'complete' sets.

The building Display Energy Certificate (DEC) states a current performance of 64C, a rating indicating average performance that meets the proposed 'Minimum Energy Performance of Buildings' parliamentary bill, but leaves opportunities for improvement.

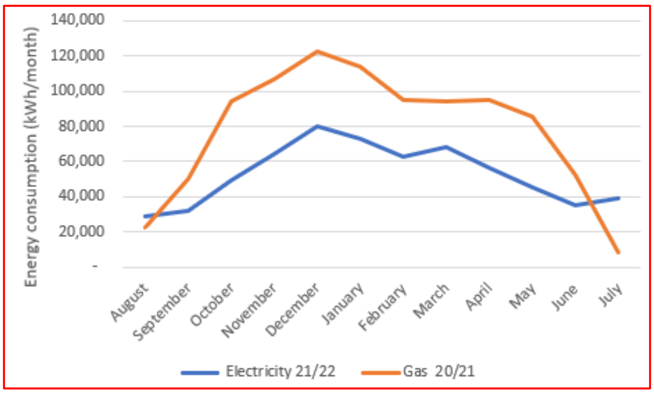

Figure 2: HCB energy performance data

2.2 Energy benchmarking

The energy benchmarking technique reviews the performance data against that of similar functioning buildings, as detailed in the Chartered Institution of Building Services Engineers (CIBSE) guide F (Altan,2014). Performance is rated as 'good' or 'typical' practice.

A potential drawback of this methodology is its simplicity, categorising a building as an overall type and using this as basis for comparison without considering multiple room functions with significantly varied average consumptions.

Therefore, the HCB was considered as a composite building type relative to internal floor area of functions. Information was gathered on room functions from the floor plan drawings and site walkover survey. The functions were logically interpreted where elaboration was required and grouped into primary function categories. These categories were further simplified into functional types that aligned with existing CIBSE benchmarks performance values within guidance document F.

The type simplification required additional assumptions, and each was considered to ensure the composite value remained representative of overall building usage and more accurate than singular classification. The 'general space' and 'facilities' categories were grouped into the 'office' benchmark, as it was interpreted that office buildings contain these areas and therefore the reference values account for this. 'Computer rooms' were allocated under the 'laboratory' benchmark as consumption is assumed to be similarly high.

Table 2: HCB room functions initial categorisation

Grouped categories	*Included room functions*
Computer rooms	IT suite, Tech support
Facilities	Kitchen, Showers, WC
General space	Corridor & undefined, Electrical switch room, File server room, Gas meter room, Lobby, Plant room, Post room, Stairway & lift, Store
Laboratory	Concrete wet area, Environmental science lab, Geotechnics lab, Hydraulics lab, Lab (general), Materials science lab, Medical lab, Pavement research lab, PCB research lab, RF&M research lab, Structures lab, Workshop
Lecture rooms	Lecture theatre & room, Practice suite
Library	Post graduate research
Office rooms	Counselling suite, Meeting room, Quiet room, Staff room & office

Table 3: HCB function categorisation into CIBSE types

Building type reference (CIBSE)	*Included grouped categories*
Lecture room, arts	Lecture rooms
Library, naturally ventilated	Library
Office, naturally ventilated, open plan	Office rooms, General space, Facilities
Science Laboratory	Laboratory, Computer rooms

The proportional area for each reference CIBSE building type was estimated utilising the plan drawing information. As total internal area was defined the DEC, remaining floor area was assigned to the 'general space' category.

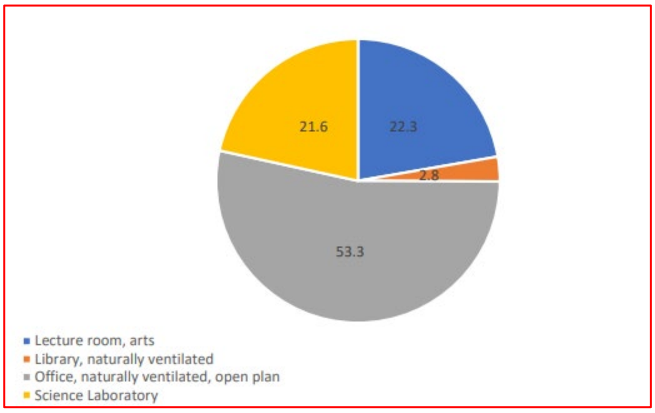

Figure 3: HCB relative proportion of floor space occupied by functions of CIBSE building types

Table 4: Building type reference benchmarks

Building type reference (CIBSE)	*Standard benchmarks (kWh/m²/year)*			
	Electricity		*Gas*	
	Good practice	*Typical practice*	*Good practice*	*Typical practice*
Lecture room, arts	67	76	100	120
Library, naturally ventilated	46	64	115	161
Office, naturally ventilated, open plan	54	85	79	151
Science	155	175	110	132

Laboratory				

Table 5: HCB energy performance and composite benchmarks

Fuel type	*Annual consumption per unit area (kWh/m²/year)*	*HCB composite benchmarks, kWh/m²/year*	
		Good	*Typical*
Electricity	84.55	78	102
Gas	121.50	91	140

The building performs within the upper and lower benchmarks for both fuels. Comparatively, electrical consumption is more efficient, consuming approximately 11% more than the 'good' benchmark, with gas 33% greater. It could therefore be inferred that total consumption is acceptable, however, there is potential for improvement to achieve 'good' performance and reach affordable offsetting ranges.

2.3 CUSUM

CUSUM assesses heating or cooling energy consumption relative to predicted values based on climate temperatures. The results illustrate variance in values, aiding in the identification of inefficiencies. From the site walkover, gas has been identified as the heating energy source and electricity as cooling.

Heating requirement is based on degree days, measurements of the variance between locational air temperature and a standard baseline. For this study, a base of 15.5ºC was utilised as recommended in CIBSE TM46:2008. The HCB is located in UK region 7 of 18, West Pennines. Data was obtained for Crosby, with approximate coordinates: 53.30 North, 3.06 West, the closest available set in the Business Energy Efficiency (BizEE) software tool.

Cooling CUSUM was not assessed during this study as the electricity consumption data obtained was not limited to cooling only, resulting in an inability to plot trending relationships with degree days.

Figure 4 illustrated a relatively strong positive correlation with a strong data fit, defining a relationship between higher degree days and higher energy usage. This is as expected, with greater consumption occurring at greater variance between inside and outside temperature. At 0-degree days gas is still consumed, which could be resultant of other building functions such as water heating.

Overall, the CUSUM highlight periods of over- and under-estimated values but a very similar total cumulative energy usage over the year. A downwards overall trend would be much more preferential, describing building efficiency improvements resultant of reduced energy usage and enabling new baseline performance targets to be defined. Heating energy consumption is therefore identified as a potential area for improvement.

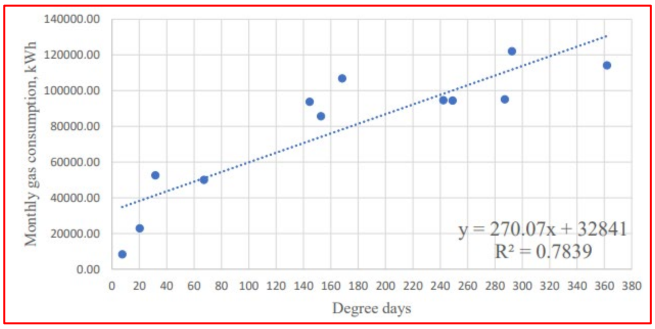

Figure 4: HCB monthly gas consumption vs heating degree days (2020/21 period)

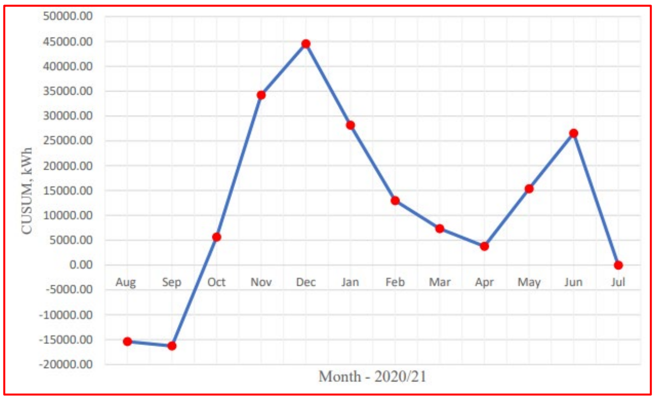

Figure 5: HCB gas consumption CUSUM (2020/21 period)

2.4 Fabric assessment

Fabric U-value thermal properties define its ability to resist the passage of heat. Higher U-values indicates greater heat losses and result in poor energy performance by increased consumption to account for this wastage and maintain comfortable internal temperatures for occupants (Najjar,2019).

For the fabric assessment, the major elements of walls, roof, windows, and floor were considered. Existing U-values for the HCB were obtained from CIBSE guide A, typical entry examples with descriptions that matched the fabric details as observed from site investigation and the building drawings. These values are reviewed against the design threshold and improved performance recommended targets as defined within building regulations L2B.

Comparatively, the assessment highlights a discrepancy between current and target fabric heat retention properties. This variance is representative of significant industry changes to best practice given the new prioritization of sustainability and climate change. Fabric is therefore identified as an area that could be improved for the benefit of reducing energy consumption.

Table 6: HCB fabric existing and target U-values

Building element	***Material details***	***CIBSE Guide A***		***Building Regulations L2B***		
		Existing fabric U-Value (W/m^{2}K)	*Ref.*	*Threshold U-value (W/m^{2}K)*	*Improved U-value (W/m^{2}K)*	*Ref.*
Wall	External walls masonry brick / blockwork - no insulation	2.09	Table 3.48, 3 a)	0.7	0.3	Table 5
Roof	Slate tiled roof, pitched to all sides – no insulation	2.5	Table 3.49, 3 a)	0.35	0.16	Table 5
Floor (1)	Concrete slab with vinyl floor	3.59	Table 3.52, 1 a)	0.7	0.25	Table 5
Floor (2)	Concrete slab with carpet	2.35	Table 3.52, 1 b)	0.7	0.25	Table 5
Window	Single glazing	5.75	Table 3.23	1.6	-	Table 3

3. Technology system proposal

3.1 Overview of improvement approach

The previous evaluation identifies that energy consumption currently sits within adequate performance ranges, however, there is room for further improvements to attain a more environmentally sustainable building, with potential economic benefits to the university. Developments that reduce current carbon emissions can assist in bringing volumes down to a range that enables an affordable net-zero offsetting scheme.

The Institute of Environmental Management and Assessment (IEMA, 2020) GHG management hierarchy details partial substitution of consumption, through renewable generation, as the third-best approach to reduction. This is arguably the most appropriate for an existing building case-study such as this, whereby there is inability to significantly ‘reduce’ consumption by removing the use of plant and equipment (which are required for its educational services). To ‘eliminate’ emissions is also unachievable in retrofit, but improvements to current operations are regarded as a significantly preferential environmental strategy in comparison to new-build replacements.

Potential renewable energy technologies are therefore reviewed for implementation in this study. The selection and justification of the most viable best solution is complex given the multitude of parameters that impact success. To aid in the identification, the multi-criteria decision-making approach of AHP is applied.

3.2 Analytic Hierarchy Process methodology

The Analytic Hierarchy Process (AHP) technique critically appraises options in relation to a matrix of weighted criteria and parameters in order to quantify solution suitability (Hopkins, 2001). The outcome is a quantitative total ranking of options from most to least viable. The outline process of delivering this methodology is as follows:

- Define the assessment criteria and sub-criteria
- Establish criteria weights and scoring definition
- Identify the technologies being assessed
- Investigate literature and obtain all relevant information against the criteria
- Establish performance scores for technologies against criteria
- Calculate total score rankings

The overarching criteria are based on the key triple bottom line of sustainability principles. The sub-criteria were identified and adapted as appropriate to fit the purpose and scale of the HCB development. These were obtained from energy-based studies by Budak et al (2019), Haddad et al (2017), Heo et al (2010) and Shmelev and Bergh (2016).

Table 7: Overarching criteria and sub-criteria

Overarching criteria	*Sub-criteria*
Economic (A)	A.1 Capital cost (CAPEX)
	A.2 Operation and maintenance (O&M)
	A.3 Levelised cost of electricity (LCOE)
Technology (B)	B.1 Technology readiness level (TRL)
	B.2 Production capacity
	B.3 Service life
Environmental (C)	C.1 Lifecycle carbon emissions
	C.2 Area impact (noise, visual pollution, land usage, wildlife)
Geography (D)	D.1 Locational potential
Security (E)	E.1 Vulnerability to incidents or catastrophic consequence

Table 8: Performance score definitions

Overarching criteria	*Score*	
	0	*10*
Economic (A)	Very expensive	Economic (A)
Technology (B)	Low-capacity potential	Technology (B)
Environmental (C)	Not suitable	Environmental (C)
Geography (D)	Low potential in location	Geography (D)
Security (E)	Very vulnerable to incident	Security (E)

Weighting of criteria enables alignment with study and stakeholder priorities. Given the purpose of this study, the achievement of greater economic and environmental performance were assumed to be overarching targets, however, the prioritisation of the other criteria was unknown. Wang et al. (2009) review of multi-criteria methodologies reported that equal weighted criteria can produce near results to weighted, with the advantage of minimal priority knowledge. Budak et al (2019) alternatively utilised questionnaires to obtain rankings which resulted in significant variance of 16% between most and least priority. To avoid significant assumption, or limit the scoring accuracy, this methodology combined approaches. Increased weightings based on Budak (2019) and Heo (2010) are assigned to the priorities criteria, with remaining distributed evenly.

Table 9: Criteria weighting

Overarching criteria	*Weight (%)*
Economic (A)	25
Technology (B)	15
Environmental (C)	30
Geography (D)	15
Security (E)	15

3.3 Evaluation of technologies

The renewable energy technology options investigated were based on those considered in Budak et al's (2019) study and investigated in the ARUP (2009) 'Renewable Energy Capacity Study' for the Liverpool region. Consideration was made to the case-study scenarios requirement of on-site renewable generation, that could be feasible in a singular building retrofit. Options such as hydroelectric and tidal energy are omitted due to requirement of significant infrastructure, land, and costs, assumed unfeasible for adoption by the university.

This study utilised secondary data collection through extensive literature review to define the performance scores of the renewable energy technology alternatives against each criteria, guided by the established sub-criteria. Where possible, information was obtained from peer reviewed journals to improve confidence in the accuracy of reported information. Papers were selected that offered information across all of the considered technologies to maintain consistency of information. Additionally, quantitative data was utilised for relevant criteria to enable direct comparison and relative scoring.

Table 10: Renewable energy alternatives

Renewable energy alternative	*Example implemented technology*
Solar	Rooftop photovoltaic panels
Wind	On-site wind turbines
Geothermal	Ground source heat pump
Biomass	Biomass fueled boiler

The performance scores against all criteria are recorded in table 11. The rankings identify solar as having the highest total, suggesting it is the most viable option for implementation in the HCB. An overview of key information obtained in the study in relation to each criteria is as follows:

3.3.1 Economic

Economic quantitative data for all technology options was obtained from the 2022 iteration of the National Renewable Energy Laboratory (NREL) electricity annual technology baseline. The assessed economic sub-criteria are defined as follows:

- CAPEX - plant requirements, electrical infrastructure, construction, owner costs, permitting, site costs.
- O&M– labour fees, taxes, scheduled &unscheduled maintenance, consumables, and replacements.
- LCOE for 30-year period – measure of current net cost of generation, evaluated over its installation lifetime.

Wind scored as the highest performing, with the lowest CAPEX of 1359.60 $/kW, similarly to 1523.11 $/kW for Solar, and the significantly lowest LCOE of 25.22 $/MWh. Solar was valued at second, with the significantly lowest O&M of 17.22 $/kW.yr.

Geothermal and biomass had similar high CAPEX costs of 6521.46 $/kW and 4360.20 $/kW respectively, significantly greater than the other alternatives. Biomass also had the greatest O&M and LCOE values, suggesting that it was

Table 11: Total performance scores

Renewable Energy Alternative		*Solar*		*Wind*		*Geothermal*		*Biomass*	
Evaluation Criteria	*Criteria Weight %*	*Score*	*Weighted Score*	*Score*	*Weighted Score*	*Score*	*Weighted Score*	*Score*	*Weighted Score*
Economic	25	8	20	9	22.5	6	15	4	10
Technology	15	7	10.5	5	7.5	6	9	5	7.5
Environmental	30	7	21	6	18	6	18	3	9
Geography	15	7	10.5	6	9	3	4.5	7	10.5
Security	15	9	13.5	8	12	6	9	7	10.5
Total score	100		75.5		69		55.5		47.5
Ranking		**1**		**2**		**3**		**4**	

unviable economically for implementation.

3.3.2 Technology

Technology performance was defined in the study by a combination of TRL, production capacity and service life. TRL is an established methodology for measuring technological maturity quantitatively, with higher values indicating a readiness for implementation and proof of success. Information was obtained from Raffaini and Manfredi (2022) who defined TRL values as:

- TRL 1 - Basic principles observed
- TRL 5 – Technology validated in relevant environment
- TRL 9 – Actual system proven in its operational environment

.

Production capacity was obtained from the NREL electricity annual baseline (2022) ‘capacity factor’ values, the ratio of output to that of theoretical maximum. Service life, defined as the median number of years to which the technology provides useful output, is secure and operable, was also obtained from NREL published information.

Solar obtained the highest overall score in this parameter, with the highest TRL of 7-9, shared with wind, and the highest potential service life of 25-40 years. The remaining options shared a service life average of around 20 years.

Geothermal was ranked second due to its high-capacity potential, however, it shares a low TRL with biomass that limits confidence in its ability to produce energy as expected.

3.3.3 Environmental

The environmental parameter was assessed by quantitative carbon emission values, and qualitative information about local area impacts by its on-site installation.

Information for lifecycle carbon emissions across all stages was obtained from the 2014 Intergovernmental Panel on Climate Change (IPCC) data. The United Nations Economic Commission for Europe (UNECE) produced a more recent data set in 2020, but as this did not cover all the considered technologies of this study it was omitted. The results for technologies shared across the two data sets were identified as being very similar, such as 11 and $12 gC0_2e/kWh$ for wind, reinforcing the suitability of the 2014 set utilised.

Biomass was ranked as very poor performing despite operational benefits of no minimal noise and no visual impacts resultant of its potential for confinement internally to the building. The emissions data showed as significant ($230 gC0_2e/kWh$), and consequences to wildlife habitats, biodiversity, land usage and air pollution are unfavorable (Rahman et al, 2022, Sayed et al, 2021).

Wind was found to have the lowest emissions of $11 gC0_2e/kWh$, however, it has potential local impacts to the building aesthetics, noise and visual pollution, land consumption and local wildlife welfare (Rahman et al, 2022, May et al, 2020). Solar scored highest, sharing similar emissions to geothermal of $41 gC0_2e/kW$,but, with notably minimal local impacts. The theorised impacts on birds by these installations were found to have no direct evidence in Taylor’s (2013) study.

3.3.4 Geography

Renewable energy utilises natural sources which are subject to variable intensity at geographical location, which ultimately limits maximum achievable power output. Information for performance potential of the technologies was obtained from the Renewable Energy Capacity Study for the Liverpool City Region, conducted by ARUP in 2009. This report was assumed to be relevant given no significant changes to the locational geography relative to that of global change have occurred.

Solar and biomass scored the highest, both with median-high potential for microgeneration at individual buildings and anticipated to contribute to future renewable production in Liverpool. Similarly high scores were obtained for wind resultant of its slightly lower identified potential. Geothermal was identified as the least viable geographically, with the report highlighting very low potential and queried feasibility in the developed urban environment.

3.3.5 Security

Sarma and Zabaniotou (2021) noted the importance of resilience in renewable energy systems, a key requirement to prevent potentially hazardous resultant impacts. This factor interrelates to the socio-economic considerations of reliability in supply and safety in operation.

Security data was obtained from Budak et al’s (2019) assessment, which scored different renewables from the feedback of 38 topical experts. From this data set, solar was ranked as very resilient with a 9-10 rating, with similarly high score attained by wind of 8-9. Biomass had a more varied security scoring across experts of between 6-9, with geothermal receiving moderate ratings of 6-7.

3.4 Discussion of implementation and limitations

This work offers critical analysis of Energy and thermal performance of HCB and integration of sustainable technologies. Evidence of justification based on the use of CUSUM, fabric efficiency and renewable energy benchmarking is done by employing the AHP method. Consideration of AHP indicated that solar energy is the preferred option when compared to other renewable sources of wind, geothermal and biomass. The solar PV technology implementation has potential to have significant economic and environmental sustainability benefits to HCB, reducing carbon emissions and creating financial savings.

Solar energy is typically harvested with photovoltaic (PV) panel technology that converts irradiance to a usable electrical output. Studies by Ifaei (2020), Charles (2019) and

Fan and Xia (2017) all verified that successful implementation is achievable in retrofitting applications.

In terms of viability, there is no spatial capacity around the external perimeter or adjacent areas of the HCB, however, the large exposed rooftop area has potential for installation. Greater area enables larger installations and thus more power generation, with proportional increases to emission reductions. In alignment with BREEAM 'land use and value', this approach utilises commercial land more efficiently, without socio-economic consequences of consuming additional land that has alternative sustainable potential, such as socially for residential property.

To implement, short-term capital investment for enabling works is required. It was identified in the site walkover that the condition of the roof needs improvement by removal of excessive vegetation and repair of elements. In addition, the roof will need structural loading assessment, and safe access for maintenance in operation, as is essential to maximise performance (Fan and Xia,2017). In alignment with the previous assessment, investment into the roof structure presents an additional opportunity for fabric improvement which could result in larger benefits to energy performance.

A notable disadvantage of solar is its low capacity. Actual power is limited by weather, shading, dust, maintenance, intermittency, and locational irradiance, with no production outside of sun hours. These impacting factors must be considered to maximise efficiency, potential output and sustainable benefit.

Fan and Xia (2017) studied maintenance, noting that 6-year period is optimal for retrofitting scenario. This enables repairs, reducing periods of performance reduction and outage, and cleaning to remove dust, limiting dynamic shading reductions. Static shading additionally restricts the maximum irradiance received. In rooftop installations obstructions are minimised by fixing height, however, the HCB has accommodation flats to the south-east that would still impact effective area. By inspection, the significant roof area of the structure would still enable an installation of beneficial size within 90 degrees of south for optimal yearly exposure.

4. Conclusion and next steps

This study has conducted an energy performance analysis of the case-study Henry Cotton Building using three analysis techniques of compound energy benchmarking, CUSUM and fabric assessment. The information has been used to understand performance issues and where improvements can be made for more sustainable energy consumption.

The paper has employed the AHP methodology to assess potential renewable energy solutions that could be installed in the case-study building to reduce emissions through energy substitution. By utilising peer assessed journals and verified database information a detailed review has been conducted on these options relative to key criteria that defined successful implementation to present the most viable option.

The results present solar energy as having the highest cumulative score and is therefore considered the most viable technology for implementation, with wind identified as the next best option. Geothermal and biomass attained significantly lower scores and are regarded as unsuitable for this case.

To achieve complete carbon neutrality, the implementation of any renewable energy alternative at an in-situ retrofit scale will result in sufficient performance increases independently. This technology will only achieve reduced emissions equivalent to the volume of energy consumption to which its generation substitutes. The university must look at achieving further reductions towards economically viable offsetting levels through investigating additional improvements such as the following:

- Fabric improvements – poor thermal performance was identified in the building analysis. An opportunity to improve the roof fabric could be combined with solar installations, however, additional improvements could be made such as the inclusion of mineral wool quilt insulation between ceiling and joists, additional render or EPS installation on walls and replacement of windows.
- Water technology – the site investigation identified that no current consumption improvement strategy is in place. Improving conservation can aid energy efficiency through reductions to electricity consuming plant operations. One potential solution to be investigated is the use of water catchment systems, to utilise natural rainwater for non-treatment required purposes, such as WCs and appliance
- Low carbon supply – the intermittency of renewable energy and its natural source reliance results in limited generation potential that misaligns with total demands. Installation of low carbon energy supply alternatives could be investigated such as air-source heat pumps (ASHP). These technologies can enable non-renewable but dependable energy at reduced emission contributions.
- Occupant education – changes to behaviours such as heating settings, control of lights and use of water can alter energy consumption. This could be improved passively through education, signage and housekeeping policy.

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