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Inclusion of on-site renewables in design-stage building life cycle assessments

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Abstract

This paper investigates the inclusion of renewables in building life cycle assessments. On-site renewable electricity generation is increasingly common in the built environment, but existing guidance for the inclusion of these renewable systems in design-stage life cycle assessment is limited. The life cycle assessment of a building with 42.8 kW_{peak} solar photovoltaic array is used as a case study to investigate the effect of different assumptions on the assessment outcome. The case study results are then used to suggest good practice. The paper also highlights where further research is required to provide reliable design-stage assessments in future.

Keywords: renewable; solar; energy; design; life cycle analysis

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1. Introduction

1.1. Background

The built environment is a significant contributor to global carbon emissions. In Europe, it is responsible for 42% of final energy consumption and 35% of the greenhouse gas emissions (GHGs) [1]. The built environment accounts for an even greater proportion of emissions in the developing world, where construction is booming. The motivation for reducing carbon emissions is both clear and urgent; anthropogenic carbon emissions are the primary cause of global climate change, which is the greatest threat to both human life and economic prosperity of this century.

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Policy and design to reduce carbon emissions associated with the built environment has historically focused on the reduction of carbon emissions resulting from operational use [2]. However, in many cases, embodied carbon impacts are also significant, particularly in relation to the built environment [3]. Embodied carbon refers to the GHG emissions associated with the other stages of a product's life cycle, including (but not limited to): resource extraction, manufacture, transport, construction, maintenance and disposal [4].

1.2. Life cycle assessment

Life cycle assessment attempts to consider the total impacts attributable to a product, considering the combined effects of both operational and embodied impacts. Many of the measures proposed to reduce a building's operational GHG emissions result in an increase in embodied emissions [2]. Therefore, reporting practices which consider only the operational impacts of these actions may result in an overestimate of their effectiveness. Consequently, life cycle assessments are a useful tool to ensure a holistic view of environmental impacts.

As well as a tool for reporting and documenting the impacts of buildings after their construction, there is growing interest in the use of preliminary life cycle assessments as a design tool [5,6,7]. Carbon emissions and other sustainability indicators are increasingly desirable as design criteria, and life cycle assessments offer an opportunity to consider these criteria in a quantitative manner. The ability to compare different building options using simple, fast, and reliable life cycle analyses would allow for the calculation of an environmental cost estimate to be produced alongside estimates of financial cost.

However, aspects of the existing guidelines for building life cycle assessments can pose challenges at the design stages due to uncertainties regarding how the construction and operation of the building will be conducted. In order to use life cycle assessment as a practical tool during these stages, it must be possible without knowledge of details which are only decided later in the design process. The method should also provide an answer which is not orders of magnitude different from the results of an assessment conducted once these details are included. An understanding of the assumptions to which the assessment has the greatest sensitivity is invaluable in determining where guidance should be focused [8].

1.3. On-site Renewables

On-site renewable generation is one approach to reducing the operational environmental impacts of a building, and small-scale photovoltaic arrays and wind turbines are an increasingly common feature in the built environment. Indeed, the European Union (EU) requires member states to implement legislation which mandates the usage of on-site renewables as part of its initiative for "nearly Zero Energy Buildings" [9], and similar initiatives are in place around the world to encourage wider usage of decentralised, low carbon electricity generation. However, usage of these technologies implies an increase in embodied carbon emissions which will partially offset the intended reductions in operational emissions. These policies therefore rest on assumptions that on-site renewables are always an effective measure for achieving carbon emission reductions. The strength of this received wisdom can lead designers to make choices without proper consideration of their true impacts, potentially resulting in higher than expected carbon emissions [2].

This paper will firstly explain the existing guidance for accounting for on-site renewables in life cycle assessments. A case study life cycle assessment will then be conducted of an office building in Cambridge, UK, which has 42.8 kW_{peak} of solar photovoltaics installed; Greenwich House. Discussion of the results of this case study will then be used to inform recommendations on how the assessment of these systems should be approached in future.

2. Existing guidance for the life cycle assessment of buildings

The EU has issued formalised guidance for the assessment of environmental performance of buildings in the form of a suite of European Standards, CEN TC350, the English version implementation of which is BS EN 15978 [10]. As the case study falls under this guidance, and this standard is used across Europe, this paper is primarily framed with reference to the method set out in this EU standard. However, this paper should remain applicable to life cycle assessments conducted using similar alternative methods. BS EN 15978 defines a modular approach for the life cycle assessment of buildings, which is illustrated in Fig. 1. For the majority of these stages on-site renewable electricity generation plant is functionally no different from any other building component. However, renewables have unique impacts on stage B6, "operational energy use", and module D, "Benefits and loads beyond the system boundary".

Under this standard, on-site electricity generation is first assumed to satisfy building-related energy demands and then demands which are "not building-related" [10], although inclusion of the latter in the assessment is optional. It defines these loads as; "plug-in appliances, e.g. computers, washing machines, refrigerators, audio, TV and production or process-related energy in the use of the building". Electricity used on-site reduces the emissions associated with stage B6, i.e. operational energy use, whereas electricity exported to the grid is accounted for separately in module D. The results of module D are reported separately to the rest of the assessment, and so exported electricity cannot be used to directly offset emissions associated with operational energy use.

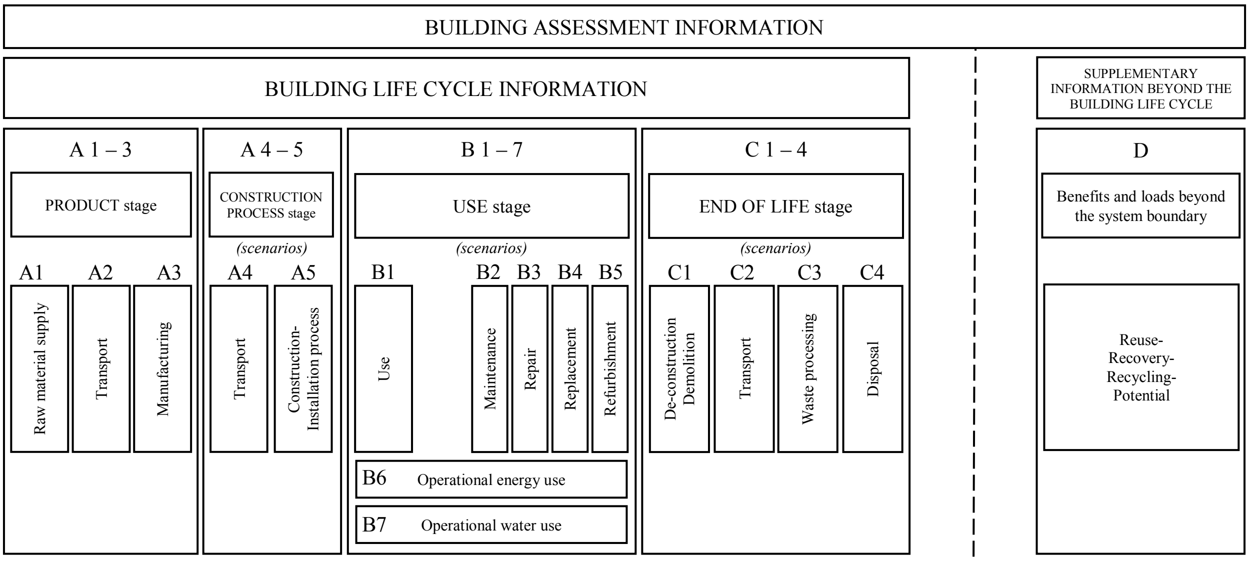

Fig. 1. Modular approach to building life cycle assessment outlined in BS EN 15978 [10].

3. Case Study: PV installation

3.1. Outline

Greenwich House, an administrative building belonging to the University of Cambridge, is host to a 42.8 kW_{peak} solar photovoltaic (PV) array. The electricity generated by the array has been logged at half-hourly intervals since April 2016, with occasional interruptions. The array provides approximately one sixth of the electricity required by the building and associated appliances, and no electricity is exported to the grid.

The inclusion of renewables in building life cycle assessment will be investigated through consideration of the existing PV array at Greenwich House, and through comparison with two theoretical arrays double and five times the size of the existing installation respectively. These scenarios are summarised in Table 1.

Table 1. Outline of installed renewable scenarios

Scenario	PV rating (kW_{peak})	PV area (m^2)	Annual Generation *(kWh)*	% of Annual Consumption
No on-site renewables	0.0	0	0	0.0
Existing solar photovoltaics	42.8	250	40,600	16.8
Double existing solar photovoltaics	85.6	500	81,200	33.7
Largest plausible solar photovoltaic array	214.0	1,250	203,000	84.2

An array double the size of the existing array is estimated to generate one third of the electricity required by the building over the course of a year, whereas the larger array would theoretically supply the majority of the building's electricity requirements. The practicalities of installing arrays of this size on site have not been considered, and it has been assumed that data from the existing installation can be scaled linearly to estimate the characteristics of these proposed arrays. Due to local transmission constraints, it is not permitted for the site to export electricity back to the grid in practice. However, this will be disregarded for the purposes of analysis of the theoretical arrays, as the aim of this study is to highlight the practical challenges of applying the existing methods for conducting life cycle assessments, rather than to provide a design proposal for this particular site.

3.2. Building electricity demand and on-site electricity generation

A report produced in December 2016 as part of the University of Cambridge Living Laboratory for Sustainability [11] indicated that the existing PV array at Greenwich House was on track to achieve an annual generation in line with the expected 40,600 kWh, and more recently available data supports this. The building's annual electricity consumption is ~241,000 kWh. Consumption is generally stable with little seasonal variation, except during the Christmas/New Year holiday period in late December, where it is significantly decreased due to lower building usage. The consumption profile correlates well with the generation profile of the PV modules, thereby facilitating greater on-site electricity usage than would otherwise be the case. An outline of the typical daily profile of electricity consumption and on-site renewable generation in a given month, obtained by half-hourly metering, can be found in Figure 2.

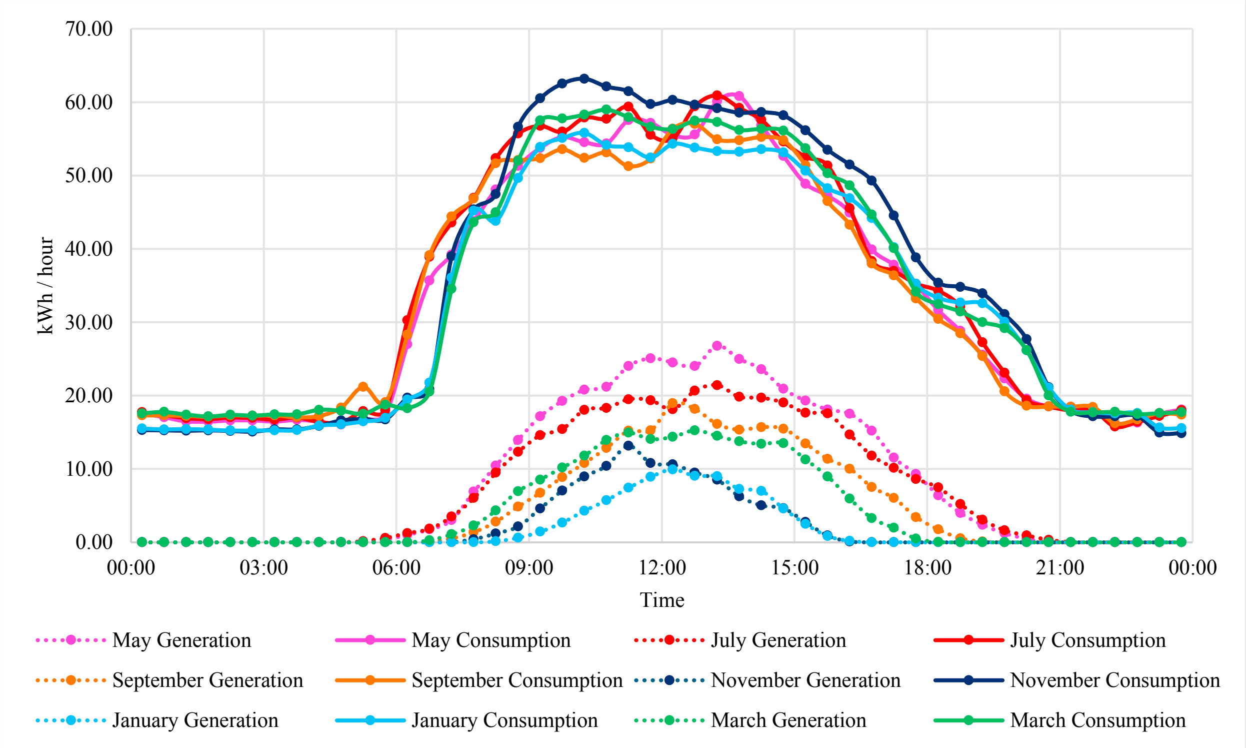

Fig. 2. Profiles of daily electricity consumption and on-site generation at Greenwich House

Table 2 summarises the proportion of electricity exported to the grid under each scenario. Figures 3 and 4 display the daily profiles of electricity imported from and exported to the grid. These averaged profiles conceal the fluctuations due to user behavior and variations in renewable generation, resulting in electricity being exported to the grid even when a time-averaged view indicates that electricity is usually imported.

Table 2. On-site electricity generation, consumption and export to grid

Scenario	Annual Generation *(kWh)*	% exported	On-site renewable consumption *(kWh)*	Exported *(kWh)*	Imported *(kWh)*
No on-site renewables	0	0.0	0.0	0.0	241,000
Existing solar photovoltaics	40,600	0.0	40,600	0.0	200,400
Double existing solar photovoltaics	81,200	9.3	73,700	7,500	167,300
Largest plausible solar photovoltaic array	203,000	37.3	127,300	75,700	113,700

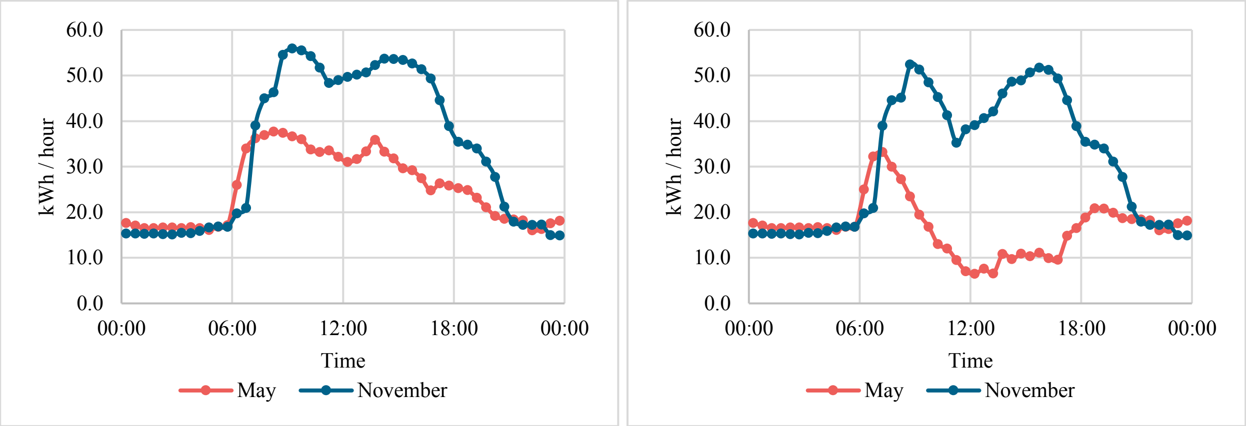

Fig. 3. (a) Profile of daily electricity import at Greenwich House. (b) Expected profile of daily electricity import if solar array capacity were doubled.

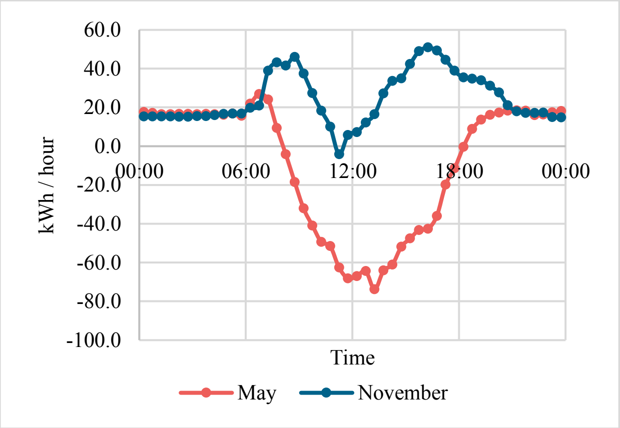

Fig. 4. Expected profile of daily electricity import if solar array capacity were quintupled.

3.3. Life cycle assessment of poly-crystalline solar photovoltaics

The solar PV installation at Greenwich House is made up of 173 Hanwha QCells 280W Polycrystalline Modules and 2 ABB TRIO-20.0/27.6-TL-OUTD string inverters. Environmental Product Declarations (EPDs) were not available for these products, and so it was necessary to review literature regarding PV arrays in order to establish the approximate embodied carbon costs of this array. Table 3 displays the calculated carbon emissions per kW of rated capacity of domestic-scale poly-crystalline PV arrays investigated by other authors. A figure of 2,000 $kgCO_2e/kW_{peak}$ is used for this case study as a mid-range estimate based upon the data considered, but this figure could be as low as 1,000 $kgCO_2e/kW_{peak}$, or as high as 5,000 $kgCO_2e/kW_{peak}$ in practice.

Table 3. Review of embodied emissions of domestic poly-crystalline solar photovoltaics

Author	Embodied emissions *($kgCO_2e/kW_{peak}$)*	Notes
De Wild-Scholten, 2014 [12]	1,536	Cradle-to-gate
Laleman, 2011 [13]	1,670	Assumed to be cradle-to-gate.
Raugei, 2007 [14]	1,730	Cradle-to-gate. (Calculated from cell efficiencies, solar irradiation, lifetime, gCO2/kWh.)
Alsema, 2006 [15]	1,224	Cradle-to-gate. (Calculated from Annual Generation, lifetime & gCO2/kWh.)
Battisti, 2005 [16]	4,727	Cradle-to-grave. Electronic-grade silicon.
Hondo, 2005 [17]	2,107	Input-output analysis. Solar-grade silicon. (Calculated from load factor, lifetime, gCO2/kWh, and solar irradiation data for Tokyo.)
Hondo, 2005 [17]	1,732	As Above. Assumes scaling up of PV production.
Tripanagnostopoules, 2005 [18]	2,740	Cradle-to-grave.

3.4. Assumptions regarding end of life

Due to the youth of the mass market for solar PVs, consumer behavior regarding end of life is still uncertain. Photovoltaic modules exhibit gradual decreases in efficiency over time before failure [19]. Users may choose to remove and replace installations as a whole due to partial failure or overall reductions in efficiency. Alternatively, they may choose to replace individual components or modules as they fail, keeping older modules in use until failure, despite their decreased efficiency. Whilst the photovoltaic modules installed at Greenwich House are expected to function for at least 30 years, they could remain in use for longer than this if lower efficiency levels are deemed acceptable. The way in which waste will be disposed of is also uncertain. Whilst the EU Waste and Electrical Equipment Directive [20] aims to ensure that PV modules and components will be collected and recycled at end of life, it remains to be seen how effectively this will be implemented, or whether the UK will continue to abide by this practice following its departure from the EU.

3.5. Life cycle assessment of Greenwich House carbon emissions

Operational gas and water usage data for Greenwich House was obtained from the University of Cambridge Estate Management Division, and carbon impacts for electricity, gas and water usage were estimated using UK Government GHG conversion factors for company reporting [21]. Detailed data regarding the embodied emissions associated with the building were not available. As the embodied emissions of the building are not the focus of this paper and serve primarily to give context to the carbon reductions achieved by the usage of on-site renewables, these emissions were estimated using the Gross Internal Floor Area (GIFA) of the building, which is approximately 5,460 m^2. Based on work done by De Wolf [22] and Clark [23], the embodied emissions per unit of GIFA was then assumed to be approximately 1,000 $kgCO_2e/m^2$. A summary of the life cycle assessment of carbon emissions associated with Greenwich House can be found in Table 4. These scenarios assume that the PV array will be completely replaced after 30 years. A reference study period of sixty years was used for the life cycle assessment.

Table 4. Life cycle building carbon emissions for Greenwich House (60 years)

	Greenhouse Emissions *(tCO_2e)*						
Life cycle stage according to BS EN 15978:	A1-5, B1-5, C1-4		B6		B7		D
Scenario:	Building embodied	PV embodied	Electricity	Gas	Water	**Total**	Export
No on-site renewables	5,460	0	5,960	5,100	200	**16,720**	0
Existing solar photovoltaics	5,460	170	4,950	5,100	200	**15,880**	0
Double existing solar photovoltaics	5,460	340	4,140	5,100	200	**15,240**	-190
Largest plausible solar photovoltaic array	5,460	860	2,810	5,100	200	**14,430**	-1,870

3.6. Accounting for grid decarbonisation and marginal displacement

The life cycle assessment results in section 3.5 do not account for the decrease in carbon impacts of electricity usage over time that would result from decarbonisation of the electricity grid. The trajectory for grid decarbonisation is uncertain, and assumptions must be made regarding the rate and extent to which decarbonisation will occur if it is to be incorporated into life cycle assessment. Accounting for decarbonisation reduces the expected effectiveness operational energy emissions reduction measures, but assumes that carbon reduction measures are implemented outside the scope of the building life cycle assessment (i.e. decarbonisation of the electricity grid).

Both the initial assessment in section 3.5, and an assessment that accounts for grid decarbonisation assume that the average carbon emissions produced per unit of electricity is a valid proxy for carbon emissions resulting from on-site electricity usage. However, the addition of renewable electricity generation to the grid does not result in proportional reductions in all forms of large-scale electricity generation. In practice, fossil-fueled power generation will be reduced before nuclear fission or renewable output is decreased, due to both practical considerations and the typically higher marginal financial cost of generation of these systems. This is the case in most, if not all, grids which rely to a large extent on fossil fuels for electricity generation. As a result, the carbon emissions displaced by additional marginal renewable electricity generation are generally higher than average grid emissions. Thomson [24] found the marginal displacement factor of wind power in the UK to be potentially as high as 0.628 $kgCO_2e/kWh$, or 0.562 $kgCO_2e/kWh$ when inefficiencies caused by the fluctuating nature of renewable electricity generation were accounted for, compared with a system-average emissions rate of 0.510 $kgCO_2e/kWh$ during the same period.

The difference between the marginal displacement factor and the average grid emissions in the UK is likely to become more significant as a result of decarbonisation, as the displaced generation capacity will primarily be gas-fired combined-cycle generation. As this form of generation results in emissions of approximately 0.45 $kgCO_2e/kWh$ [24], the UK marginal displacement factor is likely to remain at this level while average emissions tend towards zero. Applying this factor to operational energy usage, rather than the average grid emissions factor would result in an outcome that is more favourable towards operational energy emissions reduction measures, such as on-site renewables.

Figure 5 illustrates this point. The decarbonisation scenario assumes that the carbon intensity of electricity decreases linearly to 10% of current levels by 2045, at which point it stabilises. The marginal displacement factor scenario applies a carbon factor of 0.5 $kgCO_2e/kWh$, approximating the displacement of gas-fired generation. The default scenario uses the 2016 average emissions factor of 0.41205 $kgCO_2e/kWh$ [21].

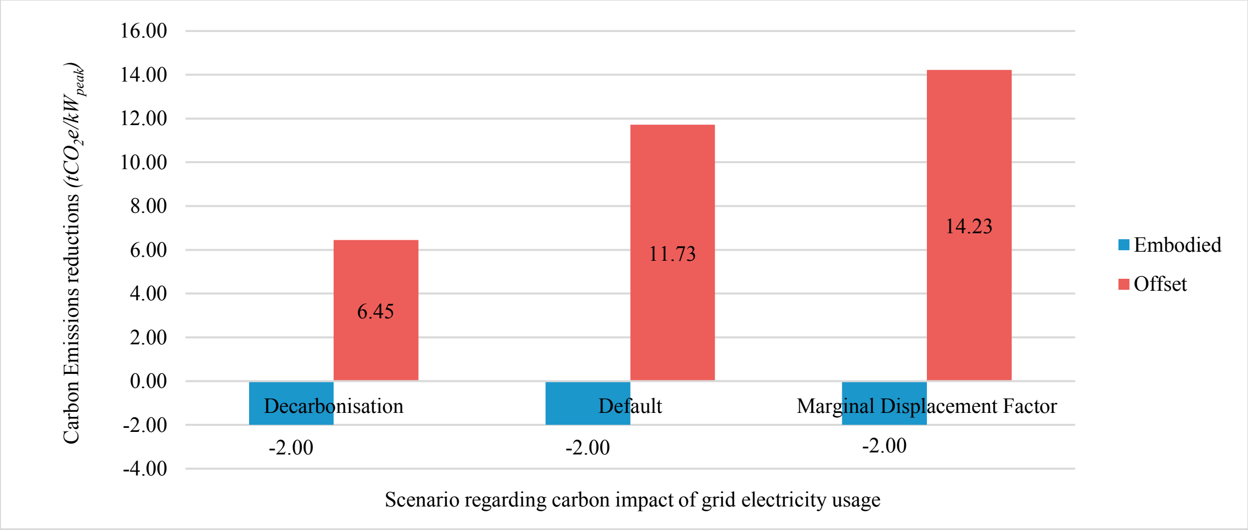

Fig. 5. Carbon Emissions reductions per kW installed photovoltaic capacity for the 42.8 kW array installed at Greenwich House. Results shown for three different electricity emissions factor scenarios over a 30 year lifetime. Emissions reductions are defined relative to the case where no renewables are installed on-site.

4. Discussion

4.1. Key assumptions for life cycle assessment including renewables

The assumptions made in a life cycle assessment can have significant impact on the assessment's results. It is good practice to ensure that these assumptions are clearly stated. The assumptions with the greatest impact on determining whether the usage of on-site renewables is effective are those regarding the carbon impact of operational energy usage. Due to the complexities of grid-scale electricity generation, and further uncertainties associated with the variation of impacts in the future, presenting the resulting life cycle impacts as a range bounded by best- and worst- case scenarios will generally be more representative than presenting the outcome of a single scenario.

The embodied emissions associated with specific renewable generation systems are also relatively uncertain in cases where manufacturers have not produced an environmental product declaration or similar. More reliable assessments would be possible if reporting of this type was more common. However, there is a sizeable body of literature covering the life cycle assessment of common PV technologies, which allows impacts to be approximated. The literature review conducted as part of the Greenwich House case study established that embodied emissions are approximately 1,000 – 5,000 $kgCO_2e/kW_{peak}$ for poly-crystalline silicon solar arrays. In combination with the carbon factor scenarios discussed in section 3.6, the best and worst case net carbon reductions that could be achieved by the Greenwich House PVs are therefore 13.8 tCO_2e/kW_{peak} and 1.5 tCO_2e/kW_{peak} respectively over a 30 year lifetime, whilst the default assumptions result in carbon reductions of 9.7 tCO_2e/kW_{peak}.

4.2. Electricity exported to the grid

Whilst the usage of electricity generated on-site to satisfy building demands clearly reduces environmental impacts, relative to the alternative of importing electricity from the grid, the current guidance defined by BS EN 15978 (as discussed in section 2) states that the benefits of exported electricity should be considered beyond the system boundary of the assessment. This is a conservative approach towards accounting for the benefits of on-site renewable generation in the life cycle assessment (i.e. it does not overestimate the benefits of exported electricity), but could encourage designers to make decisions which bring the benefits of this exported generation within the boundaries of the assessment. This could include adding electrical demands to the building or electrifying existing demands. This would also artificially inflate the apparent benefits of using electrically-based heating systems, such as a heat pumps, mechanical rather than natural ventilation systems, or even the usage of battery storage systems.

The inclusion of non-building related loads (plug loads) could also be used to shift benefits into the system considered by the life cycle analysis. Inclusion of these loads is optional under the current guidance. Whilst the decision to exclude them from the analysis would reduce the operational carbon emissions associated with the building by reducing expected electricity consumption, their inclusion would make renewables seem to be a more effective method of carbon emission reduction where electricity would otherwise be exported to the grid. Whilst it could be argued that this is a fairer representation of the actual benefits of renewable generation, and that it is reasonable for the effects of these benefits to be accounted for on-site, the fact that the result can be manipulated by the assessor is grounds for concern.

The accounting of benefits and loads beyond the system boundary in Stage D of the building life cycle assessment is primarily intended to record measures which enable easier reuse or recycling of building materials after end of life – temporally distant actions which would potentially confer benefits on future buildings but may or may not be acted on. However, grid exported electricity produces a measurable immediate carbon reduction, although this occurs off-site and is therefore spatially distant. Whilst this benefit takes place "beyond the system boundary", it is significantly different from the other benefits considered in Stage D.

In the absence of site-specific export limitations, electricity generated on-site which exceeds usage is exported to grid and will reduce the requirement for generation elsewhere. The benefits of this export will be the equivalent of the costs of importing a similar quantity of electricity at the same point in time. In cases where grid electricity generation is 100% renewable and electricity export results in little or no operational environmental benefits, additional electricity consumption would result in equally negligible costs. These impacts are a function of time and are not dependent on the direction of electricity flow into or out of the system under consideration. Whilst the benefit physically occurs beyond the system boundary, this is no different from the costs of operational electricity consumption in general, and the cause of this benefit is clearly the renewable system, within the boundary of the assessment. It would therefore be reasonable to report the benefits from exported electricity as a separate use (B) stage, rather than part of module D as recommended in BS EN 15978.

4.3. Pragmatic alternative to real-time matching of temporal variation

The existing guidance in BS EN 15978 does not address the mismatching in time of on-site generation and demand. Where the assessment is being conducted for an existing building, where real data regarding the consumption, generation and export of energy is available, this is not a concern. However, at the design stage, establishing the proportion of generated electricity which will be exported to the grid is difficult without detailed energy modelling, which may not be practical or reliable. The quantity of electricity exported is dependent on unpredictable fluctuations in both electricity demand and renewable generation. Straightforward predictions of energy consumption and generation are generally produced on an annualised basis, but obtaining the net grid export from these figures ignores the fact that electricity may be imported at some points in time and then exported at other points, potentially resulting in an underestimation of the true imports and exports. None of the arrays considered in the case study result in a net annual export of electricity, and yet the data from case study indicates that the theoretical larger arrays would result in significant export of electricity in practice. BS EN 15978 explicitly states that "exported energy shall not be deducted from the import of energy required to operate the building", implying that a time-averaged approach is not acceptable.

Whilst discrepancies in time between demands and generation are unlikely to result in significant electricity exports where annual generation is less than ~20% of annual consumption, the proportion of electricity exported from the site is difficult to predict where larger on-site renewable generation capacity is installed. Further research is required to provide indicative proportions exported for different building usages and different ratios of peak consumption to nominal installed renewable capacity.

In practice, the marginal impact of consuming or generating electricity varies over time depending on the forms of electricity generation in operation at that instant, and this in turn is a function of electricity demand. Typically, carbon impacts will be higher at times when electricity demand is high and the proportion of renewable energy generation is low. There is also generally a strong correlation between generation by renewables installed on-site and generation by similar renewables in other locations connected to the same electrical grid (e.g. solar during sunlight hours). Whilst time-averaged costs associated with energy consumption are widely used for simplicity, this disregards these costs of energy storage and reserve generation capacity at the grid level, and the benefits of demand management systems within the building for matching demands to the availability of renewable generation. The case study considered an office building where on-site renewable generation and electricity demand were well correlated, but this may not be the case for domestic buildings. As a result, the optimum level or form of on-site renewable generation for a domestic building may differ from that of a similarly sized office building. Further research is required to provide carbon reporting factors adjusted for specific energy consumption profiles if these variations are to be practicably accounted for in life cycle assessments.

5. Conclusions

A building life cycle assessment was conducted for Greenwich House, Cambridge, UK and used to demonstrate how on-site renewable electricity generation could be included within such assessments. This assessment demonstrated that the effectiveness of on-site renewables as a carbon reduction measure is significantly dependent on assumptions regarding the carbon emissions associated with the usage of grid electricity. The development of carbon reporting factors which reflect the impacts of electricity usage more accurately than average grid emissions would allow for more reliable design-stage life cycle assessments. The current guidance for life cycle assessment may result in undervaluation of the environmental benefits of electricity exported to the grid, incentivising designers to increase on-site electrical demands. Alternatively, this may discourage the usage of renewable generation in cases where they would be an effective carbon reduction measure in practice.

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References

[1] European Commission. *A resource-efficient Europe – Flagship initiative under the Europe 2020 Strategy, COM (2011) 21*, Brussels: European Commission; 2011.

[2] Moncaster, A.M. *Constructing sustainability: connecting the social and the technical in a case study of school building projects*. PhD thesis, University of East Anglia; 2012.

[3] Pomponi, F. & Moncaster, A. Embodied carbon mitigation and reduction in the built environment – What does the evidence say? *Journal of Environmental Management* 2016; 181: 687-700.

[4] UK Green Building Council. *Tackling embodied carbon in buildings.* 2013.

[5] Keoleian, G.A. The application of life cycle assessment to design. *Journal of Cleaner Production* 1993; 1: 143-149.

[6] HM Government. *Low Carbon Construction Innovation & Growth Team Final Report*. 2010.

[7] Moncaster, A.M. & Symons, K.E. A method and tool for 'cradle to grave' embodied carbon and energy impacts of UK buildings in compliance with the new TC350 standards. *Energy and Buildings* 2013; 66: 514-523.

[8] Basbagill, J., Flager, F., Lepech, M. & Fischer, M. Application of life-cycle assessment to early stage building design for reduced embodied environmental impacts. *Building and Environment* 2013; 60: 81-92.

[9] European Commission. *Directive 2010/31/EU of the European Parliament and of the Council on the energy performance of Buildings (recast)*, Brussels: European Commission; 2010.

[10] British Standards Institution. *BS EN 15978:2011 Sustainability of construction works – Assessment of environmental performance of buildings – calculation method.* 2011.

[11] Erickson, J. *Greenwich House Solar PV Analysis*. Available on request from University of Cambridge Living Lab for Sustainability. 2016.

[12] de Wild-Scholten, M., Cassagne, V. & Huld, T. Solar resources and carbon footprint of photovoltaic power in different regions in Europe, in: *Proc 29th Eur. Photovoltaic Solar Energy Conference (Amsterdam, Netherlands),* 2014, p. 3421.

[13] Laleman, R., Albrecht, J. & Dewulf, J. Life Cycle Analysis to estimate the environmental impact of residential photovoltaic systems in regions with a low solar irradiation. *Renewable and Sustainable Energy Reviews* 2011; 15: 267-281.

[14] Raugei, M., Bargigli, S. & Ulgiati, S. Life cycle assessment and energy pay-back time of advanced photovoltaic modules: CdTe and CIS compared to poly-Si. *Energy* 2007; 32: 1310-1318.

[15] Alsema, E.A. & de Wild-Scholten, M. Environmental Impacts of Crystalline Silicon Photovoltaic Module Production, presented at *13th CIRP International Conference on Life Cycle Engineering (Leuven, Belgium),* 2006.

[16] Battisti, R. & Corrado, A. Evaluation of technical improvements of photovoltaic systems through life cycle assessment methodology. *Energy* 2005; 30: 952-967.

[17] Hondo, H. Life cycle GHG emission analysis of power generation systems: Japanese case. *Energy* 2005; 30: 2042-2056.

[18] Tripanagnostopoules, Y., Souliotis, M., Battisti, R. & Corrado, A. Energy, cost and LCA results of PV and Hybrid PV/T Solar Systems. *Progress in Photovoltaics: Research and Applications* 2005; 13: 235-250.

[19] Skoczek, A., Sample, T. & Dunlop, E.D. The Results of Performance Measurements of Field-aged Crystalline Silicon Photovoltaic Modules. *Progress in Photovoltaics: Research and Applications* 2009; 17: 227-240.

[20] European Commission. *Directive 2012/19/EU of the European Parliament and of the Council on waste electrical and electronic equipment (recast)*, Brussels: European Commission; 2012.

[21] HM Government. *UK Government GHG conversion factors for company reporting (2016).* 2016.

[22] De Wolf, C., Pomponi, F. & Moncaster, A. Measuring embodied carbon dioxide equivalent of buildings: A review and critique of current industry practice. *Energy and Buildings* 2017; 140: 68-80.

[23] Clark, D.H. *What Colour Is Your Building? Measuring and Reducing the Energy and Carbon Footprint of Buildings,* London: RIBA Publishing; 2013.

[24] Thomson, R.C. *Carbon and Energy Payback of Variable Renewable Generation*. PhD thesis, University of Edinburgh; 2014.