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Procedia CIRP 105 (2022) 613–618

www.elsevier.com/locate/procedia

29th CIRP Life Cycle Engineering Conference

Environmental Analysis of Integrating Photovoltaics and Energy Storage in Building

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Abstract

The energy consumption of buildings accounts for approximately 36 % of the final energy consumption in Europe, being the largest end-user. The UK government has committed to cut greenhouse gas (GHG) emissions by 100 % below 1990 levels and bring all GHG emissions to net-zero by 2050.

To support the realisation of these goals the concept of an Active Building was formulated which refers to any building type, such as factories, offices, homes, and other structures in the built environment, which are equipped to conserve, generate, store, and release energy. The increasing deployment of rooftop photovoltaics drives the growth of energy storage to capture solar energy for later use in buildings. The Active Office was built at Swansea University, UK in 2018 and is a two-story office building. Its energy demand, including that of electric vehicle charging, is primarily met by the 23 kWp of building-integrated photovoltaics (BIPV) and 110 kW of lithium-ion (Li-ion) batteries. When the BIPV and batteries are unable to meet the demand, electricity supplied from the grid can be used.

The objective of the research is to assess the potential environmental impacts of the building energy system of BIPV and Li-ion batteries, as well as to address the lifetime and degradation of Li-ion batteries, and the associated consequences. Life cycle assessment (LCA) is employed in this research. Three operational strategies are designed regarding the interactions between the electrical grid, BIPV, and Li-ion batteries. In the best case operational scenario, using a rolling average to predict building generation and consumption, the GWP from the building operation is 33 g/kWh which is a 5 fold reduction compared with the grid emissions of 170 g/kWh. The worst case building operational strategy creates emissions of 128 g/kWh, it is still an improvement upon electricity supply by the national grid alone. This analysis demonstrates that operational strategy optimisation can reduce the environmental impacts of the Active Building concept compared with using grid electricity alone.

Keywords: Photovoltaics; Battery Energy storage; Life Cycle Assessment; Battery Operation

1. Introduction

The energy sector accounts for more than 80% of total greenhouse gas (GHG) emissions in the EU sectors in 2017 [1]. The energy consumption of buildings accounts for approximately 36 % of the final energy consumption in the world [2], being the largest end-user. The UK government has committed to cut GHG emissions by 100% below 1990 levels and bring all GHG emissions to net-zero by 2050 [3]. The Royal Institute of British Architects (RIBA) has created a 2030 Climate Challenge, setting targets for 2025 and 2030 to reduce operational energy usage and embodied emissions [4]. The Active Building concept was developed by SPECIFIC Innovation and Knowledge Centre (IKC) [5], and refers to any

10.1016/j.procir.2022.02.102

building, such as factories, offices, homes, and other structures in the built environment, which are equipped to conserve, generate, store and release energy in a controlled manner. A direct example of an Active Building is the Active Office [6,7], which was constructed to demonstrate the concept at Swansea University. The reasons behind promoting these motivational schemes are to reduce the transmission and distribution system losses and environmental pollution [8].

The decline in the cost of rooftop photovoltaic drives the application of energy storage to capture solar energy for later use in buildings. The installation of solar photovoltaic (PV) units and battery energy storage system (BESS) for residential buildings have been available on the market for some time. Meanwhile, commercial buildings or office buildings, which are larger energy consumers compared to residential individual buildings, suit the deployment of rooftop PV. An Active Building known as the Active Office was constructed on the Swansea University campus in 2018, which exceeded the 2025 RIBA targets for energy consumption of the building. The energy consumption includes electricity for heating, ventilation, power for office operation, and EV charging demand. The electricity demand can be met by the installed building-integrated photovoltaics (BIPV), the electricity grid or by lithium-ion batteries, which have stored electricity previously either from the BIPV system or the grid.

The objective of this study is to analyse the potential environmental impact of the building energy system of BIPV and Li-ion batteries, as well as addressing impacts of degradation of Li-ion batteries due to different battery operations. In section 2, the deployment of the building energy system is described. In section 3, the method and approach are elaborated upon in more detail. In the following section 4, the result and conclusion are presented.

2. System description

Active Buildings incorporate electricity generation, energy storage systems, heat pumps, and smart controls, as well as extensive data monitoring. The solar BIPV installed in the studied Active Office, offers discreet aesthetics and can be used on a curved roof, due to its flexible nature. The Active Building is grid-connected [9] with the BIPV panels and battery packs connected via inverters. The electricity flows are measured by smart meters every second (Fig.1). The annual PV generation and annual consumption of the Active Office were 19.5 MWh and 22.7 MWh respectively in 2020. Whilst some of this data was collected during the COVID pandemic lockdown, the building systems and heating was left running to enable the building operation to continue to be evaluated. The 25 kWp BIPV can generate up to 20 kWh on a sunny winter day, and up to 155 kWh on a sunny summer day. For commercial buildings, the energy demands and BIPV electricity generation follow a similar trend with higher demand/generation during the day and low demand and zero generation during nighttime. However this match is seasonal with generation exceeding consumption from March to October only.

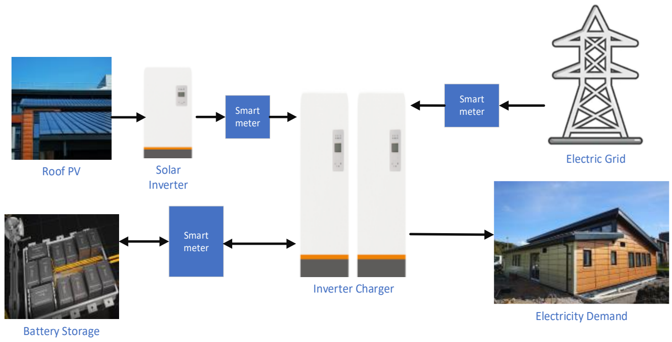

Fig. 1. System deployment of an Active Building

3. Method

Three operational strategies are utilised regarding the interactions between the electrical grid, BIPV, and Li-ion batteries. The default (first) operational strategy works as follows: when there is excess power ($P_{pv}(t)$-$P_{den}(t)$ >0), the batteries are charged: excess power after charging the batteries is exported to the electric grid; when the electricity generated from BIPV cannot meet the demand ($P_{pv}(t)$-$P_{den}(t)$ <0), the batteries are discharged; further power demand can be met by the electric grid. The second operational strategy considers potential economic benefit by charging the batteries from both the BIPV in the day and then the grid at night when the electricity tariff is lower. The batteries both meet the needs of the building and discharge to the university grid at peak hours when the electricity is a higher price. The third strategy uses a 72 hour rolling average of the generation and consumption to estimate genertion / consumption over the next 24 hours. This data then runs through control logic to determine how much electricity import from or export to the grid. During periods of high BIPV generation there is export as a fixed rate and during net import scenarios, a fixed import is used. The magnitude of the power into or out of the grid is a function of the anticipated load, generation, and current storage capacity. By optimising the charge rate the battery can also operate in the most effective manner.

Life cycle assessment (LCA) is employed to assess the potential impact. The fuctional unit is 1 kWh electricity delivered to the building.

13 mid-point impact categories are assessed and compared. Two mid-point impact categories were chosen to be compared in detail; firstly global warming potential (GWP) since reducing this impact is the main focus of the Active building, secondly mineral depletion (MDP) since this has been shown to increase with the use of PV [10]. The impacts of GWP, and MDP from the current electricity supply are based on a study by Raugei [10]. The data taken from this study excludes biogenic carbon from the GWP value.

To highlight any burden shifting 11 further effects were considered: human toxicity (HTP) including both carcinogenic and non-carcinogenic, fossil resource scarcity (FDP), stratospheric ozone depletion (ODP), photochemical ozone formation (human health) (POFP), fine particulate matter formation (PMFP), terrestrial acidification (TAP100), freshwater eutrophication (FEP), marine eutrophication (MEP), freshwater ecotoxicity (FETP), marine ecotoxicity (METP), terrestrial ecotoxicity (TETP). The other impacts which are not available in this study, are assessed based on the electricity grid data to the UK grid in 2018, i.e. 26.5 % fossil fuel power, 22 % nuclear power, 2 % hydropower, 19.5 % biomass and waste power, 25 % wind power (both onshore and offshore), and 5 % photovoltaic. SimaPro is used to conduct the assessment based on Ecoinvent 3 database. ReCiPe (H) is employed as impact assessment method. The impact results for the BIPV come directly from a study by Stamford [10]. Stamford used German manufacturing data for the production of the CIGS (including system inverter), with a 30 year lifetime and without considering end of life. The installed Li-ion battery battery supplied by BYD is lithium iron phosphate (LFP). life cycle assessment data of manufacture LFP battery is taken from the study by Liu [12]. Based on the degradation model (considering both calender and cycle life) developed by Schimpe [11], the lifetime of the battery was calculated to be 44 years, 41 years, and 44 years in three operational strategies respectively. The stored temperature is assumed to be 15°C. The average annual full cycles were 145, 230, and 154 in three operation strategies respectively whilst the average depth of discharge (DOD) are calculated to be 32 %, 50 %, and 34 %. These lifetimes and annual cycle rates were then used to determine the impact of 1 kWh of electricity supplied by the battery in each scenario.

4. Result and Discussion

The building has been operating with three strategies since 2018. The combination of electricity sources consumed by the building is presented in Fig. 2.

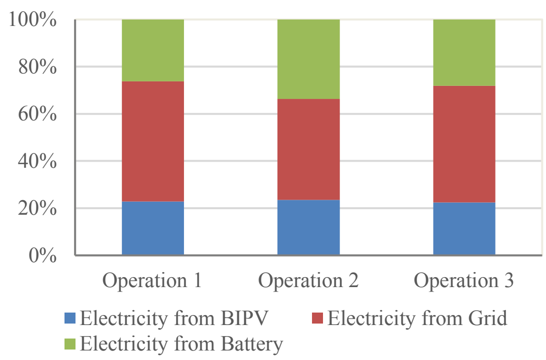

Fig. 2. The share of electricity sources used in the three-operation strategies.

In operation 1, which was undertaken for a total of 224 days, the average daily energy consumptions from BIPV, electric grid, and battery are 16.6 kWh, 37.0 kWh, and 19.0 kWh respectively, in operation 2 (548 days) 17.5 kWh, 31.8 kWh, and 24.9 kWh and in operation 3 (294 days), 13.0 kWh, 28.6 kWh, and 16.2 kWh.

The average daily consumption is higher in operation 2 however the roundtrip efficiency (RTE) is decreased (Fig. 3). RTE includes the energy loss during battery storage, DC/AC inverter, uninterruptable power supply (UPS) and the associated losses. The exact causes of this variation in round trip efficiency are being investigated with the standby power requirements of the UPS likely to be a contributory factor, depth of discharge could also affect the RTE.

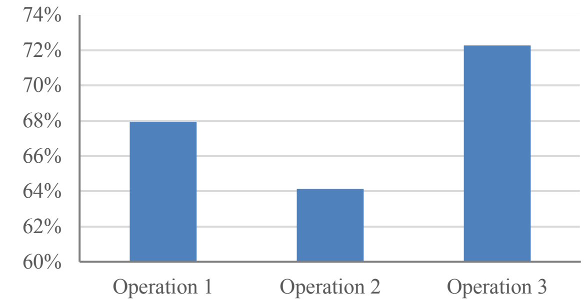

Fig. 3. Roundtrip efficiency of the battery for the three-operation strategies

The GWP impacts from the electricity consumed by the building are presented and compared in Fig. 4. As expected direct consumption from the BIPV has the lowest CO_2 emissions at 25 g/kWh which compares favourably to the grid electricity emissions at 170 g/kWh. For the three operational strategies the net CO_2 emissions are 102 g/kWh, 128 g/kWh, and 33 g/kWh which correspond to a reduction of 68 g/kWh, 42 g/kWh and 137 g/kWh for the three strategies respectively compared to the situation where the building had been supplied by the electricity grid alone.

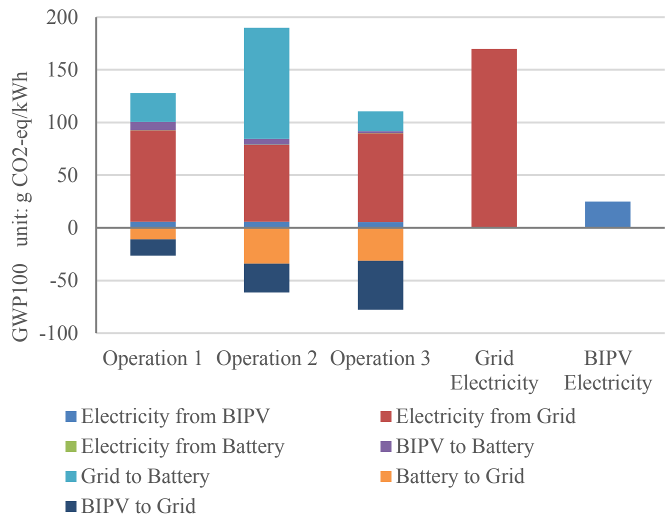

Fig. 4. The GWP impacts from 1 kWh electricity consumed by the building in the three operational strategies, BIPV alone and grid electricity alone. Negative values mean a reduction in environmental emissions.

When compared against the energy generated from BIPV, the building energy systems have significantly higher GWP. The increased GWP impacts from studied building are a result of the carbon intensity of the grid and the RTE of the battery system. In operation 2, the RTE is the lowest, this coincides with an increased amount of electricity charged/discharged through battery per kWh delivered to the building. This is an area of further investigation and these two factors are not necessarily related.

The MDP impacts per 1 kWh electricity consumed by the building are presented and compared in Fig. 5. The MDP impact from electricity generated from BIPV is 5.5 g Cu-eq/kWh. This is significantly higher than electricity from the grid, which is 0.3 g Cu-eq/kWh. The MDP impacts are seen to be significantly higher in the studied building than that from grid electricity. When the building exports to the grid the MDP impact is positive in Fig.5, representing an increase in the MDP impacts of that exported electricity. More than 99 % of MDP impacts from operation strategies come from the BIPV. The impact of the battery on MDP is low due to the long lifetime / high energy throughput of the battery and the absence of cobalt and nickel in the battery chemistry.

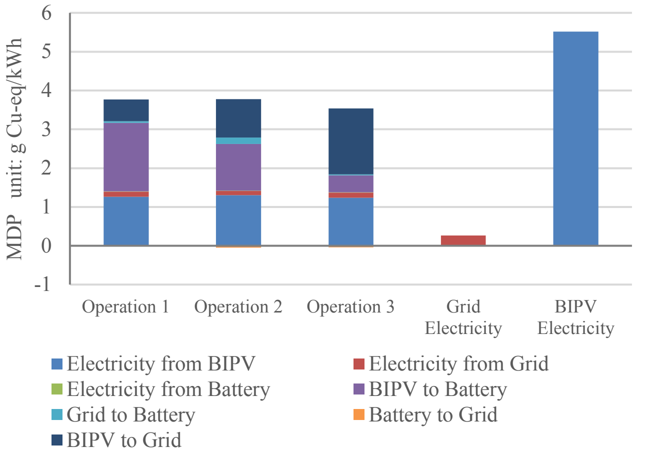

Fig.5. The MDP impacts from 1 kWh electricity consumed by the building in the three operational scenarios compared with grid electricity and BIPV generated electricity.

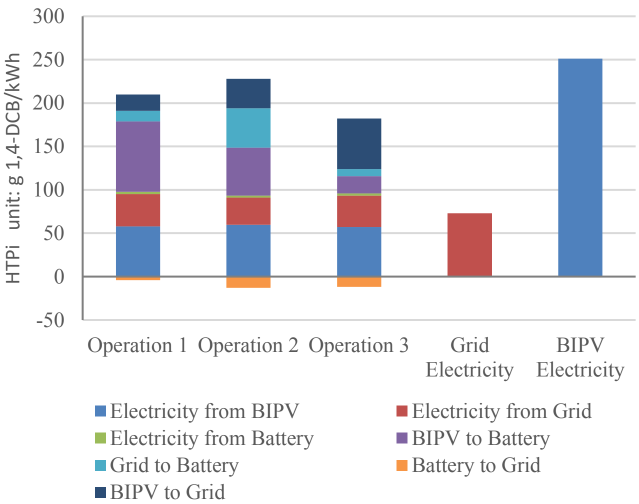

Fig.6. The HTP impacts (carcinogenic and non-carcinogenic) from 1 kWh electricity consumed by the building in the three operational strategies compared with electricity generated from the grid and BIPV.

The HTP impacts from 1 kWh electricity consumed by the building are presented in Fig. 6. Electricity generated from BIPV has an impact of 251 g 1,4-DCB/kWh, more than three times higher than that from the grid, which is 73 g 1,4-DCB/kWh. The HTP impacts from the three-operation strategy are 206 g 1,4-DCB/kWh, 215 g 1,4-DCB/kWh, and 170.4 g 1,4-DCB/kWh respectively. Operation 3 has the lowest HTP impact than the other two operations.

With the exception of MDP and MEP the three operation strategies show the same trend regarding impact results. Operation strategy 2 has the highest impacts followed by followed by operation 1. Operation strategy 3 has the lowest impacts across all assessed impact categories except MDP as shown in Fig. 7. Since an annual average electricity mix is used for the grid electricity impacts, the low impacts reported for operational strategy 3 are attributed to a higher RTE of the battery and increased self-consumption of electricity generated by BIPV in operation 3. By following a predictive strategy, operation 3 ensures that the battery has spare capacity to store the electricity from the BIPV on a sunny day, without discharging too much that the batteries get depleted and the building needs to draw from the grid. However extreme changes in the weather can reduce the effectiveness of using a rolling average strategy. Research is ongoing to develop the most effective methods of predicting PV output and linking this with a day-ahead battery management system to improve the operational management system further [14,15]. Following a fixed time tariff economic strategy (operation 2) creates the highest impact since there are more cycles between the battey and the grid. The more cycle of electricity in operational strategy 2 is environmentally detrimental because energy is lost due to the RTE. No environmental advantage is attributed to the temporal load shifting of the battery since an annual average grid impact is used in the calculation for both the charge and discharge cycles. In the current scenario this could be considered correct for the majority of energy systems [16]. However this is likely to change during the next decades as the UK grid decarbonizes and storage is required more frequently to avoid curtailment of renewables.

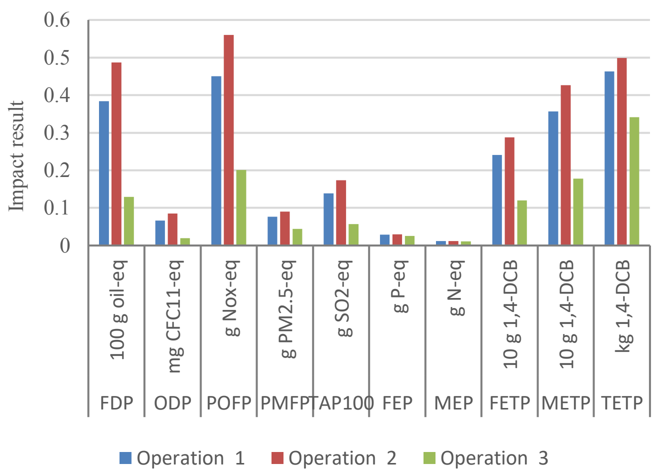

Fig.7 Impact results of 10 impact categories from 3 operational strategies.

5. Sensitivity analysis

Future electricity generation will provide a different scenario than current under both national and international climate change policy. Therefore a sensitivity analysis was performed analyzing the building system of BIPV + battery storage in future energy scenario to determine if there are environmental benefits in the renewable energy scenario.

The 2050 electricity analysis is based on a future electricity two-degree scenario (TDS) in 2050 provided by the National Grid [17]. This consists of 58.2 % wind power, 9.2 % nuclear power, 2.1 % hydropower, 0.9 % tidal power, 7.6 % biomass and waste, 7.1 % photovoltaic, 4.2 % gas-fired power, 7.0 % other renewables, and 3.2 % energy storage. This represents a future potential electricity scenario with high renewable energy especially wind power. The battery and BIPV impacts are based on the same references and calculation to the previous analysis. TDS was used to determine a new average annual environmental impact per kWh of grid electricity which are presented in Table 1. The environmental impacts were assessed by SimaPro based on Ecoinvent database. LCIA method is ReCiPe(H).

Table 1 Environmental impact results TDS 2050. Function unit g/kWh

Impact category	Unit	TDS 2050
GWP	g kg CO_2-eq	28.6
FDP	g oil-eq	9.32
ODP	g CFC11-eq	0.0000268
POFP	g NOx-eq	0.1781
PMFP	g PM2.5-eq	0.406
TAP100	g SO_2-eq	0.0983
FEP	g P-eq	0.0102
MEP	g N-eq	0.00112
FETP	g 1,4-DCB	4.8
METP	g 1,4-DCB	6.19
TETP	g 1,4-DCB	228
HTP	g 1,4-DCB	63.82
MDP	g Cu-eq	0.382

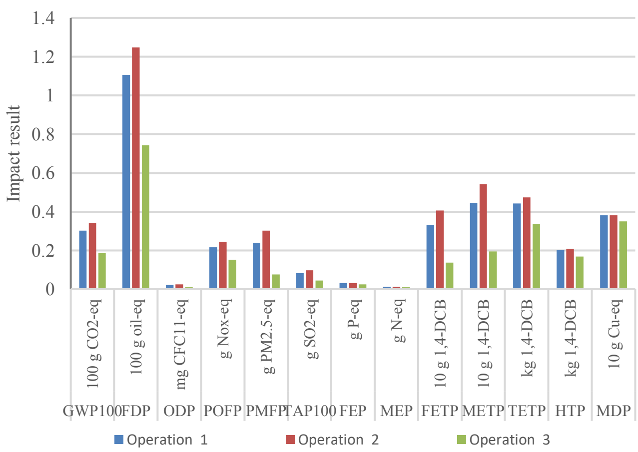

Fig.8 Life cycle impact results of three operation strategies based on a TDS in 2050.

The environmental impact results for the three operational strategies assesed using the environmental impacts of the 2050 grid are presented in Fig.8. It shows operation strategy 3 has the lowest impact results of all assessed impact categories, with GWP of 19 g/kWh.

6. Conclusion

This study presents the potential environmental impacts of the building energy system of BIPV and lithium-ion battery storage. The assessment incorporates the effects of degradation of the Li-ion batteries.The results show the building energy system can reduce GWP from energy consumption to 33 g/kWh, a 5 fold reduction on 2019 grid emissions. However if the operational strategy is not optimised the GWP of the building rise to 102 g/kWh. Conversely the MDP impact is 10 fold higher for the building energy system compared with the 2019 grid, due to the high impact from the BIPV system. In a 2050 TDS there is still a benefit of using the building energy system with GWP reducing to 19 g/kWh a 1.5 fold reduction compared with the 2050 projected grid emissions.

The use of battery storage can increase the self consumption of electricity generated from BIPV, with minimal impacts associated with Li-ion batteries. After comparing three battery operational strategies, the results show the BIPV and battery storage system have better environmental performance with a predictive import/export operational strategy 3 in both the current and a 2050 electricity scenario. The influence of operational strategy on environmental impacts is important to note, such that usage strategies can target minimising environmental impact as a relevant control strategy. Further works are needed to explore the correlation between battery operational strategy, round trip efficiency of the battery and the environmental consequence of such building using time-of-use factors. The influence of operational strategy on environmental impacts is important to note, such that usage strategies can target minimising environmental impacts as a relevant control strategy. Further works are needed to explore the correlation between battery operational strategy, round trip efficiency of the battery. Further work can look at the marginal environmental impacts of such building based on time-of-use energy data.

Acknowledgements

This work was supported by the Engineering and Physical Sciences Research Council (EPSRC) through ECR Fellowship NoRESt (EP/S03711X/1) and SPECIFIC Innovation and Knowledge Centre (EP/N020863/1 and EP/P030831/1). Matt Roberts was supported by a Leveraged University Research Studentship, provided by the University of Bath. Dr. Stephen Allen was supported by the “The Active Building Centre Research Programme” [EP/V012053/1].

References

[1] EU Parliament. Greenhouse gas emissions by country and sector (infographic). 2019;2020.
[2] WorldGBC. Annual Report 2020- World Green Building Council . San Marcos 2021;22.
[3] Parliament U. The Climate Change Act 2008 (2050 Target Amendment) Order 2019. Statutory Instrum 2019;1056.

[4] RIBA R. 2030 climate challenge. Royal Institute of British Architects: London, UK 2019.
[5] Clarke J, Searle J. Active Building demonstrators for a low-carbon future. Nature Energy 2021:1-3.
[6] SPECIFIC. WHAT ARE ACTIVE BUILDINGS? 2016;2021:1.
[7] SPECIFIC. Active Office -The UK'S first energy-positive office space. 2018:1-12.
[8] Clarke J, Jones P, Littlewood J, Worsley D. Active buildings in practice. In: Anonymous Sustainability in Energy and Buildings: Springer; 2020, p. 555-564.
[9] Brennan DA, White C, Barclay M, Griffiths T, Lewis RP. Performance Characterisation and Optimisation of a Building Integrated Photovoltaic (BIPV) System in a Maritime Climate. Future Cities and Environment 2019;5.
[10] Raugei M, Kamran M, Hutchinson A. A Prospective Net Energy and Environmental Life-Cycle Assessment of the UK Electricity Grid. Energies 2020;13:2207.
[11] Stamford L, Azapagic A. Environmental impacts of copper-indium-gallium-selenide (CIGS) photovoltaics and the elimination of cadmium through atomic layer deposition. Sci Total Environ 2019;688:1092-101.
[12] Schimpe M, von Kuepach ME, Naumann M, Hesse HC, Smith K, Jossen A. Comprehensive modeling of temperature-dependent degradation mechanisms in lithium iron phosphate batteries. J Electrochem Soc 2018;165:A181.
[13] Liu W, Liu H, Liu W, Cui Z. Life cycle assessment of power batteries used in electric bicycles in China. Renewable and Sustainable Energy Reviews 2020:110596.
[14] A Sorour, M Fazeli, M Monfared, A Fahmy, J Seale, R Lewis. Forecast-based Energy Management for Domestic PV-Battery Systems; a UK Case Study, 2021, IEEE Access 9, 58953-58965
[15] M. Monfared, M. Fazeli, R. Lewis and J. Searle, "Day-Ahead Prediction of PV Generation Using Weather Forecast Data: a Case Study in the UK," 2020 International Conference on Electrical, Communication, and Computer Engineering (ICECCE), 2020, pp. 1-5.
[16] BEIS, Policy paper; Valuation of greenhouse gas emissions: for policy appraisal and evaluation, https://www.gov.uk/government/publications/valuing-greenhouse-gas-emissions-in-policy-appraisal/valuation-of-greenhouse-gas-emissions-for-policy-appraisal-and-evaluation, Published 2 September 2021
[17] National Grid E. Future Energy Scenarios. National Grid Electricity System Operator: London, UK 2019:1-166.