A geospatial assessment of the rooftop decarbonisation potential of industrial and commercial zoned buildings: An example of Irish cities and regions

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ABSTRACT

This paper describes a framework for estimating the effectiveness of photovoltaic and rainwater harvesting technology deployment on industrial and commercial zoned buildings to facilitate reducing national GHG emissions. Decarbonisation technologies pathways were investigated which may aid in meeting national decarbonisation targets, and their potential role at local administrative area scale evaluated. A finding arising from application of this method was that a small number of larger industrial and commercial buildings, representing only 4% of the sectors buildings, were found to account for 38% of its decarbonisation potential. Future carbon emission scenarios identified that electricity demand may be expected to increase for the industrial and commercial sector up to 2030, and that the technological potential for current photovoltaics systems have the potential to reduce GHG emissions by 4% more than currently planned Irish grid-scale decarbonisation trajectories. The method may be adopted at European scale, using local data on climate and building attributes, and is applicable at national, regional and local scales. The paper concludes with a review of technologies which may aid further decarbonisation studies, which include improved data availability for 3D building generation, and enabling technologies such as machine learning algorithms applied to satellite imagery.

Introduction

The importance of the industrial and commercial sector in facilitating city and regional environmental sustainability has received significant attention within the academic literature. Studies range from utilisation of waste heat produced by the sector for residential heating requirements[1], building life cycle and cost analysis[2,3,4], and the deployment of renewable energy[5,6]. This paper builds on this research agenda by investigating the rooftop decarbonisation potential of industrial and commercially zoned buildings in Irish cities and regions.

Ireland is projected to significantly exceed its European Union carbon emissions reduction targets for both 2020 and 2030, with emissions projected to remain largely unchanged over this time period[7]. Unlike European counterparts, Ireland has failed to decouple economic growth and greenhouse gas (GHG) emissions[8], with increases in industrial and commercial activity, coupled with a fossil intensive electricity grid, cited as the key reasons[7]. In 2014 the Irish government outlined its National Policy Position on Climate Change, which stated that there was a need for an aggregate reduction in carbon dioxide (CO₂) emissions of at least 80% by 2050 compared to 1990 levels in the electricity generation, built environment, and transport sectors[9]. In 2015, the Irish government published an energy white paper, titled Ireland’s Transition to a Low Carbon Future 2015–2050, outlining how Ireland planned to transform its energy system by 2050, so as to reduce GHG emissions by 80% to 95%, over 1990 levels[10]. In addition to these targets, the Irish government published the National Development Plan (NDP) 2018–2027 which allocated €22 billion towards meeting climate change targets. Proposed measures relevant to industrial and commercial buildings within the NDP included a Renewable Electricity Support Scheme, Support Scheme for Renewable Heat, energy efficiency investments in commercial and public sector buildings, and energy research funding for wind, wave, solar, biomass, biofuels, biogas and hydrogen[11]. The Irish Government’s recent Climate Action Plan 2019[12] has set national targets for 70% of electricity to be generated from renewable energy sources by 2030, with the phase out of coal and peat. Detailed action plans at a local authority level in relation to how such national targets may be met are currently lacking.

To facilitate Irish national policy makers and local authorities in...
decoupling industrial and commercial activity and national carbon emissions, there is a need to quantify the industrial and commercial sectors decarbonisation potential for each city and region. In previously published work, Irish settlement size was found to be a strong predictor of environmental performance in relation to material and energy flows [13,14]. Similar relationships have been observed elsewhere, with commercial and industrial floor space and electricity usage in London boroughs found to be strongly correlated ($R^2 = 0.90$), and similarly in Buenos Aires ($R^2 = 0.97$) [15]. According to Ref. [6], the exploitation potential of a renewable energy resource for a site or area can be realised in various ways:

1. Resource potential: for photovoltaics, the annual incident solar radiation, and other relevant environment parameters such as ambient temperature and wind speed;
2. Technical potential: available suitable surface area, system technical performance, sustainability criteria if applicable;
3. Economic potential: technology costs, avoided supply costs;
4. Market potential: deployment considering competition with other sources, policies, legal-permitting aspects, incentives, and socio-cultural factors.

This study focuses on the resource (solar radiation and precipitation) and technological potential (available roof area and system technical performance) of photovoltaic and rainwater harvesting systems on Irish Industrial and commercially zoned building. Ref. [16] categorised methodologies utilised to assess the deployment potential of decarbonisation as either low-level, medium-level and high-level methods. Low-level methods utilise aggregate statistical data such as estimating roof area from population density [17,18], medium-level methods combine aggregate statistical data with spatial data derived from Geographic Information Systems (GIS) [19,20,21,22], while high-level methods utilize advanced methods for rooftop digitization, in-solution calculations, and accounting for factors and shading of buildings [6,23]. This study is an example of the medium-level methods combining Irish aggregate statistical data relating to local climatic conditions, and spatial data relating to available roof area derived using GIS. Another example is a previous study on the influence of meteorological variables on photovoltaic systems located in different geographic zoned in Mexico [24]. The method adopted here is intended to represent a low computational load method for estimating the rooftop decarbonisation potential of industrial and commercially zoned buildings in Ireland.

Methods

The method described here estimates the rooftop decarbonisation potential of Irish industrial and commercial buildings, and was developed from a method adopted in a previous study on the decarbonisation potential of rooftops and carparks of Irish higher education institutions (HEIs) [25]. Ref. [25] described a method, based on visual inspection of satellite imagery, designed to identify the similarities in the building carbon footprint characteristics of HEIs, and quantifying the similarities in footprints of HEIs and industrial and commercial buildings in relation to size, shape and density. Due to the greater building footprint of industrial and commercial buildings in Ireland compared to HEIs and to allow for more in-depth analysis, the method described for the HEI sector was adapted through utilisation of the QGIS application rather than Google Earth Pro, to access the ability to import vector layers relevant to building footprint and zoning of commercial and industrial areas in Ireland, coupled with the ability to intersect various layers of data to generate further insights. Following a published classification of relevant medium and high-level methods [16], the following city and regional decarbonisation studies were analysed to synthesise the steps for the method adopted here: solar photovoltaic potential in the European Union [6], solar photovoltaic potential of Mumbai [19], solar and wind potential of Leeds [20], solar potential map of the UK [21], solar PV systems in the Maldives [22], rooftop PV potential assessment in Seoul, [23,26], and rainwater harvesting in Jordan [27]. Based on this review, the following steps were taken in a preliminary scoping for Irish industrial and commercially zoned buildings.

1. OpenStreetMap OSM footprint and Co-Ordinated INformation on the Environment (CORINE) land use classification for industrial and commercial zones on the QGIS application was adopted.
2. Disaggregation of Irish building footprint data to local administrative area level in Ireland through adoption of QGIS.
3. Application of appropriate utilisation factors for rainfall runoff coefficients and installed capacity per unit available area for each selected decarbonisation technology.
4. Assessment of local climatic conditions for each administrative county area, to estimate potential energy and material output from deployed technologies. The largest urban area in each administrative area was selected as a proxy for the entire administrative area.
5. Quantification of potential carbon savings from deployed technologies were calculated.

The steps adopted include the utilisation of OSM building footprints, CORINE land cover classification zoning, coupled with decarbonisation technology utilisation factors and climate GIS tools employed to estimate the decarbonisation potential for industrial and commercial sector buildings at national scale. The method adopted here is intended to present a low computational load method for estimating the rooftop decarbonisation potential of industrial and commercially zoned buildings in Ireland and elsewhere.

Estimation of building footprint of industrial and commercial buildings

This research utilised the OSM building footprint vector layer composed of polygons for Ireland and Northern Ireland [28], to estimate footprints of commercial and industrial buildings. This was achieved by intersecting the OSM building footprint layer with a vector layer generated from CORINE Land Cover that represents 121 Industrial and Commercial land uses for 2018 [29], by using the intersection geoprocessing tool on QGIS. As an example of outputs, a screenshot from the QGIS application of Industrial and Commercial zone (blue) and the intersecting building footprints of Industrial and commercial buildings (grey) for Dublin City is shown in Fig. 1. The total building footprint of buildings that falls on the boundary of a CORINE zoned area was included to avoid the situation where only a fraction of a building’s roof area was deemed suitable for decarbonisation technologies, due to planning constraints. One major constraint encountered when utilising volunteered GIS data, such as OSM building footprints, is variability in completeness of data [30,31,32]. The OSM database layer was compared to a reference layer generated in [25] for Irish HEI buildings in order to estimate completeness of data. It was found that the OSM layer building was composed of 937 buildings for the Irish HEI sector while Google Earth building footprint based on publicly available campus maps was 649. Difference in building numbers was due to physically linked buildings tended to be counted as one building when utilising Google Earth building footprints based on campus maps, whereas the OSM data set based on machine learning algorithms allowed greater disaggregation of building complexes. The OSM building footprint area (1,131,104 m²) was also 9% higher than roof area estimated with Google Earth (1,036,888 m²). Building footprint area differences may be due to extensions to existing HEI buildings, as the Google Earth data was based on 2016 HEI maps, while OSM data was updated in 2019. Also, Bing Maps was utilised as the reference layer for generating OMS building footprints maps, which may account for differences in area size due to differences in the satellite imagery dataset.
used.

Disaggregation of building footprint data to local administrative area level in Ireland using QGIS

The building roof area of the industrial and commercial zones was further disaggregated to local authority administrative area level, to facilitate local authorities in developing local scale decarbonisation plans in cooperation with industrial and commercial actors. Administrative area scale building footprint was estimated for the industrial and commercial zone by intersecting the building footprint for industrial and commercial zone polygon layer with the administrative counties vector layers for each administrative area [33].

Identification and application of appropriate utilisation factors, runoff coefficients and installed capacity per unit available area for each decarbonisation technology

Previous studies relating to the PV potential for industrial and commercial buildings have been reviewed [34], and formulation of the method adopted here was guided by these reviews. Utilisation factors of 0.60–0.65 (100 m² of roof area corresponds to between 60–65 m² suitable roof areas for building integrated PV, as a result of solar and architectural constraints as identified for commercial buildings in USA [35] and 0.30–0.5 in Israel [36]. The technological PV potential of commercial buildings in Delaware was estimated at 71.51 million ft² for a total rooftop area of 157.88 million ft² together with the ratios of flat roof (56%), sloped pitch at 10° (29%) and sloped pitch roof at 30° (15%) [37]. This corresponds to a utilisation factor of 0.45. Based on monitoring of a PV installation at confectionary factory in Dublin, with a utilisation factor of 0.46 [38], here a utilisation factor between 0.4 and 0.5 was applied to the Irish industrial and commercial sector. A 26 kW PV installation on an Irish flat roofed building occupied an area of 254 m² [25]. This resulted in a PV capacity per unit area factor of 0.102 kWp/m².

Previous studies relating to industrial and commercial building rainwater harvesting deployment at a national scale were not identified in the literature: therefore, the assumption was made that all of the roof area for industrial and commercial buildings was suitable for rainwater harvesting (that is, utilisation factor of 1.0). In Ireland, the runoff coefficient of roofs was found to be between 0.7 and 0.9 [39], similar to that utilised for Irish HEIs [25] as shown in Table 1.

Assessment of local climatic conditions for each administrative area to estimate energy and material output from deployed technologies

The Photovoltaic Geographic Information System (PVGIS) [40] energy calculator was utilised in this study to estimate the potential solar photovoltaic energy output per kWp. Input data for all building integrated PV in this study were based on those utilised for HEI buildings [25] and include: use of the PVGIS-ERA5 database, crystalline silicon systems of 1 kWp with systems loss of 14%, zero azimuth, and 35° slope.

Rainfall volumes per annum were estimated based on 30-year rainfall averages between 1981 and 2010 [41] from weather stations within each administrative area or from the nearest weather station (Table 2). The largest town or city of each administrative area was utilised as a proxy to estimate solar electricity generation potentials and the nearest weather station to each town or city was utilised to estimate

| Variable                | Technology       | Utilisation Factor | Installed Capacity per Unit Available Area and Runoff Coefficients |
|-------------------------|------------------|--------------------|---------------------------------------------------------------------|
| Roof Area               | Photovoltaics    | 0.4 and 0.5        | 0.102 kWp/m²                                                         |
|                         | Rainwater harvesting | 1.0              | 0.700 and 0.900 m³ harvest water/m³ rainfall                        |
Quantification of annual carbon savings from deployed technologies

The final methodological step was calculation of the carbon savings associated with deployment of each technology. Similar to findings from a previous study [25], the amount of electricity or water generated from the technology installed was multiplied by the relevant carbon emission factor of each activity. The Irish national grid electricity carbon emission factor of 482.8 gCO2/kWh for 2016 [42] was utilised to estimate the emissions offset by replacing grid electricity with onsite PV generation. There were no published emissions factors available for Irish water supply emissions that may be offset by rainwater harvesting systems. Due to the subsequent need for proxies and the observed similarity in planning and urban form between Ireland and the UK, the UK water supply emission for 2016 of 0.344 kgCO2e/m3 [43] was adopted here to estimate carbon savings from rooftop rainwater harvesting in Ireland.

Results

Estimation of building footprint of industrial and commercial buildings in Ireland

The number of buildings and associated footprint area for industrial and commercial zoned buildings was calculated for Ireland (Table 3). The range of buildings zoned within the industrial and commercial zone included warehouses, data centres, pharmaceutical plants, headquarters for information and communication technology companies, and financial sector buildings.

In relation to building profile characterisation for industrial and commercially zoned buildings in Ireland, it was evident that smaller buildings (< 1000 m2) made up the majority of buildings. Thus, 70% of buildings collectively accounted for just 16% of the sector’s total footprint (Fig. 2). Conversely, the 4% of buildings which were > 5000 m2 in area accounted for 38% of industrial and commercial building footprint. Thus, prioritising decarbonisation actions for the larger buildings may offer the greatest initial decarbonisation potential for the sector.

Application of the method showed that the total Irish industrial and commercially zoned building footprint was ~ 18 times larger than that of the HEIs [25], and thus showed a major decarbonisation potential in meeting national decarbonisation objectives. (It is also of interest to note here that ~ 30% of the HEI building footprint is included in the CORINE industrial and commercial zone.) A significant association was

Table 2
Largest urban area and nearest weather station for each Irish administrative area.

| Administrative Area | Largest Urban Area (CSO, 2016) | Nearest Weather Station |
|---------------------|-------------------------------|-------------------------|
| Carlow              | Carlow                        | Kilkenny                |
| Cavan               | Cavan                         | Clones                  |
| Clare               | Ennis                         | Shannon                 |
| Cork City           | Cork                          | Cork Airport            |
| Cork County         | Cobh                          | Cork Airport            |
| Donegal             | Letterkenny                   | Malin Head              |
| Dublin City         | Dublin                        | Dublin Airport          |
| Dublin South        | Rathcoole                     | Casement                |
| Dun Laoghaire-Rathdown | Dun Laoghaire               | Casement                |
| Fingal              | Swords                        | Dublin Airport          |
| Galway City         | Galway                        | Belmullet               |
| Galway County       | Tralee                        | Belmullet               |
| Kerry               | Tralee                        | Valenica                |
| Kildare             | Newbridge                     | Casement                |
| Kilkenny            | Kilkenny                      | Kilkenny                |
| Laois               | Portlaoise                    | Birr                    |
| Leitrim             | Carrick-On-Shannon            | Belmullet               |
| Limerick City       | Limerick                      | Shannon Airport         |
| Limerick County     | Newcastle West                | Shannon Airport         |
| Longford            | Longford                      | Mullingar               |
| Louth               | Drogheda                      | Clones                  |
| Mayo                | Castlebar                     | Belmullet               |
| Meath               | Navan                         | Mullingar               |
| Monaghan            | Monaghan                      | Clones                  |
| Offaly              | Tullamore                     | Birr                    |
| Roscommon           | Roscommon                     | Belmullet               |
| Sligo               | Sligo                         | Belmullet               |
| Tipperary North     | Nenagh                        | Birr                    |
| Tipperary South     | Clonmel                       | Kilkenny                |
| Waterford City      | Waterford                     | Rosslare                |
| Waterford County    | Tramore                       | Rosslare                |
| West Meath          | Athlone                       | Mullingar               |
| Wexford             | Wexford                       | Rosslare                |
| Wicklow             | Bray                          | Casement                |

Table 3
Industrial and commercial sector building footprint in Ireland.

| Attribute                              | OpenStreetMap for 121IC (CORINE Industry and Commercial Zone) |
|----------------------------------------|---------------------------------------------------------------|
| Number of buildings                    | 17,986                                                        |
| Minimum building size (m²)             | 10                                                            |
| Maximum building size (m²)             | 84,014                                                        |
| Footprint area (m²)                    | 20,939,982                                                    |
| Average roof area m²/ building         | 1164                                                          |

Fig. 2. Industrial and commercial building number and footprint area by building footprint size.
found between HEI building footprint area at HEIs and industrial and commercially zoned buildings (excluding these HEI buildings) at 1000 m² intervals was found (Spearman Rank, R² = 0.95). This finding, coupled with the campus-like layout of many industrial and commercial buildings, supports the observation that there are considerable similarities among HEI, industrial and commercial building footprints.

**Disaggregation of building footprint area by administrative area**

The number of buildings and building footprint area for industrial and commercial zoned buildings was disaggregated to each local administrative area (Table 4). It should be noted that as building footprints may cross administrative boundaries, there was some double counting of building numbers and footprints, which was estimated to represent 0.3% of building numbers and 0.1% of the building footprint. Due to this negligible level of double counting, it was disregarded when carrying out calculations of the potential for decarbonisation technologies for the industrial and commercial zoned buildings nationally.

**Decarbonisation technology deployment potential**

The potential PV installations that may be deployed was found by applying the utilisation factors and installed capacity per unit area (Table 2) to the industrial and commercial footprint area of each administrative area (Table 4). National PV installed capacity was estimated at between 855,490 kW and 1,069,363 kW for utilisation factors of 0.4 and 0.5 respectively.

**Climatic conditions to estimate energy and material output**

From data on local climatic conditions, it was possible to estimate the electricity output for building integrated PV, and the volume of rainwater that may be harvested from rooftops, for each administrative area. The minimum, maximum, mean and standard deviation of rainfall and solar potentials across Irish administrative areas are shown in Table 5. The greatest solar potentials are available in the east and south east regions of Ireland, while the southwest and west regions had the highest rainfall values. Based on these climatic variables, national electricity output for building integrated PV at industrial and commercial zoned buildings was estimated between 851 GWh and 1063 GWh for utilisation factors of 0.4 and 0.5 respectively. Potential rainfall volume that may be harvested was estimated between 13,415,404 m³ and 17,248,376 m³ for runoff coefficients of 0.7 and 0.9 respectively.

**Decarbonisation potential at industrial and commercial zoned buildings in Ireland**

Based on a national grid electricity carbon intensity of 482.8 gCO₂/kWh for 2016 [42] the potential reduction in carbon emissions due to building integrated PV was estimated (Table 6). Potential carbon savings for industrial and commercial buildings nationally from PV was found to be between 410,652 tCO₂ and 512,703 tCO₂ for utilisation factors of 0.4 and 0.5 respectively. To estimate carbon saving from the deployment of rainwater harvesting systems, the volume of rainwater that may be harvested was multiplied by the water supply emission factor for 2016 (0.344 kgCO₂e/m³) to estimate carbon savings from onsite rainwater harvesting [43]. Total carbon savings nationally for industrial and commercial buildings was estimated to be between 4615 and 5933 tCO₂e for runoff coefficients 0.7 and 0.9 respectively (Table 6).

The carbon emissions associated with electricity consumption from industrial, commercial and public service sectors in Ireland for 2016 was reported to be 8.25 Mt CO₂ [44]. The proposed savings resulting from PV installations on industrial and commercially zoned buildings identified in this study, for a 2016 steady state system, would reduce sectoral electricity emissions by 6.2%. The potential future carbon emissions associated with the industrial, commercial and public service sector were categorised into three scenarios, as shown in Fig. 3, namely: (1) No improvement in grid electricity intensity from 2016, (2) Decarbonisation trajectory based on extrapolation of grid decarbonisation intensity between 2010 and 2016 and (3) Decarbonisation trajectory scenario plus PV deployment. For the first scenario, electricity final consumption from industrial, commercial and public service sectors in Ireland is projected to increase by 60% compared to 2016, by 2030 [44] resulting in a 60% increase in emissions. The second scenario accounts for projected electricity grid intensity decarbonisation based on extrapolation to 2030 of historical Irish national electricity grid decarbonisation for the period 2010–2016, resulting in a grid intensity of 331 gCO₂/kWh by 2030 (a 31% reduction compared to 2016). This would result in carbon emissions for the sector increasing to 9.05 Mt CO₂, an increase of 9.7% in relation to the 2016 baseline for the grid.
The method employed here is designed to provide preliminary learning, would allow for analyses of large data sets [52,53,54]. While such datasets, utilised in conjunction with machine texturized building datasets in cities in Germany, Austria and the Netherlands [51], and OpenStreetMaps data are available, opportunities also exist for machine learning algorithms applied to satellite imagery, to allow for verification of decarbonisation technology deployment. Employment of such technologies will allow for more accurate and straightforward building characterisation, and for monitoring the future performance of rooftop-based decarbonisation technologies.

Future research agenda to develop approach

The method described here has the potential to be applied to industrial and commercial zones in other European countries where CORINE zoning is available [48], and OpenStreetMaps data are available, offering the potential for pan-European preliminary estimates of outcomes for the deployment of decarbonisation technology. Additionally, the method may be adapted to other CORINE land cover zones such as (i) continuous urban form and (ii) discontinuous urban form. To allow for more detailed analysis of the decarbonisation potential of rooftop-based decarbonisation technologies will allow for more accurate and straightforward building characterisation by building characterisation, and for monitoring the future performance of rooftop-based decarbonisation technologies.

Table 6

| Technology                     | Carbon Saving Potential |
|-------------------------------|-------------------------|
| Photovoltaic (0.4 utilisation factor) | 416,652 tCO₂         |
| Photovoltaic (0.5 utilisation factor) | 512,703 tCO₂         |
| Rainwater Harvesting (0.7 runoff coefficient) | 4615 tCO₂e        |
| Rainwater harvesting (0.9 runoff coefficient) | 5933 tCO₂e        |

Decarbonisation scenario. The third scenario adds the carbon saving potential from onsite electricity generation from PV to the projected grid decarbonisation scenario which would limit emission growth to 5.4% by 2030, based on 2016 baseline. These scenarios suggest that the greatest decarbonisation potential for the sector is from decarbonisation of the national grid through largescale renewable electricity projects offsite, while the carbon offset from onsite PV generation decreases over time due to this projected electricity grid decarbonisation (32% reduction in grid intensity). This suggests that the earlier PV is deployed on industrial and commercially zoned buildings, the greater the carbon emissions they will offset. It may be expected that improvements in PV efficiency over time will improve the potential electricity output of PV systems, but would need to improve by 33% to keep pace with projected national grid decarbonisation. This medium-level method highlights the technological deployment potential associated with PV and rainwater harvesting, which may contribute to more reliable future decarbonisation projections for Ireland, which in general have adopted low-level methods based on aggregate statistical data [45,46,47] without appropriate consideration of spatial data derived through application of GIS.

Discussion and conclusions

This paper describes the development and the successful application of a method for estimating the deployment potential of rooftop decarbonisation technologies on industrial and commercial zoned buildings in Ireland. The potential carbon savings resulting from this feasibility study include up to 513 ktCO₂ for building integrated PV and almost 6 ktCO₂ for roof rainwater harvesting technologies. Such decarbonisation studies based on roof area for Ireland previously have not been reported in the academic literature. The implications of this research from a national decarbonisation policy context is the identification of the technological deployment potential for each local administrative area in contributing to national decarbonisation targets, which was found to be lacking in Ireland’s current national planning. The need for prioritisation of large industrial and commercial buildings was also evident, with building profile characterisation by building footprint finding that a small number of large buildings (4% of total buildings) account for the greatest overall carbon reduction potential (38% of total area). Carbon emission scenarios identified that electricity demand is expected to rise for the sector up to 2030, with decarbonisation of the national grid limiting growth in carbon emissions. Large scale deployment of PV on industrial and commercially zoned buildings have the potential to reduce GHG emissions for the sector by a further 4%. Future scenarios highlighting that PV efficiency would need to increase by a third to keep pace with national grid decarbonisation potential based on historical trends. The proposed method has the potential to be applied to industrial and commercial zones in other European countries where CORINE zoning and OpenStreetMaps data are available, offering the potential for pan-European preliminary estimates of decarbonisation technology deployment. Freely available LiDAR data would allow for more detailed analysis by allowing 3D building databases to be generated. Opportunities also exist for machine learning algorithms applied to satellite imagery, to allow for verification of decarbonisation technology deployment. Employment of such technologies will allow for more accurate and straightforward building characterisation, and for monitoring the future performance of rooftop-based decarbonisation technologies.

![Fig. 3. Decarbonisation projections for the industrial, commercial and public service sector in Ireland.](image-url)
CRediT authorship contribution statement

William Horan: Conceptualization, Methodology, Writing - original draft. Susan Byrne: Methodology, Writing - review & editing. Rachel Shawe: Visualization, Writing - review & editing. Richard Moles: Investigation, Writing - review & editing. Bernadette O'Regan: Supervision, Funding acquisition, Writing - review & editing.

Declaration of Competing Interest

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