Whole life carbon of photovoltaic installations

TECHNICAL REPORT - FEBRUARY 2022

ELEMENTA

WILLMOTT DIXON

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Abstract

This study investigates the embodied and operational carbon impact of roof mounted solar photovoltaic (PV) installations. It includes an in-depth assessment of the embodied carbon of PV systems and frames a discussion on the most relevant metric for making decisions on the installation of PV.

Photovoltaic (PV) is an important source of renewable energy generation, and rooftop solar can contribute a significant part of the government roadmap to meet UK climate targets. This paper explores the interplay between embodied carbon impact and the operational carbon savings for various roof mounted PV system installations.

This study concludes that a 'payback' approach for PV installations (i.e. embodied carbon impact compensated by the operational carbon savings) is not the right metric while we are in midst of an energy transition towards 100% renewables. Embodied carbon will have to be invested to achieve full grid decarbonisation and rooftop solar PV should continue to play a vital role in supporting this transition. Nevertheless, the study found that the embodied carbon to be between 520 – 780 kgCO2e/ kWp, which is less than the operational carbon savings over a 25-year study period based on a UK grid.

The study concludes that rooftop solar PV can represent a valuable investment of embodied carbon, but that built environment professionals should employ detailed embodied carbon assessments to ensure that impacts are minimised through intelligent design and specification decisions on a project-by-project basis.

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Introduction

Why does it all matter?

As the latest IPCC report[1] reminds us, 2020-2030 is a very decisive decade, our last chance at preventing climate breakdown and run-away climate change. All parts of the economy will have to transition to net zero with urgency and at pace for us to stabilise the climate and limit global warming below 1.5 degrees C.

Elementa Consulting, forms part of an international network of engineers and consultants collaborating under a single “deep green” umbrella. We enable every client to protect the health of our planet, by taking a regenerative approach to the design, performance and function of buildings, communities, districts, and cities. We provide a full range of building and district systems engineering, analysis, and sustainability consulting services, delivered by staff widely regarded as innovative leaders in their fields. Our work spans the globe, delivered from offices in Australia, Canada, Europe, and the United States. Our projects are located in over 30 countries – with more than 100 net zero energy buildings. Elementa Consulting are proud to be founding signatories of the World Green Building Council’s Net Zero Carbon Buildings Commitment, signatories of UK Engineers Declare, and primary authors of CIBSE TM65 Embodied carbon of building services: a calculation methodology and CIBSE TM65.1 Embodied carbon of building services: residential heating.

Willmott Dixon has responded to the climate emergency with a sector-leading sustainable development strategy, Now or Never. Our decisive decade, which sets out how the business will commit to becoming net zero carbon by 2030. Furthermore, by 2030, all of Willmott Dixon’s projects, where they have early-stage design responsibility, will be delivered to net zero operational carbon standards. As part of Now or Never, the contractor is assembling a suite of technical solutions they intend to test using whole life carbon and cost modelling approaches, to be able to offer a net zero carbon option on all projects going forward. One of those solutions is Willmott Dixon’s community solar energy offer, that provides PV infrastructure, capital free through a power purchase agreement partnering with a community energy organisation.

What is this research trying to address?

Solar photovoltaic (PV) panels play a central role in decarbonising our grid. PV panels are becoming a ubiquitous solution to increase on-site renewable energy generation, on both new build and major refurbishment projects, to meet net zero operational carbon goals. Capital costs for PV systems have also decreased significantly in recent years due to the economies of scale manufacturing for large grid-scale solar installations. The Renewable Energy Hub reports that in 2021 enough energy was generated by PV across the globe to power over 30 million households[2] . However, like any other product, PV installations come with an embodied carbon impact: greenhouse gas emissions associated with production; construction; in use and end of life stages. Moreover, PV panels require accessory equipment such as support, cabling, and inverters, which also have an embodied carbon impact.

Rooftop solar PV is required to achieve a decarbonised grid, therefore the embodied carbon of PV needs to be better understood. However, we often find that we don’t yet have all the data available to make decisions. This study is a first attempt to provide further insight.

We encourage others to further this work with larger datasets and look to manufacturers of these systems, to collect better data and make it more freely available to built environment professionals. We also suggest similar studies are carried out for other renewable energy generation technologies (e.g., wind, solar thermal).

Carbon balance of PV installation over life span

Figure 1 shows an example of the total carbon balance of a typical PV installation over an assumed life span of 25 years. The carbon impact of a PV installation over its lifetime can be expressed as the cumulative sum of its associated embodied carbon and its operation carbon savings, taking into account repair/replacement and end of life decommissioning.

1 IPPC Report from Working Group I issued in August 2021 [AR6 Synthesis Report: Climate Change 2022 — IPCC]

2 https://www.renewableenergyhub.co.uk/main/solar-panels/solar-panels-carbon-analysis/

3 https://www.leti.london/_files/ugd/252d09_879cb72cebea4587aa860b05e187a32a.pdf

4 https://www.cibse.org/knowledge/knowledge-items/detail?id=a0q3Y00000IPZOhQAP

There is an initial embodied carbon impact associated with producing and installing the entire system onsite (modules, mounting system, associated equipment, etc.). This is shown by the tall blue column in Figure 1.

The PV panels produce renewable electricity and for every kWh generated, it is assumed that the grid does not need to produce this kWh of electricity, thus the ‘avoided’ carbon emissions are thought of as an operational carbon saving. The ‘dirtier’ the electricity grid, the greater the amount of carbon is avoided. This also means that as the electricity grid decarbonises, the avoided emissions are smaller, and thus the energy generated by PV panels has less and less of a carbon-reducing impact (or offset mechanism).

There is a period of repair and replacement (e.g., the inverter), shown at 12.5 years, which also has an associated embodied carbon impact. At end of life of the PV system - the decommissioning, waste processing and recycling also have an embodied carbon impact.

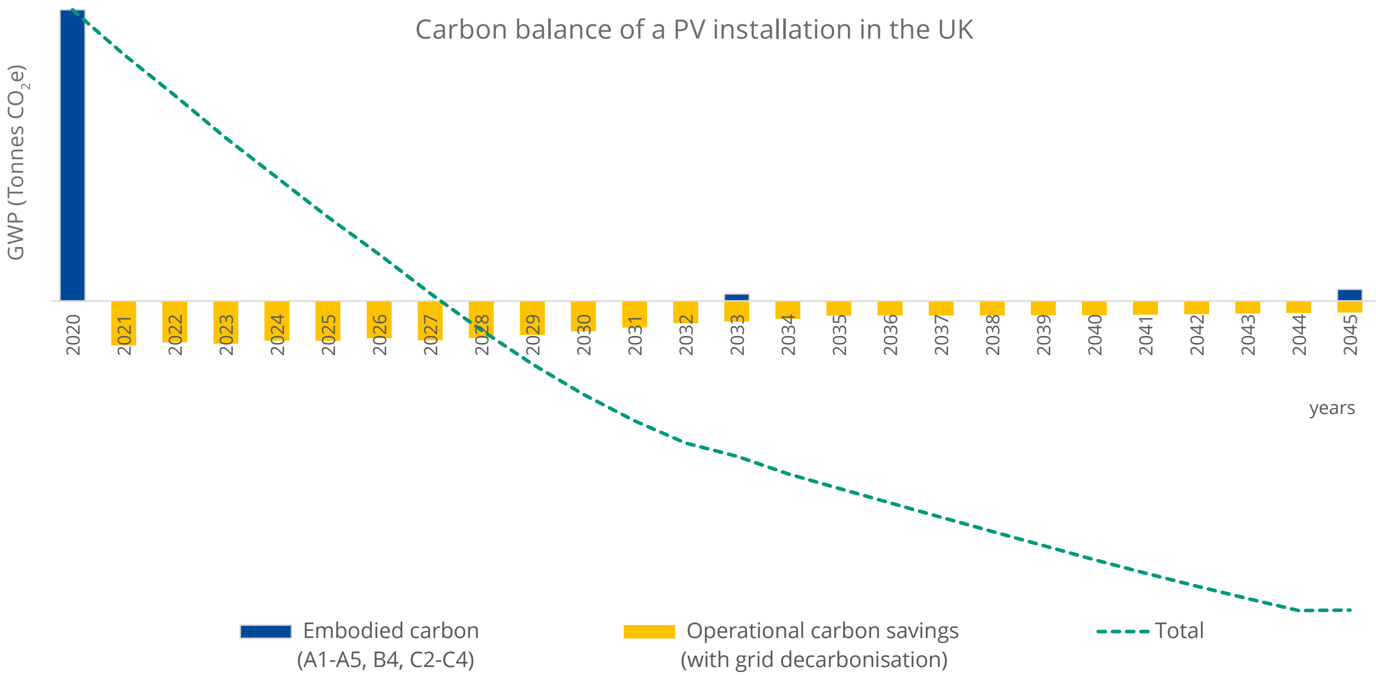


Figure 1 – Whole life carbon balance of a typical PV installation. The operational carbon factor used include a decarbonisation scenario (see p.11).

Definition of Terms

Carbon definitions and lifecycle stages - This study aligns with the WLCN, LETI, RIBA definition of carbon published in May 2021[3] and EN 15978 framework around lifecycle stages:

- **Embodied carbon:** greenhouse gas emissions associated with A1-A5 (product & construction), B1-B5 (use), C1-C4 (end of life).
- **Operational carbon:** greenhouse gas emissions associated with energy use (B6) and water use (B7) during the building lifetime. This study only explores carbon savings within B6 associated with PV electricity generation.
- **Whole life carbon:** greenhouse gas emissions associated with embodied carbon, operational carbon and any benefits or loads associated with reuse, recycling and recovery (module D). However, Module D is not considered within this study.

Environmental Product Declaration (EPD): independently verified and registered document that communicates transparent and comparable information about the life cycle environmental impact of a product (CIBSE, 2020).

CIBSE TM65 [4]: embodied carbon calculation methodology for building services equipment published by CIBSE in 2020, authored by Elementa Consulting, to be used when no EPDs are available. Two levels of calculations are possible depending on manufacturer data collected: basic and mid-level.

Objectives

The use of solar photovoltaic (PV) for onsite renewable energy generation is now a significant factor in the vast majority of new projects to help achieve net zero operational carbon objectives for new-build or major refurbishment projects, in line with LETI guidance and the UKGBC Advancing Net Zero Framework.

While solar PV is a proven and highly reliable means of renewable energy generation, it has, along with all MEP products and construction materials, an embodied carbon impact associated with its manufacture, supply, maintenance and end of life.

This research aims to understand the embodied and operational carbon impact of rooftop solar PV. It explores different installation types across 4 different scenarios.

As building embodied carbon targets are further refined and developed (e.g., RIBA 2030 challenge and LETI targets[5]), the question of whether to include the embodied impacts of PV installations within the embodied carbon building target becomes important. PVs are needed therefore we need to understand their embodied carbon implications and identify any opportunities to reduce its impact.

5 [Embodied Carbon Target Alignment.]

Right: Boulder Commons Campus
The large PV[array for this project is sized to offset all of the energy that the campus uses over the course of a year, in order to achieve the Zero Net Energy goal. Elementa/Integral Group project.

Scope of the Study

Case studies

To investigate this topic, calculations were based on two actual UK projects currently in their preconstruction phase (both set to complete in 2023). Project specific data on equipment specifications, quantities and energy generation estimates were made available via Willmott Dixon's supply chain partners using industry-recognised and accredited design software (see Table 1).

Project	Building Type	Location	kWh annual PV generation	kWpeak	PV panel area m²	Roof type / PV orientation
A	School	Wiltshire	417,265 kWh	437.6	2,103	Flat - various
B	Theatre	Bristol	114,076 kWh	125.3	634	Pitched – East/ West

Table 1 – Case study projects key characteristics

Equipment included

Most existing studies[6] looking at the embodied carbon impact of PV typically only include the modules themselves. However, PV panels require accessory equipment: support, wiring, inverters and quite often optimisers (to maximise the efficiency of electricity generation). This study investigates the entire installation, and thus the scope (see Table 2):

Category	Equipment	Project A	Project B
PV	PV panels	✓	✓
Optimiser	Optimisers	✓	✓
Inverter	Inverters	✓	✓
Supports	Mounting rails	✓	✓
	Module Clamps	✓	✓
	Supports	✓	✓
Ballast	Concrete tiles	✓	N/A
Other Electronics	Generation meter	✓	✓
	Ballast	✓	✓
	DC wiring	✓	✓
	Local AC isolator	✓	✓

Table 2 – Equipment scope considered as part of the study

Ancillary equipment related to roof access and maintenance were not included in the calculations scope, as this was required for general roof construction/maintenance.

Different types of PV panels (known also as modules) exist. It was decided to explore the research question with two different module types, as quoted for by our supply chain partners on the projects:

Monocrystalline PV module: Monocrystalline cells are solar cells made from silicon crystallised into a single (i.e. mono) crystal. The manufacturing process is more complicated than other technologies (e.g., polycrystalline silicon cells) but achieves fewer defects or impurities which generally results in higher efficiencies (15-24% compared to 13-20% in polycrystalline cells). The efficiency gain in Monocrystalline systems can result in generating greater power and annual energy output from the same roof area. Most modules employing crystalline silicon wafers require an aluminium frame for structural robustness (or glass backing for frameless modules), which add significant embodied carbon. This is in addition to the mounting structure which is often an aluminium frame system to accommodate a variety of installations and roof types.

Thin-film PV module: A PV product made up of thin-film semiconductors, often about 20 times thinner than more traditional crystalline silicon wafers, deposited on glass, plastic or metal. The reduction in thickness makes thin-film solar panels more flexible and lightweight, when encased in plastic these can become flexible enough to mould to roof shapes. There are three common thin-film divisions: amorphous silicon, cadmium telluride and copper indium gallium selenide. Efficiencies in thin-film products are typically lower than more traditional panel systems (<17% for thin-film vs >21% for monocrystalline), so more roof area might be required to achieve the same power and annual energy output. However, the product is much lighter, more adaptable and requires less fixings or support. Potential downsides are about recycling the modules, where material recovery is more difficult due to the bonding process. Furthermore, the technology does not work on some roof coverings (e.g., roof tiles).

Figure 2 - Monocrystalline PV installation on flat roof

Image source

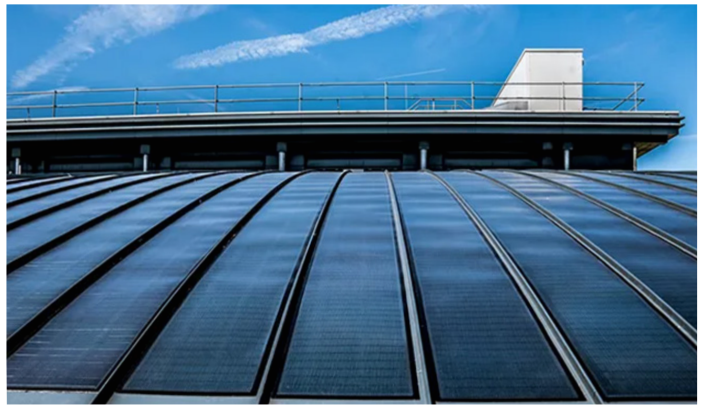


Figure 3 - Thin-film PV installation on standing seam metal roof

Image source

Scenarios considered

PV optimisers can offer benefits in terms of increased output for partially shaded systems, and improved system control/data acquisition, but are not always included within PV installations. We decided to investigate two further system options (with and without optimisers) in this study to understand the effects on the overall carbon balance.

The thin-film technology was only tested on project B, due to the roof type and covering on project A not being suitable for this system.

Table 3 below summarises the four scenarios analysed in this study.

Scenario	Project	PV type	Optimisers	Support type	Notes
Scenario 1	A	Monocrystalline	Included	Ballast + mounting frames	
Scenario 2	B	Monocrystalline	Included	Roof clamps + mounting rails	
Scenario 3	B	Monocrystalline	Not included	Roof clamps + mounting rails	Different higher efficiency inverter type used than in scenario 2
Scenario 4	B	Thin-film	Not included	Bonded to existing roof	Reduced PV electricity generation because of lower PV panel efficiency

Table 3 – The four scenarios evaluated in this study

6 For instance, Hilson Moran's study: (3) To PV or not to PV? | LinkedIn (payback in 6 years), or this study **Solar Panels Carbon Payback | The Renewable Energy Hub** (pay back in 2.5 years) or this study **Energy payback time and carbon footprint of commercial photovoltaic systems - ScienceDirect** (pay back in 0.68 to 1.96 years)

Methodology and Assumptions

Study period

The study was carried out for a lifecycle period of 25 years, which is normally considered the guaranteed service life of a PV panel. Most manufacturers provide both product and power warranties for their PV panels. Product warranties are typically shorter (perhaps 10-12 years) and cover manufacturing defects, environmental issues and premature wear and tear. Power warranties are over a longer time span and guarantee a certain level of performance at year 25, taking module degradation into account (typically a minimum of 80% power at 25 years). PV modules can last a lot longer than 25 years, but power drop off becomes harder to predict, so warranties typically only extend to 25 years. For simplicity and accuracy, we have based the service life on these power warranties in line with most Environmental Product Declarations (EPDs).

Embodied carbon calculations

Bill of materials

Material quantities of the systems tested in this study are based on supply chain partner data and can be found in the following Table 4:

Scenario	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Total weight of PV panels (kg)	24,186	7,290	7,290	3,531
Total weight of optimisers (kg)	1,258	365	N/A	N/A
Total weight of inverter (kg)	330	48	84	48
Total weight of mounting system (kg)	3,118	1,087	1,087	N/A
Total weight of ballast (kg)	21,884	N/A	N/A	N/A
Total weight of cables (kg)	90	18	18	18
Total weight of electricity meters (kg)	6	2	2	2

Table 4 – Bill of quantities by scenario

Data

Unfortunately, EPDs are not yet available for all the equipment considered within the study. As the aim was to do a generic study, the data hierarchy was set up as follow:

- 1st: create average of relevant & comparable EPDs (minimum of 3)
- 2nd: if not possible, find one plausible EPD (ideally industry average EPD)
- 3rd: if nothing available, using CIBSE TM65 calculations to estimate embodied carbon based on manufacturer information about material composition breakdown.

Table 6 on page 12 summarises the data sources. In the case of CIBSE TM65 calculations, the basic calculation method was used due to limited manufacturer information available. The basic calculation method relies on material composition breakdown, the weight of the product, as well as the complexity of the product. CIBSE TM65 defines 3 levels of complexity, level 1 designates products with a short supply chain, and level 3 long supply chains. More information concerning the selection of PV panel EPDs can be found in the results section.

Life cycle stages

All embodied carbon life cycle stages were included except: B1 (use), B2 (maintenance), B3 (repair), B5 (refurbishment), C1 (deconstruction). This was due to the lack of available data and the small impact associated with those lifecycle stages for PV modules. For A5 (construction), only impact associated with material wastage was accounted. In summary, the following lifecycle stages: A1-A5 (raw material extraction and processing, transport, manufacturing, installation), B4 (replacement), C2-C4 (transport to waste facility, waste processing, and disposal) were estimated. Module D is not included in this study.

Operational carbon calculations

The annual kWh associated with PV generation was assessed by Willmott Dixon's supply chain partner Solarsense using industry standard software PV*Sol premium 2021 (Valentin Software GmbH), which is based on UK climate data and project geometry/orientation.

Power warranties (at 25 years) allow for year-on-year power degradation estimates, typically <2% in the first year of operation and 0.55% from year 2 to 25 for monocrystalline modules and slightly higher for the thin-film modules. For the monocrystalline panel types, we have assumed a year-by-year degradation of 0.6%, and for the thin-film modules: 0.8% (Table 5 below).

PV types	Thin-film	Monocrystalline
Power warranty at year 25	80%	85%
Assumed year on year degradation	0.8%	0.6%

Table 5 - Assumed power degradations from 25-year power warranty

The conversion of generated energy data into consequent savings in operational carbon from displaced grid electricity was carried out in two different ways, as shown in the results section below:

- With a variable carbon emission factor over time, based on the UK Green book 2020 predictions for the period 2021 to 2046. These emission factors are forecast to drop considerably over time as the grid decarbonises due to increased renewable energy generation from large scale wind, solar etc.
- With a fixed carbon emission factor for 2021 of 0.291 $kgCO_2e/kWh$ as per DUKES (Digest of UK Energy Statistics); this approach is consistent with what is adopted for most building energy compliance modelling software such as SAP, IES etc. This ensures a consistent approach as embodied carbon impact associated with repair in the future does not currently take into account grid decarbonisation.

Table 6

Equipment	Product	Embodied Carbon Data source	Material composition breakdown	Service life (years)	Weight (kg)	Waste % during construction	Recycling % at End of Life (EOL)
Source	Project Specs	Data availability	Product specs			Assumption	Specs
PV modules	Monocrystalline -20% efficiency	Average between 3 EPDs: Trina Solar (TSM-DEG15M.20(II)), Jinko (KMXXXM-72H-TV (Swan)), Sun Power Energy Solutions (MAXEON 3)	See section about embodied carbon & PV panels below	25	11.5 kg per m^2	1%	88%
	PV thin-film	CIBSE TM65 Mid-level calculation, complexity level 3 used ICE average datapoint for A1-A3	Unknown – used ICE database datapoint		3.81 kg per m^2		15%
Optimiser	Solar Edge P801 Worldwide(v1)	CIBSE TM65 Basic calculation, complexity level 2	25% aluminium, 60% electronics, 15% plastics (Global values)	25	2.1 kg per unit	0%	n/a*
	Solar Edge P850 Worldwide(v1)				2.3 kg per unit	0%	
Inverter	SE25K	CIBSE TM65 Basic calculation complexity level 2	0.3% stainless steel, 13.4% steel, 4.6% zinc, 12.2% copper, 7.7% aluminium, 14.6% electronics, 3.1% ceramic, 44.1% epoxide resin (Global values)	12	138 kg per unit	0%	
	SE82.8				48 kg per unit	0%	
	Solis-100K-5G (v3)				kg per unit	0%	
Mounting Rails	K2 SolidRail medium 42	CIBSE TM65 Basic calculation complexity level 1	100% aluminium (European)	25	1.34 kg per m	5%	
	K2 D-Dome Rails				1.305 kg per m	5%	
Module Clamps	K2 OneMid, middle clamp	CIBSE TM65 Basic calculation complexity level 1	100% aluminium (European)	25	0.06 kg per unit	0%	
	K2 D-Dome clamps				0.06 kg per unit	0%	
Roof Clamp / Rail Fixings	K2 S-5! Z-Mini-FL Round SeamClamp	CIBSE TM65 Basic calculation complexity level 1	100% aluminium (European)	25	0.06 kg per unit	0%	
Ballast	Concrete Tile Ballast Slabs - small	Manufacturer EPD from HBF manufacturer for results A1-A3, remaining assumptions using CIBSE TM65	100% concrete	25	4.5 kg per m^3	0%	0%
	Concrete Tile Ballast Slabs - bigger				9 kg per m^3	0%	
Generation meter	Legrand meter	Manufacturer PEP from Legrand (meter 412010)	12% copper, 0.2% steel, 20% plastic, 4% electronics	25	0.491 kg per unit	0%	80%
Comms cabling	cat6 cable UTP	Manufacturer PEP from Hager (Cable Wan blue RJ45 1m)	18.3% copper wire, 2.6% copper, tin 0.3%, 2.6% polyethylene, 3.4% polypropylene, other plastics 60.6%	25	0.05 kg per m	5%	17%
DC wiring	DC wire 6m^2	CIBSE TM65 Basic calculation complexity level 1	80% copper, 20% PE	25	0.04 kg per m	5%	n/a*
Local AC isolator panel & switch	-	Manufacturer EPD from Schneider (Compact ins100 t0 ins 160)	1.6% stainless steel, 42.2% UP polyester, 7.7% Polycarbonate, 9.5% copper, 28.3% steel	20	1.15 kg unit	0%	37%

Table 6 – Summary of the embodied carbon data sources

*: n/a because CIBSE TM65 basic calculations were carried out, therefore it is included within the scale up factor.

Results

Embodied carbon results by scenarios

The following graph shows the embodied carbon impact of a whole PV installation across 25 years (assumed to be a PV service life) for different scenarios.

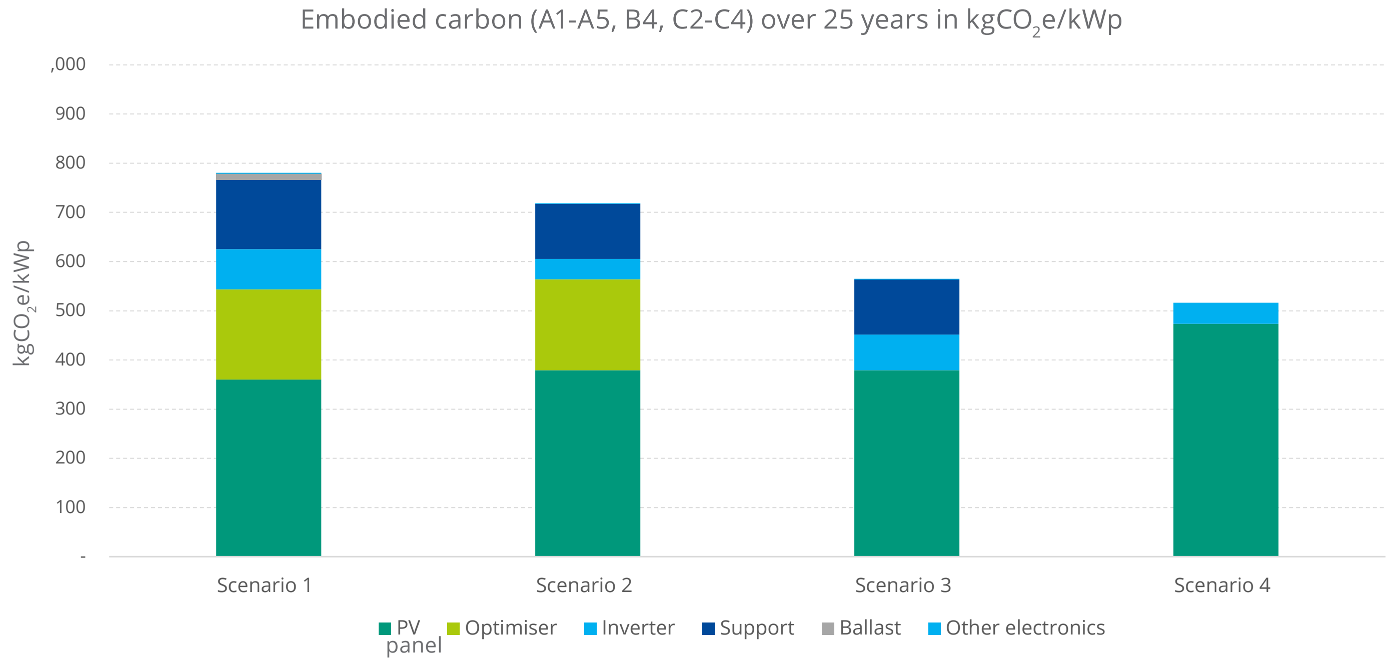


Figure 4 - Embodied carbon over 25 Years

Scenario 1: Project A, Flat roof, PV monocrystalline, Optimisers

Scenario 2: Project B, Pitched roof, PV monocrystalline, Optimisers

Scenario 3: Project B, Pitched roof, PV monocrystalline, No optimisers

Scenario 4: Project B, Pitched roof, PV thin-film, No optimisers

Embodied carbon and PV panels

The study shows that PV panels themselves have the most embodied carbon impact of a PV system: around 50% or more of the total PV installation. It should be noted that this proportion could rise quite a bit more if less attention was given to PV panel specification.

The embodied carbon data for monocrystalline PV modules used in this study, represent most recent data available (2020-2021) and also most representative of the market: Trina Solar, Sun Power Energy Solutions and Jinko together represent about 30% of the global market share.

When exploring embodied carbon data available for this study, we found an important trend in the results, which seemed to be correlated to time – meaning the embodied carbon content of PV panels is decreasing over time. Figure 5 shows embodied carbon results by kWp for different products for which EPDs were found. Figure 5 (on the following page) is aligned with Etude's study[7], which shows that the embodied carbon of PV panels is reducing over time. This is likely due to the fact that electricity grids of the countries that manufacture the panels are decarbonising.

Figure 6 (on the following page) shows the embodied carbon impact associated with A1-A3 (raw material extraction, transport to factory, manufacturing processes) for different types of PV panels per kWp. The dark green bars show the data used in the study to create the average data point used (the line represents the data used in this study).

7 [(4) The rapid fall of solar's embodied carbon | LinkedIn]

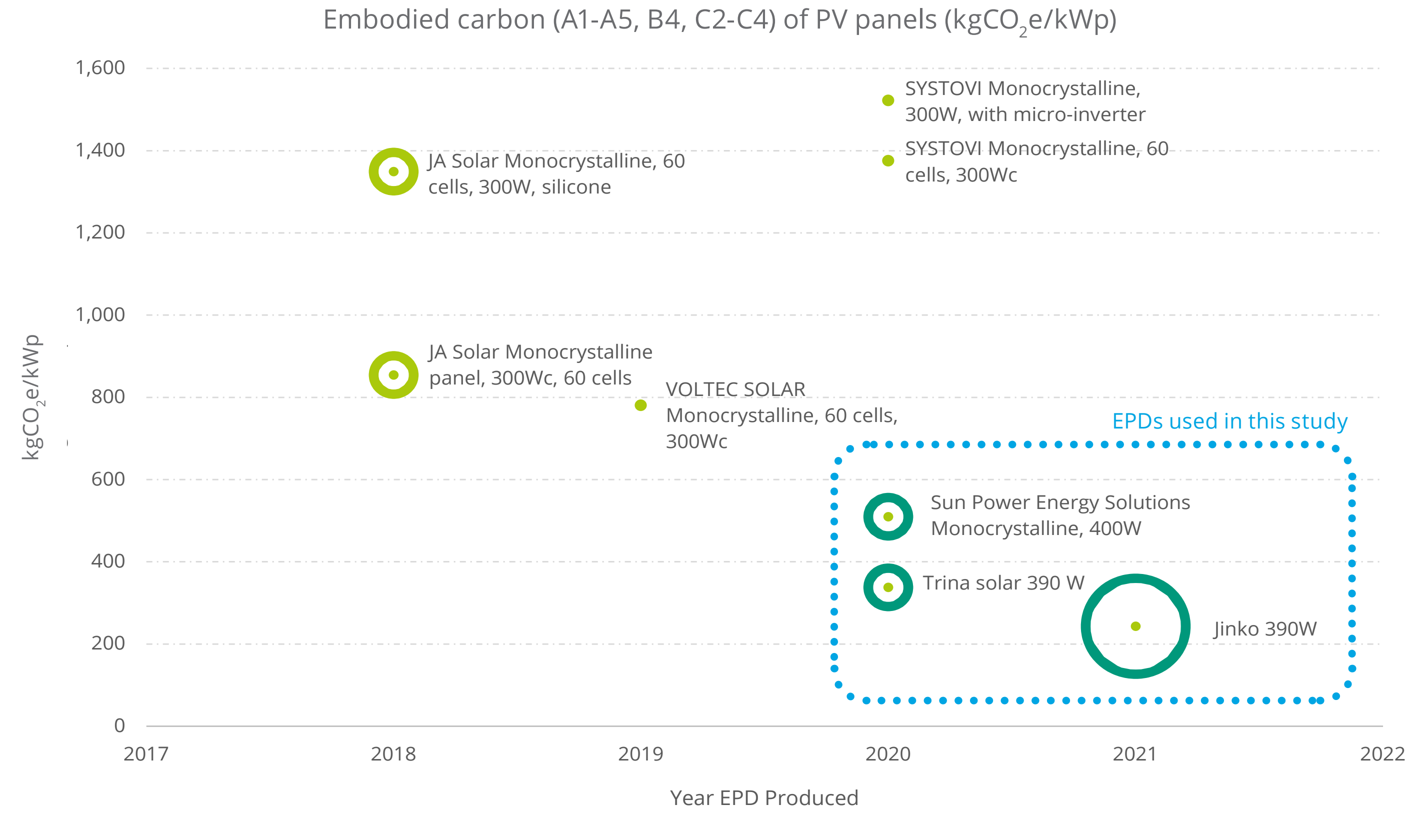


Figure 5: Embodied carbon of monocrystalline module over time. The size of the dot represent the market share, and the green dot represent the products used in the study.

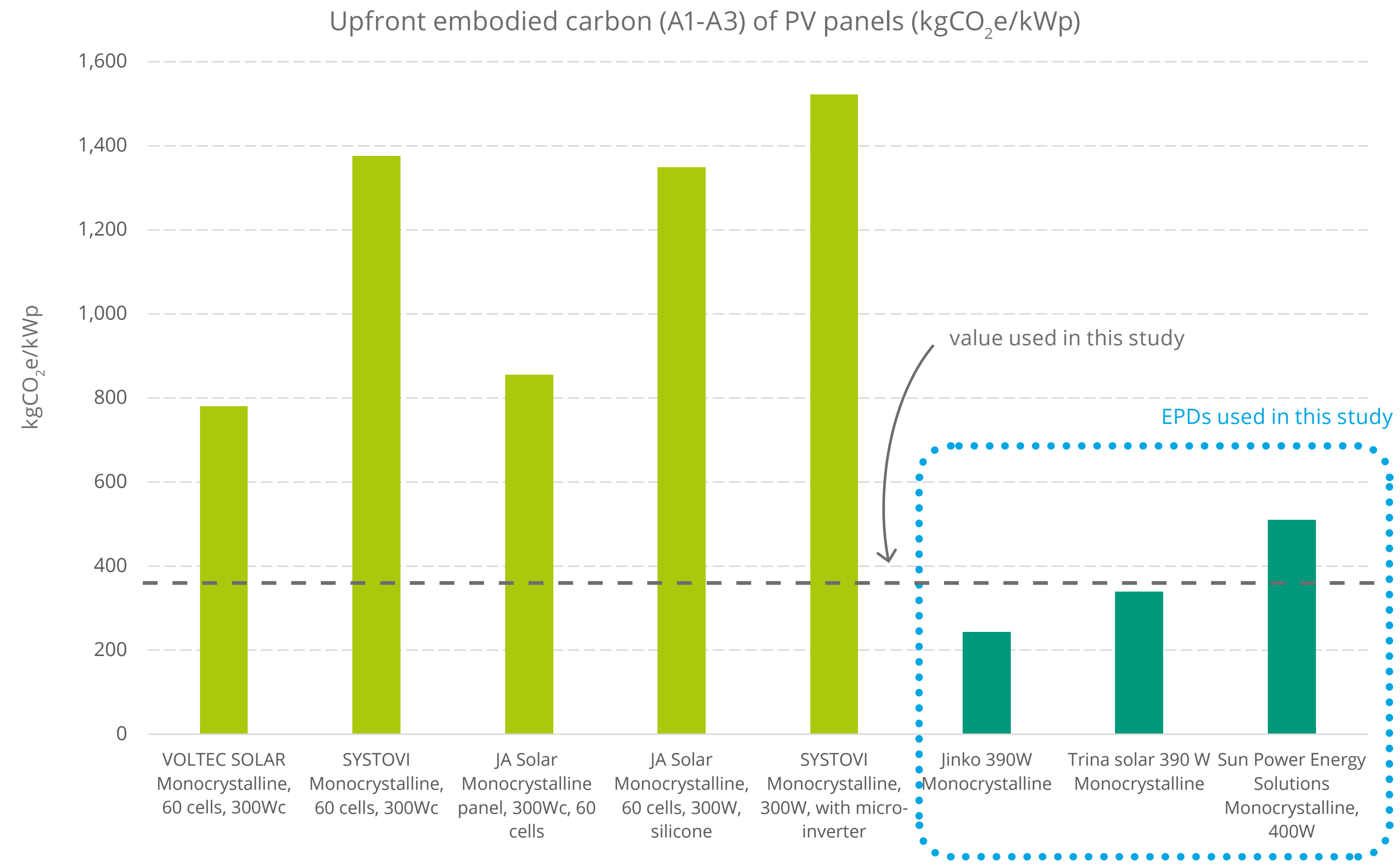


Figure 6 – Embodied carbon impact associated with lifecycle stages A1-A3 from various EPDs

Operational carbon results

Figure 7 shows the 'avoided' carbon emissions, due to the fact that the PV panels are generating electricity rather that the UK grid. These are thought of as operational carbon savings. The first bar (dark yellow) shows the operational carbon savings assuming grid decarbonisation based on information from the UK Green Guide 2020. The second bar (light yellow) shows the carbon savings assuming no decarbonisation of the UK electricity grid.

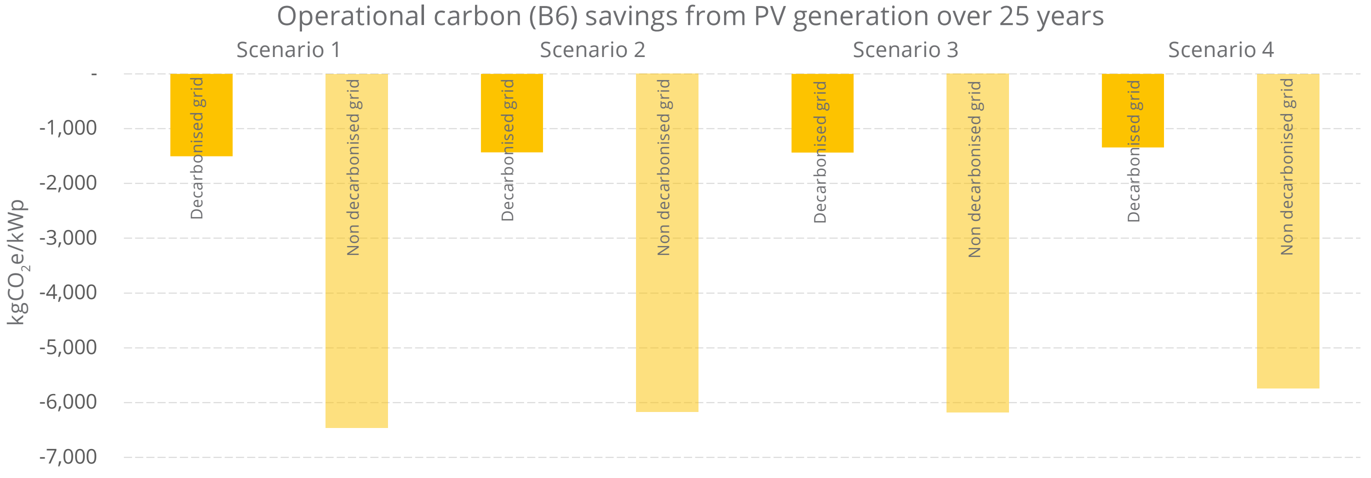


Figure 7 - Operational carbon (B6) savings for all scenarios with and without decarbonisation predictions

Embodied carbon and operational carbon combined

Figure 8 brings Figure 4 and 7 together to show both embodied carbon impact and operational carbon savings in $kgCO_2e/kWp$ for a period of 25 years. In all scenarios, even with grid decarbonisation, the operational carbon saving still outweighs the embodied carbon impact over the 25-year life span of each PV system installation.

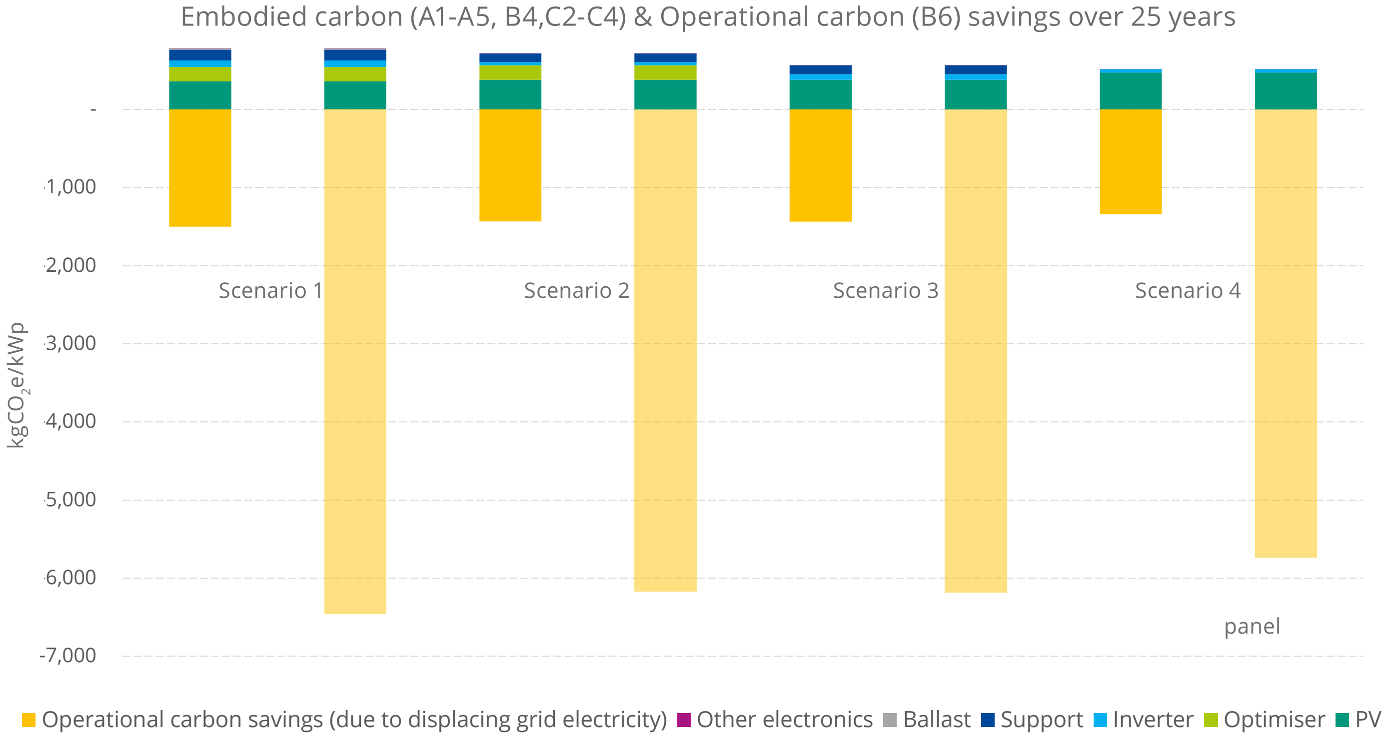


Figure 8 - Operational carbon savings and embodied carbon scenarios for all scenarios

Scenario 1: Project A, Flat roof, PV monocrystalline, Optimisers. Scenario 2: Project B, Pitched roof, PV monocrystalline, Optimisers

Scenario 3: Project B, Pitched roof, PV monocrystalline, No optimisers. Scenario 4: Project B, Pitched roof, PV thin-film, No optimisers

Hackbridge Primary School, Elementa Consulting designed the UK's first net zero carbon school at the time and the first to be 'Passivhaus plus' certified.

Discussion

Can we really compare embodied carbon and operational carbon?

In the results section, we combined operational carbon savings and embodied carbon values even though they follow different calculation methodologies: operational carbon savings are based on predicted data which the industry has a good track record at estimating, whereas the embodied carbon values rely on different types of data (both EPDs and CIBSE TM65 manufacturer forms), a number of assumptions and don't take into account decarbonisation scenarios.

Moreover, it is debatable whether embodied and operational carbon should be compared at all in this case. If we account the embodied carbon impact of on-site renewable generation, we would need to account for the embodied carbon impact associated with energy grid in case of off-site renewable or non renewable generation.

The whole life carbon study should not be done in isolation and all the relative benefits and impacts of solar PV generation for net zero carbon buildings should be considered.

PV embodied carbon compared to building embodied carbon targets

Building embodied carbon targets have been developed by LETI and RIBA[8] which are setting 'best practice' benchmark levels for the embodied carbon of typical building types.

Figure 9 shows the embodied carbon impact of the PV installation of Project A compared to the rest of the embodied carbon in the building, assuming that the embodied carbon of the rest of the school building is 675 $kgCO_2e/m^2$ – aligned with a LETI C rating.

If we assume that the project A meets the LETI energy use intensity (EUI) target of 65 kWh/m²/year, then the PV system will generate 87% of the annual energy consumption of the building.

Appendix 1 explores, how the proportion of embodied carbon of a PV system differs with schools with a different number of storeys.

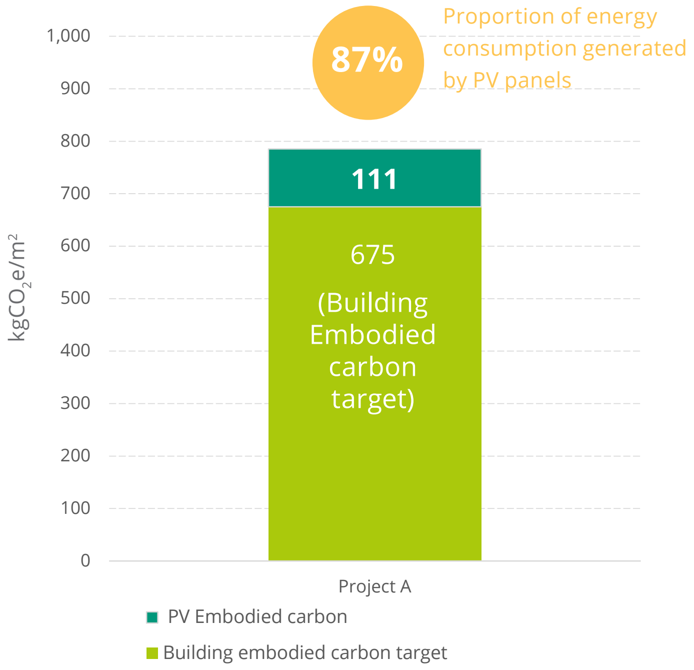


Figure 9 – Embodied carbon of a PV installation for project A (2 story) compared to total building embodied carbon target

Other points to consider about PVs:

The focus of this study is about carbon, however there are other issues to consider when procuring PV panels:

- **Ethics:** the supply chain should follow anti-slavery legislation to ensure it is free from slavery, forced labour and other human rights violations*.
- **Other environmental impacts:** the product should ensure for instance low environmental toxicity, high recycling rates. EN 15804 compliant EPDs disclose other environmental impacts than climate change and should be also taken into consideration.
- **Human health impacts:** the supply chain should ensure an extraction and manufacturing process which is not harmful with red-list free materials.

*/ some studies show it is not always the case: **https://www.shu.ac.uk/helena-kennedy-centre-international-justice/research-and-projects/all-projects/in-broad-daylight**; **https://www.antislavery.org/solar-panel-industry-uyghur-forced-labour/**

8 **https://www.leti.london/carbonalignment**

Technical discussion points

Difference between flat and pitched roof:

The results (expressed in $kgCO_2e$ per kWp) indicate that the flat roof option has a slightly higher embodied carbon impact, as it needs more support and requires concrete tiles. Surprisingly the PV yield is also higher for the flat roof option, which is a result of the suboptimal roof orientation of our pitch roof case study. This has resulted in a better net whole life carbon balance for the flat roof, but also highlighted the importance of project specific factors.

For the case that both systems were set up to have a similar orientation, it might reasonably be expected for the flat roof (with lower pitch) to generate less solar yield, thereby creating fewer carbon savings. A further factor was that project B (the pitched roof installation) also suffers from shading issues from neighbouring buildings. So, while the embodied carbon impact is a relative constant number (generally higher for flat roof systems), the operational offsets vary by many factors such as the geography, orientation, and pitch. This shows that we cannot make general conclusions and specific project-based calculations need to be carried out to make an informed design decision.

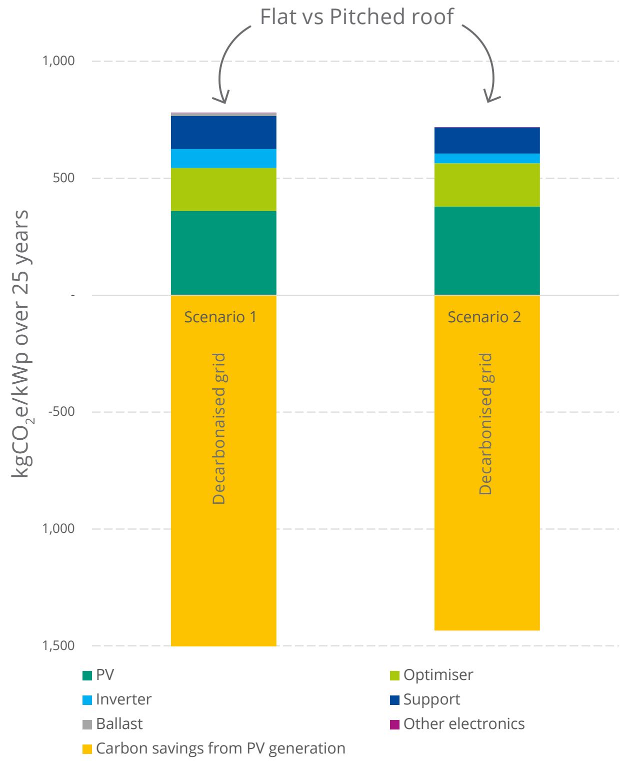


Figure 9 - Embodied carbon (A1-A5,B4,C2-C4) & operational carbon (B6)
Scenario 1: Project A, Flat roof, PV monocrystalline, Optimisers
Scenario 2: Project B, Pitched roof, PV monocrystalline, Optimisers

The impact of PV optimisers:

PV optimisers offer a range of benefits such as safety, control, monitoring and more flexible system design (different panels and orientations can be utilised) but the most relevant to yield are the removal of mismatch losses (from manufacturing tolerances and shading).

Optimisers are most useful for difficult roof configurations, e.g. a roof with more than one orientation and localised shading issues. A simple roof design without any shading issues will benefit very little (in terms of additional yield) but will take an embodied carbon penalty for the additional components. This is the case for our case study project B (with optimisers) where very small yield increases are offset with a rather large increase of embodied carbon (due to additional components). Optimisers are often applied for panel pairs, so result in a large number of additional equipment use.

In our case study, the no optimiser option (Scenario 4) was further improved by a more efficient inverter (as specified by the supplier), resulting in higher conversion efficiency (i.e. increased yield). Again, while the embodied carbon figures are locked through specification, the project specifics will govern whether optimisers can provide operational carbon offset advantages through better yield. This shows that once again project specific calculations need to be carried out to make informed design decisions.

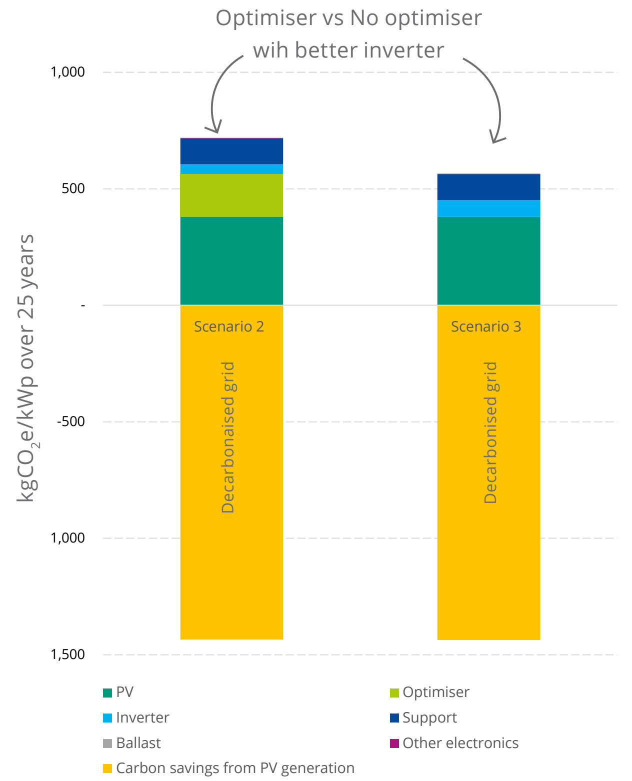


Figure 10 - Embodied carbon (A1-A5,B4,C2-C4) & operational carbon (B6)
Scenario 2: Project B, Pitched roof, PV monocrystalline, Optimisers
Scenario 3: Project B, Pitched roof, PV monocrystalline, No optimisers

Difference between monocrystalline and thin-film technology:

Although thin-film technology has a lower efficiency, it doesn't require any additional roof mounting systems/ supports, and the embodied impact of the panel itself is similar to that of an equivalent monocrystalline panel - this could be interesting from a whole life carbon perspective.

However, thin-film technology is currently only available at significantly higher total capital cost, compared to conventional roof mounted PV systems. Moreover, the availability of embodied carbon data is scarce. Thin-film manufacturers were contacted to carry out CIBSE TM65 calculations, but unfortunately data was not made available, so instead ICE A1 to A3 data was used to estimate total embodied impact.

Although it seems from these initial calculations that there is a carbon benefit in using thin-film rather than more standard monocrystalline PV, it should be noted that it is said that the recycling rate is quite low for thin-film and it is also known for its toxicity issues, especially regarding the use of cadmium-telluride (See article **[Review on Life Cycle Assessment of Solar Photovoltaic Panels]** for further information).

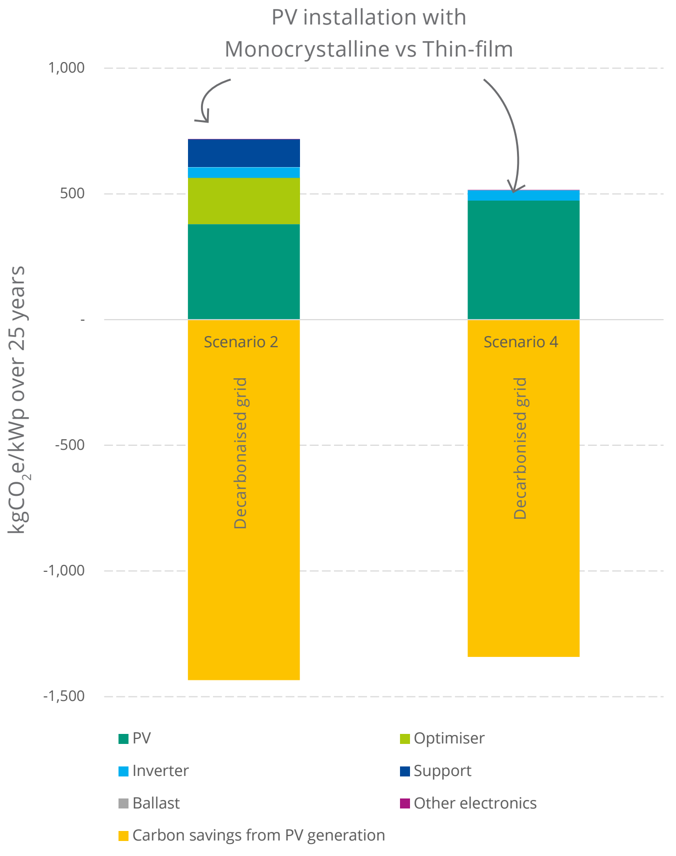


Figure 10 - Embodied carbon (A1-A5,B4,C2-C4) & operational carbon (B6)
Scenario 2: Project B, Pitched roof, PV monocrystalline, Optimisers
Scenario 4: Project B, Pitched roof, PV thin-film, No optimisers

PV as an offset mechanism - 'why it is not about payback'

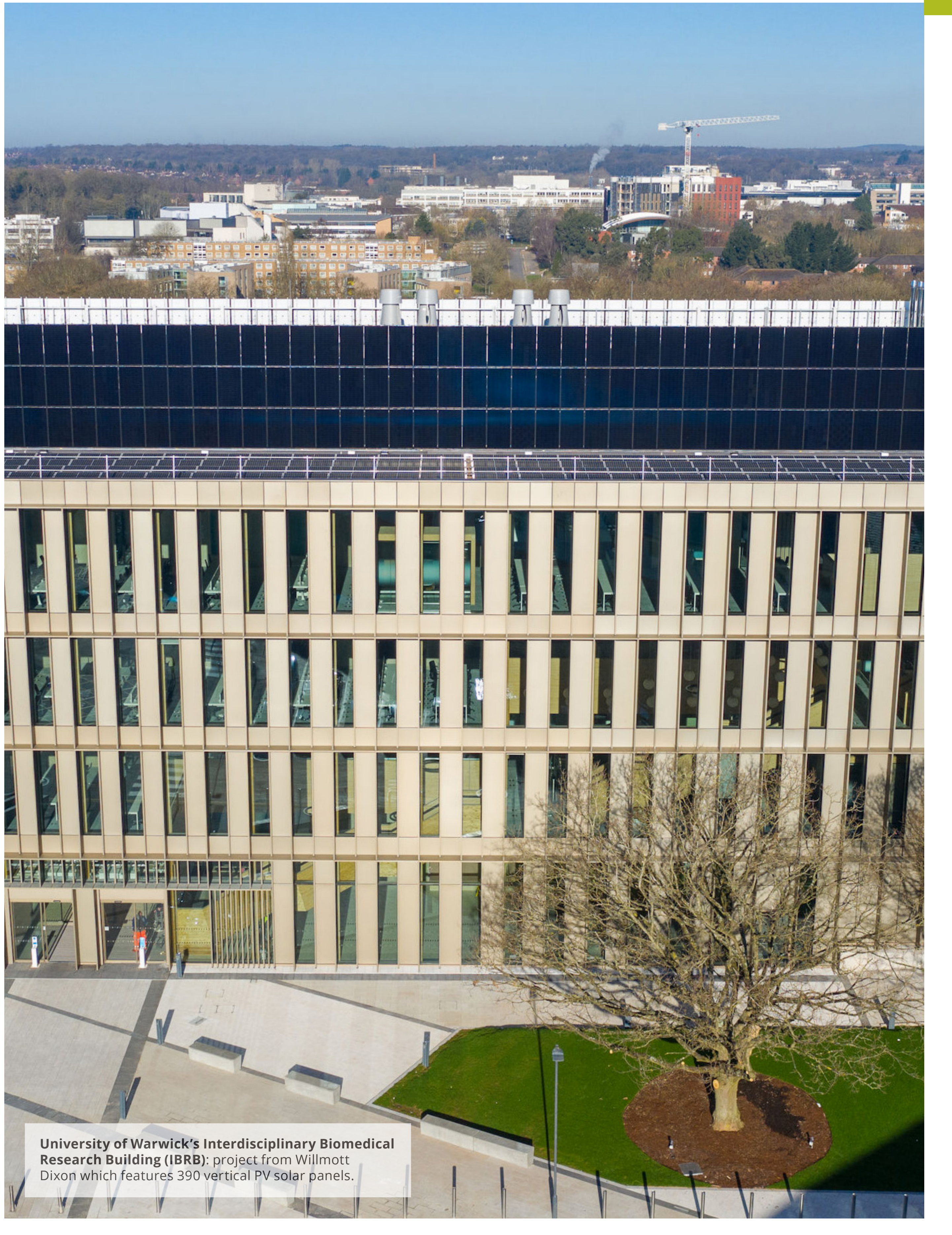
We are used to thinking about the payback of measures that reduce carbon emissions – for example a financial payback (a result of energy savings) when installing additional insulation.

Recently, the industry has started looking at both the embodied carbon impact and operational carbon savings to evaluate the net effect of carbon reduction measures. This can inform decision making based on whether the embodied carbon outlay is worth the operational carbon reductions. It is tempting to take this same approach when considering whether to install PVs or not, However, doing so might have unintended consequences and could ignore other important global factors. For example, when carrying out these calculations, the future decarbonisation of the grid is taken into account based on the assumption that significantly more renewable generation will be added to the grid in coming years. In order to meet our climate targets, we need to shift progressively to 100% renewables, so new installations of PV and other renewable energy systems are required to decarbonise the grid further

This means we need to 'invest' embodied carbon into installing renewable energy infrastructure. Without that initial 'embodied carbon' investment the grid will not decarbonise further. As the grid decarbonises, local supply chains also benefit from accessing renewable energy, reducing the upfront embodied carbon content of their products.

Intuitively we can understand that PV installations are required to decarbonise our electricity grids and to move away from fossil fuels such as coal and gas. The UK grid needs to substantially increase capacity to deal with the likely increased demand of the energy in the future (e.g. heat pumps and electric cars) and rooftop solar PV represents a significant opportunity to support this renewable energy generation push.

Even though our results suggest that PV as a pure carbon offset mechanism will be less useful going forward (as operational offsets diminish in line with decarbonisation), the additional renewable capacity to help balance supply and demand will be far more important in its contribution to the energy transition.



University of Warwick's Interdisciplinary Biomedical Research Building (IBRB): project from Willmott Dixon which features 390 vertical PV solar panels.

Conclusions

Main takeaways of this study

The whole life carbon performance of PV installations is strongly affected by design decisions (e.g. roof type, pitch, orientation, etc.) and as such, we strongly recommend to model and test different scenarios to find the optimum project specific solutions.

While embodied carbon impacts generally are more fixed than operational savings (which depend on project specific parameters), it can be valuable to test different PV module types against their whole life carbon performance. In some cases, lower efficiency components can also reduce embodied carbon impacts (e.g. thin-film modules).

A 'payback' approach for PV installations, i.e. embodied carbon impact compensated by the operational carbon savings, is not the right metric during an energy transition towards 100% renewables. Embodied carbon will have to be invested to achieve full grid decarbonisation and rooftop solar PV should continue to play a vital role in supporting this transition.

Our findings

- While the embodied carbon impact of a whole PV installation (i.e., PV modules and all supporting infrastructure) appear significant in all options explored as part of this study, the carbon savings from PV generation in a UK context provided a significant net benefit (i.e. operational savings outweighed the impact) in all tested scenarios (with and without decarbonisation scenario).

- In the future when operational savings reduce further (in line with grid decarbonisation), the embodied carbon content of PV components will become even more important, and this is something that supply chains will have to respond to by decarbonising their own operations, responsibly sourcing components and better data.

- When looking at PV installations at a component level, PV modules remain the single largest embodied carbon impact. However, contribution from the supporting infrastructure (mounting systems, ballast, inverters, optimisers etc.) is significant and should be accounted for and minimised in design and embodied carbon calculations.

- While embodied carbon impacts for equipment are relatively fixed, the operational savings from generated renewable energy depend heavily on the project specific parameters: roof orientation, pitch, geography, roof and panel design. Although it is not possible to draw many general and universal conclusions from our small study size, there are strong cost and value incentives for designers to maximise generation efficiency and yield, and therefore maximise operational savings.

- Our study found that a thin-film PV option might be able to deliver a measurable embodied carbon saving against more conventional PV system configurations. Questions around recycling of thin-film systems (components are bonded), limited roof system compatibility, and current higher capital costs mean that this likely to remain a specialist option for now.

- The pros and cons of PV optimisers (from a whole life carbon standpoint) are not straight forward and should always be tested on a project-by-project basis and evaluated together with other criteria (e.g. shutdown control benefits, monitoring requirements). In some instances, more efficient inverters might give equivalent yield benefits while decreasing the embodied carbon impact, while projects with complex roof geometry and shading issues would probably still benefit from optimisers.

- One of the main conclusions of this initial study is the need for the solar PV manufacturing industry to provide lower embodied carbon PV panels and further robust EPDs to investigate the embodied carbon impact associated with PV installations.

Our call to action

While the whole life carbon impact of a PV installation is a key factor in net zero building decision making, we should acknowledge that the availability and quality of embodied carbon data at product level is still quite limited, and that encouraging further work in this area is important.

To improve data and measurements, the key action we believe is needed, is to bring the PV manufacturing industry on this journey with us to work on lower embodied carbon components and provide better EPD data.

Embodied carbon can be further reduced through intelligent design, specification and procurement decisions, but we need to validate scenarios through models, and we need to feed these models with the best data available.

We need to work with the PV manufacturing industry to enhance the service life of PV installations to reduce replacement frequency (therefore less material extraction and manufacturing) and ensure components can be readily recycled and recovered at the end of their useful life. Also needed is full disclosure of impacts through the supply chain, not only on climate change but also on other environmental impacts while ensuring ethical practices.

We need supply chains to take this feedback on board and work with consultants and contractors to improve data and decarbonise their own production facilities.

We need customers to specify low embodied carbon components and drive the market in the right direction. Further research is required into how PV embodied carbon impacts compare to the embodied carbon of other renewable energy generation systems, to fossil fuel energy generation systems, and importantly, how such embodied carbon impacts are reflected in grid emission factors from generation systems and the distribution infrastructure.

Appendix 1

What is the embodied carbon of PV compared to the rest of the building - for various building heights?

Industry embodied carbon total building targets are now appearing, such as LETI/RIBA targets, which are setting 'best practice' benchmark levels for the embodied carbon of typical building types.

These targets do not typically include the embodied carbon of PV, as it is thought that this would disincentivise the installation of PV panels. PVs in effect become part of the wider energy grid infrastructure, helping to decarbonise electricity; if they are not installed on the building they (or other renewable energy) will need to be installed elsewhere in the UK. However, as PVs are paid for and installed by a specific building contract, excluding them potentially means the associated embodied carbon is not counted anywhere. Not including them also raises questions about where the boundary lies for building integrated PV; for example, when used as a facade. An additional benefit would be the incentive for manufacturers to develop products with reduced embodied carbon and increased energy efficiency.

To help understand the relative impact of the embodied carbon of PV systems compared to the rest of the building a study was undertaken to understand the embodied carbon of a PV system compared with the total building. The relative PV system size compared to total building floor area relates to the number of storeys of the building. Hence the study uses the embodied carbon data from the PV installation of Project A from the main body of this report, to understand the relationship between embodied carbon of the PV system, embodied carbon of the building, and the proportion of energy consumption that is generated onsite for a single storey school, as well as a school with 2,5 and 10 storeys. In this study it is assumed that the schools meet the LETI EUI target of 65 kWh/m²/yr and the embodied carbon of the building aligns with a LETI C rating.

If the school had had just one storey, the embodied carbon impact of the PV system installation (221 $kgCO_2e/m^2$) would have represented an additional 33% of embodied carbon, however it would generate 1.7 times the annual energy consumption of the school. If the building had been a 10-storey building, the PV system would have only represented an additional 3% of embodied carbon, however the PV system would only be capable of generating 17% of the annual energy consumption.

Embodied Carbon of PV Installation
in relation to total building target of 675 $kgCO_2e/m^2$ (A1-A5, B4, C2-C4) over 60 years

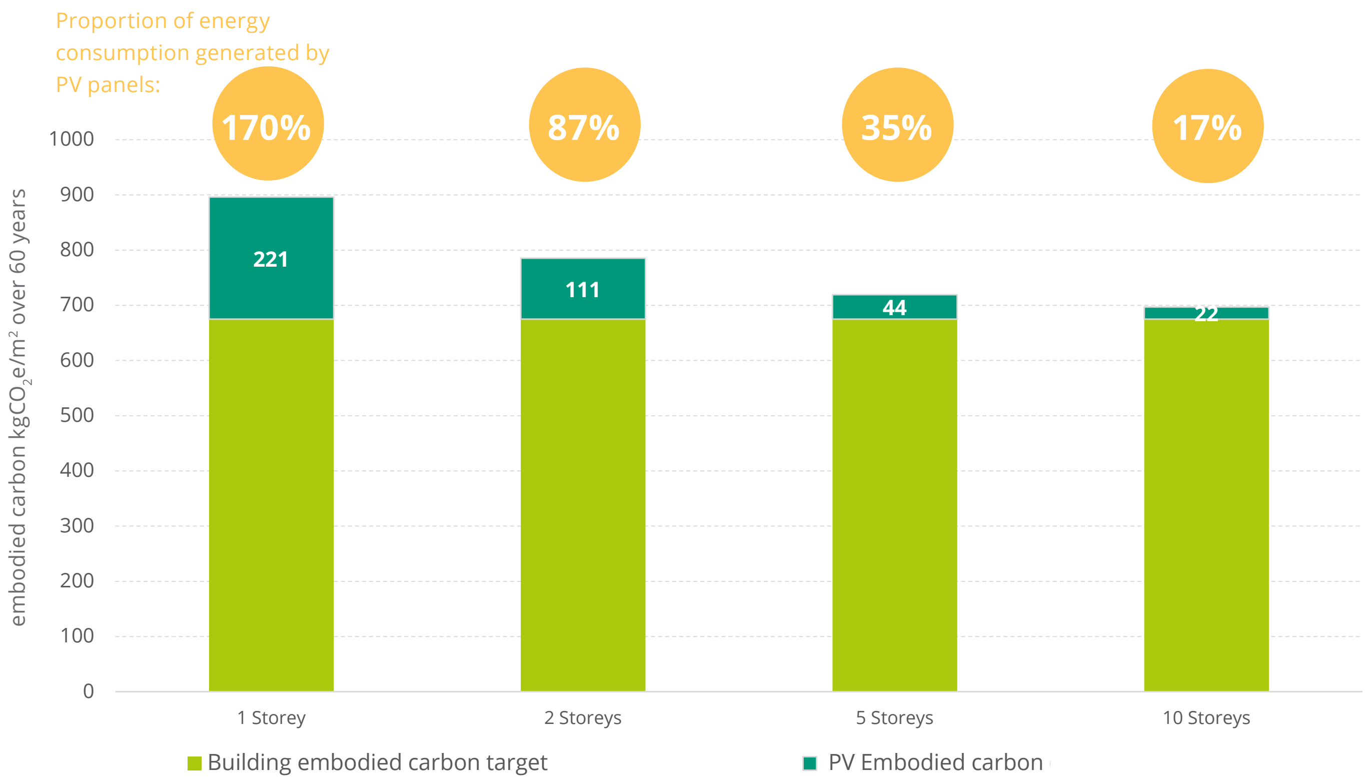


Figure 11 - Embodied carbon of the PV installation of Project A (Scenario 1) in relation to total UK building embodied carbon target at various number of storeys hight.