Decarbonising the Built Environment

Dr. Richard O Hegarty & Dr. Oliver Kinnane

What we built | How we build | What we build with | What is left

Retrofit and reuse | MMC | Concrete | CCUS

This project has been funded by DAVY under the *NexSys Strategic Partnership Programme* with the objective of reviewing the state of the art related to technologies and materials that can reduce the environmental impact of buildings and construction. The work has four focus-areas which are particularly pertinent for Irish decarbonisation: Retrofit (1. what is built?) Modern methods of construction (2. how we build?), concrete (3. what we build with?) and CCUS (4. What is left over?). This work builds on past work conducted by Dr. Oliver Kinnane and Dr. Richard O Hegarty and integrates learnings from the wider research group and project partners.

1 Introduction

Why do we need a "built environment" sector?

The built environment is emerging as a cross-sectoral area which requires its own specific emission- and energy-related accounting mechanisms. The United Nations Environment Programme (UNEP) reported that the built environment contributes towards 37% of global emissions in their latest *Global Status Report for Buildings and Construction* (United Nations Environment Programme, 2024). The authors of this present report found that Ireland's built environment equated to approximately one third of all national GHG emissions (O'Hegarty and Kinnane, 2022).

The sector's impact is significant both nationally and globally, but it is often not fully captured by current accounting systems. As an example, the "residential sector" cited in Ireland's annual GHG inventory reports prepared by the Environmental Protection Agency (EPA), only include the on-site combustion of fossil fuels. Within this classification system, electrification alone would reduce emissions to zero on the carbon balance sheets. This approach, while appropriate at a national level, risks disincentivising other potential solutions such as energy efficiency measures and/or demand-response systems with fluctuations in an increasingly renewably charged national grid.

A full life cycle approach enables an understanding of all direct and indirect emissions beyond what happens on-site. It additionally captures the material emissions required to enhance the energy performance of buildings (O'Hegarty et al., 2020a). This life cycle approach is particularly pertinent in the latest UNEP report which note that "*while energy efficiency measures are a high priority, they must be combined with material efficiency strategies.*". Habert et al. (2020) refers to this cross-sectoral classification as an "area of activity" and describes the complexities of producing carbon budgets for the "production, construction, use and end-of-life of buildings" or "buildings" for short.

The IPCC's Chapter 9 (IPCC, 2023) on buildings cites how "*Total GHG emissions in the building sector reached 12 GtCO2-eq in 2019, equivalent to 21% of global GHG emissions that year, of which 57% were* ***indirect*** *CO2 emissions from offsite generation of electricity and heat, followed by 24% of direct CO2 emissions produced* ***on-site*** *and 18% from the production of* ***cement and steel used for construction*** *and/or refurbishment of buildings.*". The material-related emissions in the IPCC's latest assessment report AR6-2022 represent an advancement over earlier versions (AR4 and AR5), which did not explicitly cover embodied emissions.

Similarly, **The IEA (IEA, 2022)** now identify direct (on-site emissions), indirect (electricity consumption) and embodied carbon emissions from processing of cement, steel etc. within their building scope: "*Altogether, buildings operations and construction emissions account for more than one-third of global energy-related emissions. Mitigation and adaptation measures are needed across the whole buildings value chain.*" and note how "*Zero-carbon-ready building energy codes should cover building operations (scope 1 and 2) as well as emissions from the manufacturing of building construction materials and components (scope 3 or embodied carbon emissions).*".

This language of Scope 1 (onsite), 2 (emissions from electricity) and 3 (supply chain emissions) has been used for over two decades in voluntary corporate GHG accounting following the **Greenhouse Gas Protocol**, developed in 2004 by World Business Council for Sustainable Development (**WBCSD**) and World Resource Institute (**WRI**) (World Business Council for Sustainable Development (WBCSD) and World Resource Institute (WRI), 2004). The rationale for this emission breakdown by scope is to assign responsibility to a given corporate entity. It is this same logic which is now seeing the adoption of a whole building sector focus from the UNEP, IPCC and IEA, as well as the introduction of life-cycle GWP at European level via the **EPBD** which cites the mandatory requirement for Life-cycle GWP disclosure by the end of this decade, and updates to the **CPR**, which now require the disclosure of life cycle GWP performance indicators for materials and components used in construction. Irish policy has also increased its focus on life cycle emissions and the latest **CAP 2024** now, for example, cites the requirement for a "*decrease by at least 30% embodied carbon for materials produced and used in Ireland*".

The policy shift at international and national level recognises the difference between categorisations for reporting and tracking emissions (for which a well-defined mature system exists) and categorisation for actionable decarbonisation (for which a sectoral focus is required). Beyond the policy shifts, the state-of-the art in the academic literature and industry-led reports have also covered the importance of national-level carbon and GHG emission accounting to some degree. This is an emerging body of literature which the current authors have already contributed towards for Ireland with their whole life carbon roadmap (O'Hegarty et al., 2022; O'Hegarty and Kinnane, 2023, 2022).

While numerous sector-specific studies, including those from residential and non-residential buildings, are prevalent in the literature, few have taken a comprehensive life cycle perspective that encompasses emissions from both the operation and construction phases of the built environment. The UKBC (UKGBC, 2021) quantified past and future Built Environment (BE)-related emissions for the UK. They concluded that 177 $MtCO_2e$, representing 25% of national emissions, could be attributed to the UK built environment, with operational emissions accounting for between two-thirds and three-quarters of all BE-related emissions. This study included both Embodied Carbon (EC) and Operational Carbon (OC) using a consumption-based accounting system, which considered imports and excluded exports. Additionally, OC emissions from regulated and unregulated energy loads and F-gas leakage were included for buildings, as well as operational emissions from regulated infrastructure energy loads, such as public lighting and waste. Drewniok et al. (2023) has more recently investigated the embodied emissions specifically by mapping out material flows.

A review of other national built environment sectors

In Australia, Allen et al. (2022) conducted a life cycle accounting study for their built environment and developed a dynamic forecasting model using a top-down approach to establish a baseline value, they applied macro-scale drivers such as population, GDP, and employment to forecast future emissions. Their study concluded that achieving a net-zero built environment would require more stringent climate policies. They reported that the life cycle GWP (including both operational and embodied emissions) for 2018 were approximately 120 MtCO2e, representing about 20% of all greenhouse gas (GHG) emissions based on Climatewatch figures for Australia. Zhu et al. (Zhu et al., 2020) quantified the embodied carbon emissions in the Chinese building sector, finding that between 1400 and 1600 $MtCO_2e$ could be attributed to the embodied emissions of residential and non-residential buildings. With reported operational carbon emissions ranging from 1800 to 2300 $MtCO_2e$. **Interestingly, embodied carbon accounted for nearly half of all building-related emissions in China**. Similarly, Chen et al. (2017) estimated that since 2000, annual embodied carbon emissions associated with building materials increased by more than 400% in 19 years. The CAIT database from Climatewatch reported total GHG emissions of 11,100 MtCO2e for China in 2015, indicating that the operation and construction of buildings in China accounted for up to 35% of all GHG emissions, according to the estimations by Zhu et al. (2020) Variations in BE-GHG emissions are expected, particularly as developing countries are constructing more and therefore emitting more carbon annually.

While only a few studies have quantified the whole life carbon impact of the entire built environment, some have investigated operational and embodied carbon separately or for specific sectors. For example, Yang et al. (Yang et al., 2022) used a bottom-up methodology to conclude that emissions from material production in the Netherlands' residential sector are less significant than those related to operational energy. Conversely, Robati et al. (2021) predicted that, depending on the future energy mix, the EC portion of a building in Sydney could account for more than 50% of its whole life carbon. Huang et al. (Huang et al., 2022) estimated that 23% of all global CO2 emissions in 2009 were embodied in the construction sector. Enkvist et al. (Enkvist et al., 2022) reported in 2022 that the production, use, and disposal of cement, steel, aluminium, and plastics accounted for almost one-quarter of all global CO2 emissions. According to the Organisation for Economic Co-operation and Development (OECD), construction material use is expected to nearly double between 2017 and 2060.

The current literature shows some level of agreement that embodied emissions are considerable and need attention but that operational emissions continue to account for the greatest portion of the sector's emissions.

Research Rationale

This current research aims to synthesize the findings of past work by the current authors as well as that of other researchers, thereby showcasing a snapshot of some Irish research focused on decarbonising the built environment's significant share of carbon emissions.

1. What we built?

Retrofit and renovation

Introduction

This section[1] focuses on what we have already built. Much of the construction sector's innovation is focused on how we build new things, or how we build with new things. But more important from a decarbonisation perspective, is how to make best use of what has already been built. For two reasons. First, it is the operational consumption of existing buildings which consumes most energy in most developed countries, and hence emits the most carbon dioxide. Second, it is arguably the best way to save material-related emissions. This section therefore focuses on existing buildings and how we can make best use of what we already have. It is primarily focused on the energy retrofit of residential buildings as well as the adaptive reuse of other building to residential buildings. For an overview of commercial reuse the reader is referred to RKD's research on reusing office buildings (RKD, 2024).

Why adaptive reuse?

Frist we explore the reuse, or repurposing of buildings. The decarbonisation of materials alone is insufficient to meet a 51% reduction in emissions by 2030 (O'Hegarty et al., 2022), other, more creative solutions are required to improve our built environment while simultaneously reducing emissions. One key decarbonisation solution, cited by the IGBC in their recent roadmap to decarbonise the built environment (IGBC, 2022), is to reactivate vacant buildings and thereby save the considerable emissions that would otherwise occur as a result of new construction alone.

[1] The contents of the work was presented at the AiARG conference in 2023 as a collaborative effort between UCD and RKD.

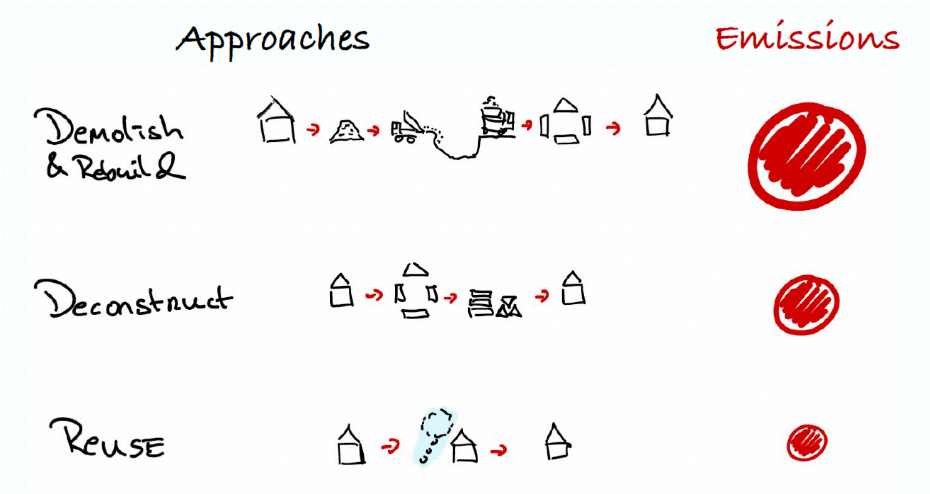


Figure 1. Conceptualising emission savings from adaptive reuse. Presented at AiARG 2023. Presented by Richard O Hegarty. Input from Oliver Kinnane (UCD), Sean Hogan (RKD), Philip Crowe (UCD), Rosemarie Mac Sweeney (RKD).

A note on vacancy

Researchers across Ireland have been investigating the complexities of vacant buildings for severalthe degr years. Dr. Cian O Callaghan of Trinity College Dublin for example highlights one of the key complexities is the underlying vacancy data and what exactly it measures. Cian notes how vacancy data is generally a secondary data, or a form of "data exhaust" (O'Callaghan and Stokes, 2022). The complexities and heterogeneous nature of measuring vacancy is further derived in Dr. Philip Crowe's report on "*How data on vacancy is created and used: Case studies from Scotland, Denmark and Philadelphia.*" (Crowe, 2019). Dr. Crowe is also director of the Centre for Irish Towns (CfIT) in UCD where the issues and complexities of quantifying vacancy and the need for Irish town revitalisation through the reactivation of derelict buildings are regularly discussed.

The carbon case for renovation

The maximum potential emission savings from this strategy can be estimated in its most simple form following the equation in Figure 2. First we need to estimate the total vacant floor space available and then multiply this by a carbon saving factor.

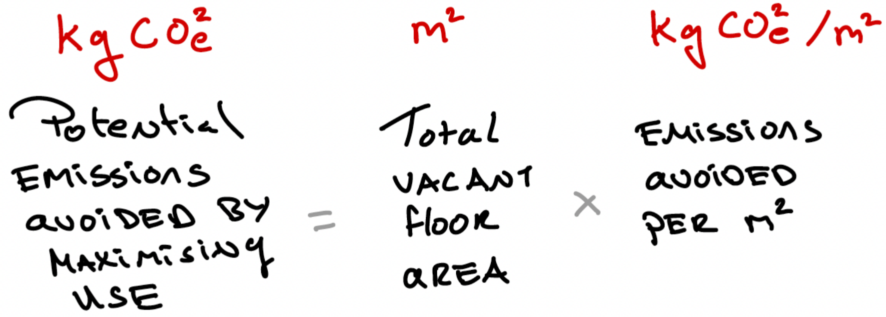


Figure 2. Equation to calculate the embodied carbon savings of repurposing all vacant buildings.

According to the latest Geodirectory report for Q2 2022 there were 29,241 vacant commercial properties out of a total of 210,924 (GeoDirectory, 2022b). The report does not categorise the vacancy rate by building type so calculating the total requires an assumption that vacant buildings are a representative sample of the non-residential building stock. The CSO (CSO, 2022) estimate that the average non-residential building has a floor area of 690 m^2 so assuming the 29,000 vacant commercial properties are a representative sample, the total vacant floor space would equate to 20 million m^2.

According to the Geodirectory's report on residential buildings there are 108,605 residential buildings either vacant or derelict (GeoDirectory, 2022a) – more than three times the number of commercial properties. But, residential building are generally much smaller than commercial buildings and embodied carbon is quantified on a per m^2 basis. Interestingly, when the average home size of 113 m^2 is assumed in accordance with the CSO's estimate for dwelling size (CSO, 2022) the total vacant floor area equates to ~12 million m^2, almost half the commercial figure.

Total vacant floor space = ~32,000,000 m^2

The second part of the equation requires an estimate of carbon savings per m^2 of vacant space saved. This topic is in a nascent stage of research with very few studies investigating the carbon savings in detail. In the absence of this data some broad assumptions are required to obtain an estimate.

The simplest method to estimate the carbon abatement by repurposing, instead of demolishing and rebuilding, is to estimate the embodied carbon of the part of the building which would typically be saved (i.e. the superstructure, substructure, and sometimes, the skin). If the structure is saved, a new structure at an average carbon cost of 400 kg CO_2/m^2 (WBCSD and Arup, 2023) would not be needed. If both skin and structure is saved the total upfront savings might be 520 kg CO_2/m^2. We assume the lower estimate in this study of 400 kg CO_2/m^2 since the façade is intrinsically linked to the operational efficiency, a topic outside of this study but which is covered in both industry reports (Leti, 2023; WBCSD and Arup, 2023) and academic papers (Reilly et al., 2020).

Emissions avoided per m^2 = 400 $kgCO_2e/m^2$

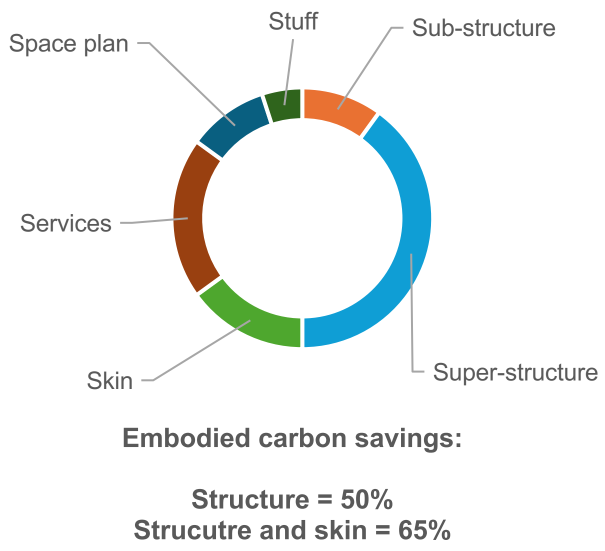


Figure 3. Distribution of upfront embodied carbon by building component. Adapted from (WBCSD and Arup, 2023).

Based on these assumptions an estimated total of 13 million tonnes of embodied CO_2e could be saved.

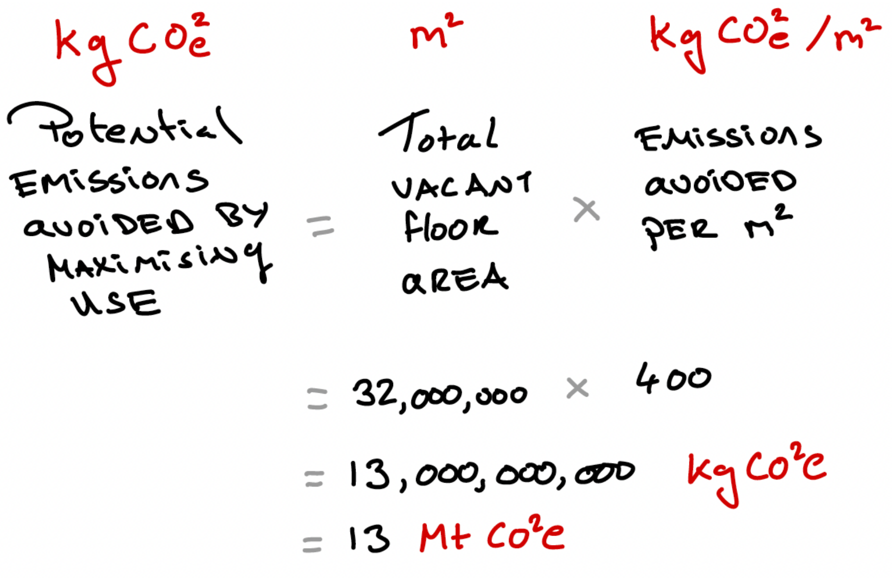


Figure 4. Estimated potential savings by repurposing our building stock

The estimate of 13MtCO2e – which is more than a year's worth of emissions from Ireland's entire transport sector – would shave 2 Mt off Ireland's built environment emissions every year until 2030, but this figure is based on several broad, generally optimistic, assumptions and needs to be contextualised. There is uncertainty over both the amount of vacant floor space, the state of this vacant floor space and the actual savings made on a case by case basis.

A more conservative estimate might be that 1 million tonnes of CO2 could be saved each year till 2030 (assuming 50% of the stock in unsalvageable – at least in its current form). But this quantification only references the direct, quasi-measurable, benefits.

Figure 5. La Fabrica (https://ricardobofill.com/la-fabrica/read/)

Retrofit Technologies - Overview

The most recent IPCC chapter on Buildings cites the importance of energy retrofit throughout (IPCC, 2023). The report identifies sufficiency, efficiency and renewable as the three key pillars for decarbonisation and documents, as calculated below. The energy retrofit of buildings plays a significant role in all three pillars.

$$CO2^{k}_{total} = Pop \times \frac{m^2}{Pop} \times \frac{EJ}{m^2} \times \frac{Mt_{CO2}}{EJ} = Pop \times Suff \times Eff \times Ren$$

In addition, the report highlights the importance of short term upskilling to implement the changes required, citing high evidence and agreement throughout the literature.

"Literature emphasizes the critical role of the decade between in 2020 and 2030 in accelerating the learning of know-how and skills to reduce the costs and remove feasibility constrains for achieving high efficiency buildings at scale and set the sector at the pathway to realise its full potential (high evidence, high agreement)"

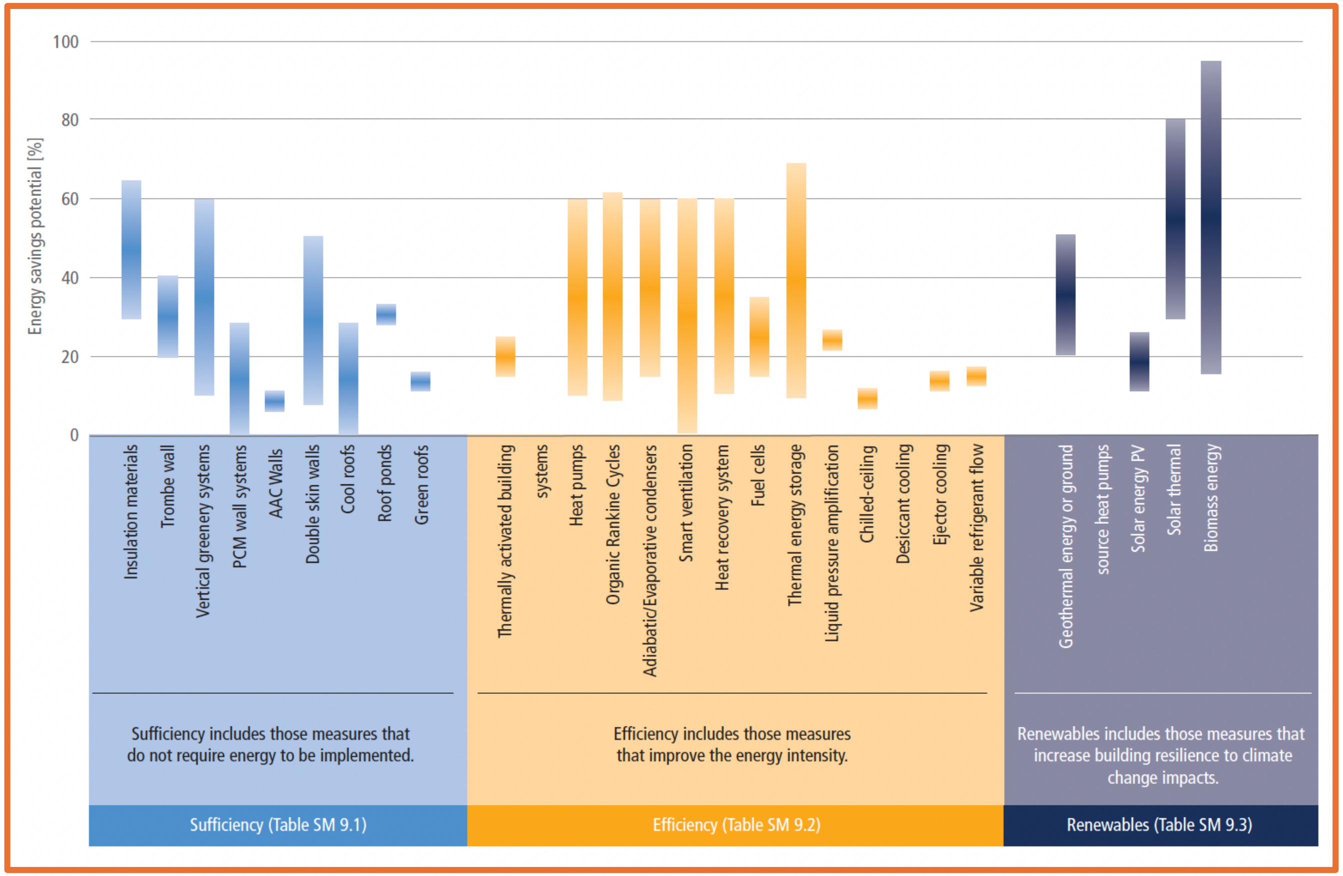


Figure 6. Figure 9.11 taken from (IPCC, 2023), highlighting the different strands and where retrofit fits in

In Ireland, the importance of energy retrofit of existing residential buildings is equally important from a national decarbonisation perspective (O'Hegarty and Kinnane, 2023). Two of the key technological drivers include building insulation and heat pumps. Both are discussed here.

Retrofit technology – insulation

The technical performance of insulation from an energy perspective is rooted in its thermal conductivity. Below is a state-of-the art summary of some of the key insulation materials and their technical specifications.

Table 4 Comparative analysis of main insulation materials on the market

Material	*λ (W m^{-1} K^{-1})*	*Thermal diffusivity (mm^2 s^{-1})*	*Operating temperature (°C)*	*Compressive strength at 10% compression (kPa)*	*Vapor diffusion resistance μ*	*Fire reaction (Euroclass)*	*Primary energy PEI n.r. (MJ m^{-2})*	*GWP (Kg CO_2 m^{-2})*	*Thickness for R=2 m^2 K W^{-1} (cm)*	*Cost for R=2 m^2 K W^{-1} (%)*
Synthetic										
PUR	0.022	0.421	−40/+110	150	148	F	147	10.35	4.4	115
XPS medium load	0.034	0.837	−50/+75	250	150	E	144	5.52	6.8	130
XPS high load[a]	0.034	0.521	−50/+75	700	150	E	144	5.52	6.8	255
EPS medium load	0.031	1.069	−40/+85	100	70	E	147	4.52	6.2	100
EPS high load[a]	0.032	1.103	−40/+85	250	70	E	147	4.52	6.2	110
Vegetal										
Wood wool[b]	0.038	0.113	n.d.	100	5	E	82	4.56	7.6	335
Mineralized wood wool[b]	0.065	0.090	n.d.	150	5	B	377	13.82	13.0	360
Cork[b]	0.039	0.171	n.d.	100	20	E	175	0.49	7.8	470
Animal										
Sheep wool[c]	0.035	0.440	−60/+80	n.d.	2	E	17	0.39	7.0	220
Mineral										
Medium density rock wool[c]	0.033	0.458	n.d.	n.d.	1	A1	63	3.62	6.6	105
High density rock wool[d]	0.036	0.250	n.d.	50	1	A1	63	3.62	7.2	155
Medium density glass wool[c]	0.032	0.777	n.d.	n.d.	1	A1	37	1.62	6.4	105
High density glass wool[d]	0.037	0.370	n.d.	50	1	A2	37	1.62	7.4	175
Aerogel	0.015	0.100	−200/+200	80	5	C	242	12.50	3.0	1300

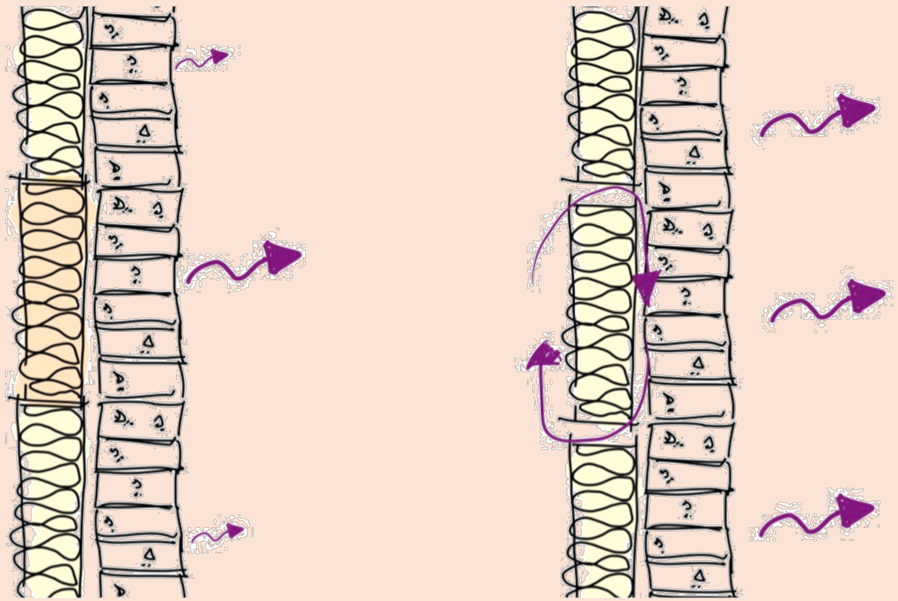
[a]Recommended for high load underfloor and walkable roof applications.
[b]Not suitable for inverted roof applications.
[c]Suitable only for pitched roof and cavity wall applications.
[d]Designed for ETICS and pitched roof applications, walkable during installation.

Figure 7. Summary of building insulation material performance (Casini, 2020)

Work conducted as part of this research project identified that while there is important technical research in highly equipped private and academic laboratories across the world, this research would look not at the performance potential but at the gap between what insulation can do and what might happen in practice.

Non-technical summary of: O'Hegarty, R., Amedeo, G. & Kinnane, O. The impact of compromised insulation on building energy performance. Energy and Buildings 316, 114337 (2024).

There is a relatively strong consensus among building professionals that insulating our buildings makes sense. At least generally speaking. The heat inside on a winter day isn't magically generated from free abundant sources of energy – well at least not yet. It is typically produced from burning oil or gas in a boiler, which then heats up water and is pumped around your house via pipes and radiators. This comes at an economic cost to the user, and an environmental cost to society in the form of carbon dioxide emissions into the atmosphere. Insulating minimizes the amount of energy we need.



But just because it makes sense generally, doesn't mean we will always do it right. Regulation is becoming increasingly stringent from a European perspective with the new Energy Performance of Buildings Directive requesting that member states re-evaluate their current codes over the next couple of years. The target is to achieve a Zero Emission Buildings standard for new buildings. The big change for me, however, is that it is now also concerned with existing buildings. In developed parts of the world like Europe, most of the buildings which will exist in 2050 have already been built today – the figure for Europe is about 85-95%. So clearly, the bigger impact is going to come from renovating existing buildings rather than from anything we do to our new buildings.

Even if all the new buildings are built to a fancy zero emission standard, there won't be any change to the sector's overall emissions, or any benefit to the 85-95% of people living in, and using, existing buildings.

So, while insulating our buildings broadly makes sense in both new and existing buildings, what's probably of equal importance is that we insulate them well. Adding insulation is costly both from a economic investment perspective, but also from an increased embodied carbon emissions perspective. That is the emissions associated with making the insulation and delivering it to site.

When we quantify the performance of our buildings during the design stage, we are quantifying a best-case scenario. Take the thermal performance of a wall for example. Here we use the laboratory-tested material values from manufactures and assume perfect precision is achieved on site when we do out our U-value calculations. The U-value is a measure of the ability of our walls, roofs and floors to lose heat. Low numbers are better.

But the reality is that a performance gap exists between how our low-energy buildings perform in practice, and how they are assumed to perform. The gap is skewed towards poorer performance in practice. This makes sense. While this gap is at least understandable, this is obviously not good and lots of research has investigated why it exists, and how we can fix it.

User-behavior is typically referenced as the primary reason for this performance gap. This is simply the mismatch between how we think people will use a building, and how they actually use the building. Think of an extreme case of leaving your heating on with the windows open – no designer is going to model that. User-behavior does impact the performance gap but the significance to which it explains the full performance gap is inconclusive. According to a review paper which looked at the literature on this (https://www.mdpi.com/2071-1050/13/6/3146), the authors concluded that “the role of occupants as significant or exclusive contributors to the energy performance gap is not sufficiently substantiated by evidence”.

So, if user-behavior isn’t the only reason for under-performance, there must also be technical reasons: under-performing boilers, heat pumps, insulation systems etc. This brings us to our own research where we investigated why, and by how much, insulation can underperform in practice. We have also studied heat pumps and other things, but we are just focusing on insulation here.

The “why and by how much” questions were motivated by an earlier study where we reviewed (and added to) the data concerned with the difference between designed and actual U-values. We found that, as more insulation is added, the performance gap on average widens. This is not to say it always does, but the chance of it occurring is at least higher.

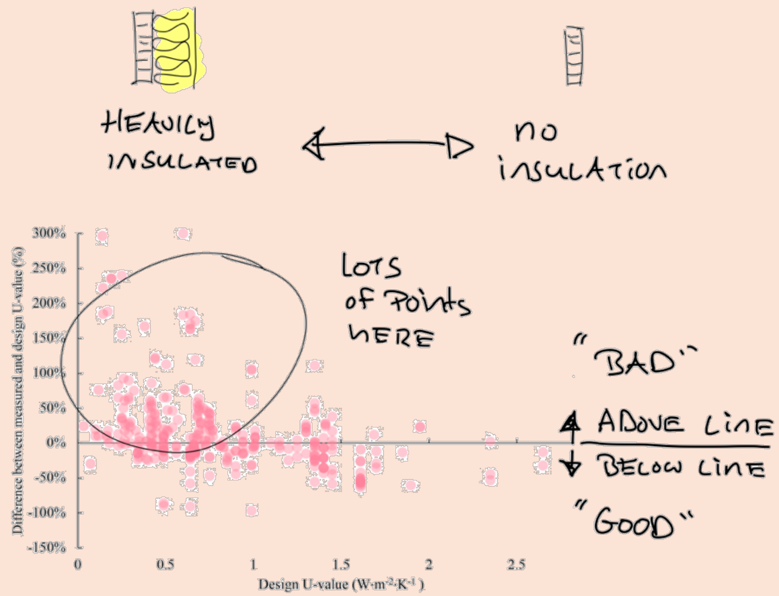
The problem we had when trying to find out why this was the case, was that most of the buildings we had measured were in-use. We couldn’t just rock up to people’s homes and start pulling bricks out of their walls for the sake of science. That usually isn’t sufficient justification for people to have their walls ripped apart. And fair enough.

So instead, we resorted to modelling some scenarios which might cause underperform. The boundaries for this modelling were determined by reviewing the existing literature (for which we need more of). Essentially, we modelled how the walls would perform IF they weren’t installed correctly. Specifically, we looked at two common culprits for insulation under-performance: 1) wet insulation and 2) air flow around the insulation i.e. thermal bypass of the insulation layer. Using different thermal modelling methods, we found that both scenarios could increase heat loss by more than 100% in highly insulated walls. The potential impact of thermal bypass in extreme scenarios is especially concerning and could increase the heat loss by more than 300%.

The degree to which insulated walls are compromised is obviously important here, and those numbers change accordingly. Measuring the degree to which modern building insulation system’s performance is compromised in practice is the obvious next step to this area of research, but quantifying this exactly is difficult. This research is by no means a finished piece. There is a massive gap in the literature on this topic, especially relative to other areas of building physics. Despite these challenges, we hope that our research can stimulate further studies in this field and encourage more investment in post occupancy evaluation.

More precision is certainly required here, but the experimental findings from past research across the world, coupled with the possible under performance shown in this study, should, at the very least, justify the need for more attention in this field. Particularly given that we need to improve the performance of more than 80% of our buildings by 2050.

Insulating our building makes sense. Insulating our buildings properly makes even more sense.



Retrofit Technology - heat pumps

Heat pumps are cited as a key technical solution for many countries with heating dominated climates. A significant part of Ireland's decarbonisation roadmap, is the roll out of more than half a million heat pumps by 2030. Switching to heat pumps at the very least enables eventual decarbonisation of the sector's heating needs. Heat pumps are also more efficient than traditional boilers but are more complex and several factors influence their performance, ranging from technical rationale (such as refrigerant selection, geometric design of heat exchangers, controls etc) through to location and occupant behaviour.

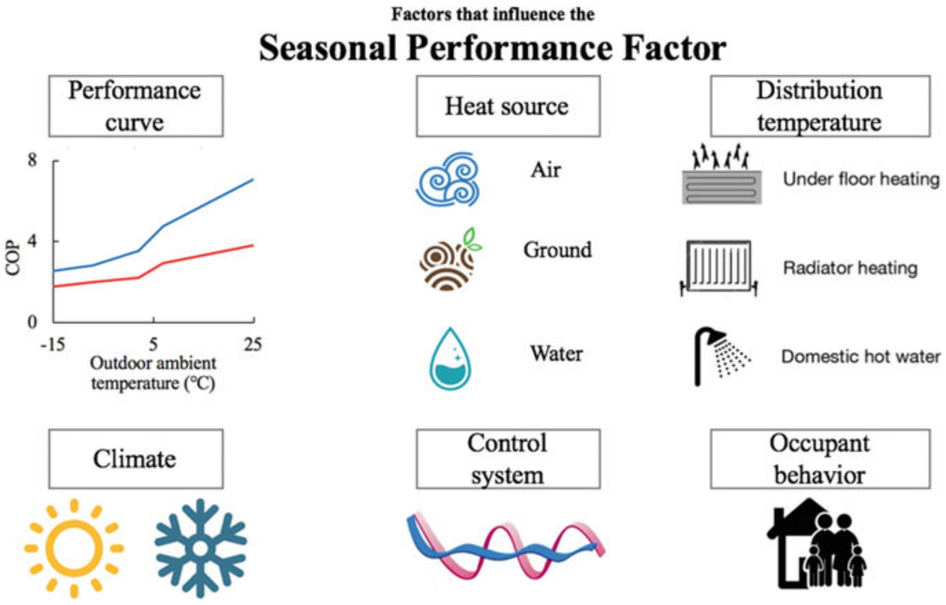


Figure 8. Factors influencing heat pump performance

The number of academic publications on heat pumps has grown considerably over the last 15 years as shown in Figure 9.

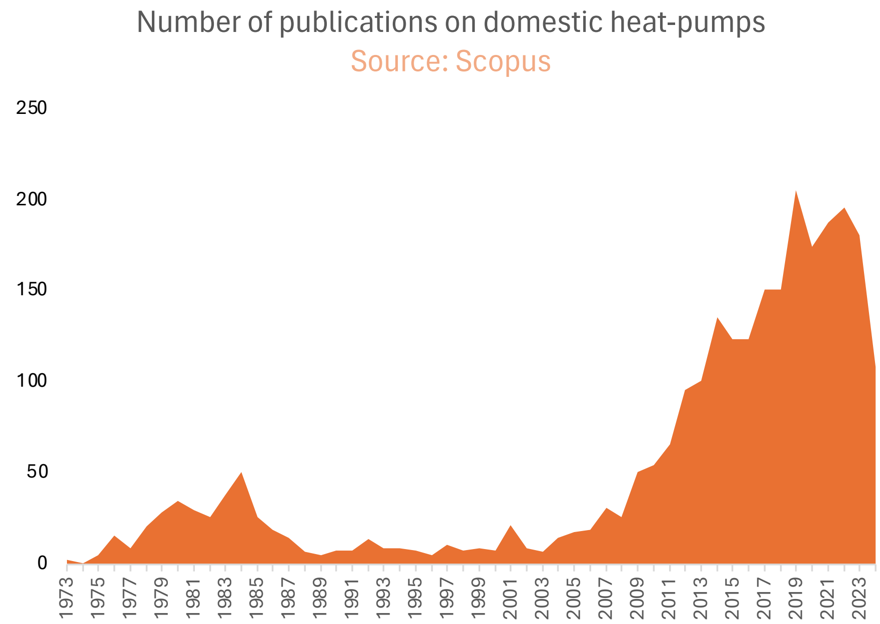


Figure 9. Number of studies on heat pumps

The authors of this current document, published a review and case study on the performance gap between actual and rated performance. The Coefficient of Performance (COP), the key metric used to quantify heat pump performance is usually marketed at around 4.0, i.e. for every unit input of electrical energy there is 4 unit outputs of heat energy. This research found that through a review of 378 heat pumps the average COP was 2.6 (R. O'Hegarty et al., 2021). In the case study the authors observed that the COP was 40% lower than the product rating and that likely reasons for this included:

- The use of temperature and humidity conditions in official heat pump rating tests which are unrepresentative of Irish climatic conditions.

- Unaccounted for heat loss in the piping between internal and external units. This was observed to be a significant issue in the case study assessed where piping was extended for practical reasons where the occupant wanted the outdoor unit on one side of the home and the indoor unit on the other side of the home internally.

- Underestimated effects of cycling. In cases where the heat pump is over sized it is prone to cycling on and off, reaching the set temperature too quickly. Consequently resulting in inefficiencies that have not been captured during product rating. Cycling can also impact the life cycle of a heat pump. Impacting cost and embodied carbon.

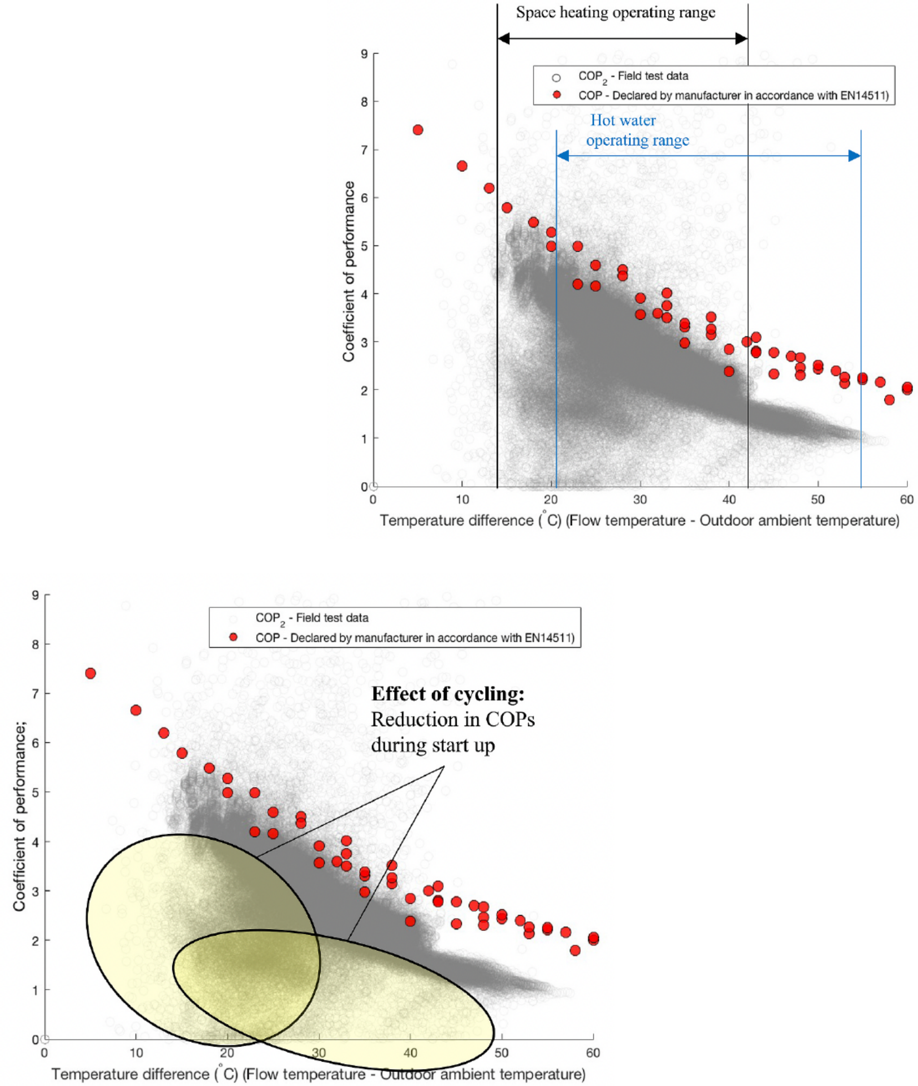


Figure 10. Comparison of field and rated performance data. Highlighting temperature operational ranges (top) and cycling (bottom. Taken from (R. O'Hegarty et al., 2021)

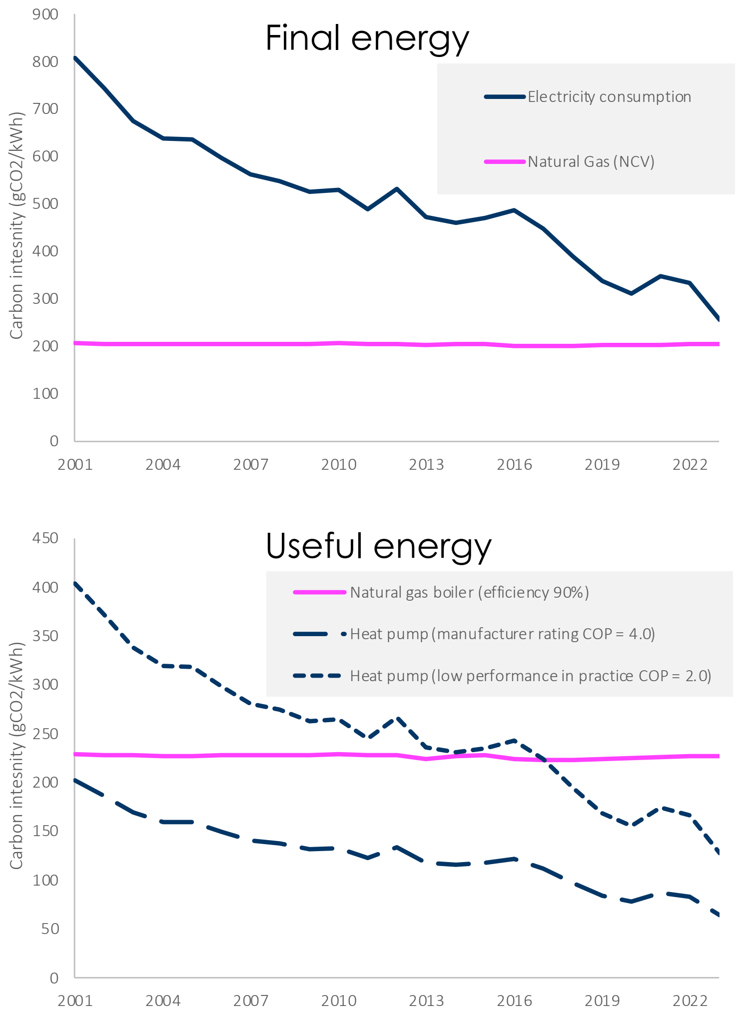


Figure 11. Comparing the carbon intensity of electricity with natural gas (top) and hence between natural gas and electricity-derived heating i.e. heat pumps (bottom)

Concluding thoughts on heat pumps

Heat pump installations feature heavily in decarbonisation plans for the building sector of heating dominated climates such as Ireland. The research to date highlights the importance of quality installation in the case of heat pumps. Other important factors include, but are not limited to:

- Heat pumps use electricity and therefore grid decarbonisation is essential to fully reap the reward of an electrified domestic heating. As illustrated in Figure 11, the heat pump is not more carbon efficient then a gas boiler in unlikely scenarios where the COP is very low and the grid is not further decarbonised. The risk of this is low given the trajectory of both.

- Dynamic demand-supply controls. Heat pumps are usually connected to storage tanks for domestic hot water preparation. This can be seen as a "thermal battery" at a national scale. Clever controls could trigger heat pumps to turn on once the grid has a surplus of electricity thereby alleviating load at other times.

- Reduced refrigerant leakage. Several studies have shown how refrigerant leakage risk in heat pump installations are the biggest source of embodied GHG emissions (Finnegan et al., 2018; Johnson, 2011; O'Hegarty et al., 2020a). Consequently, there have been developments in the use of lower impacting refrigerants such as CO2.

- High temperature heat pumps. Heat pumps are currently designed for continuous low temperature applications. This consequently results in the need for new application heating systems (larger radiators or under floor heating). High temperature heat pumps would alleviate the need to replace the hydronic system and thereby save embodied carbon.

2. How we build?

Modern methods of construction

Overview

We've discussed the importance of making best use of what we already have and some of the key technologies required to enable this. In terms of new construction we report on the move towards Modern Methods of Construction (MMC) here. Particularly relevant to Ireland. The term is first conceptualised in Figure 12 to highlight how it is in ways an umbrella term for offsite, prefabricated and modular construction and inclusive of other novel innovations such as 3D printing etc.

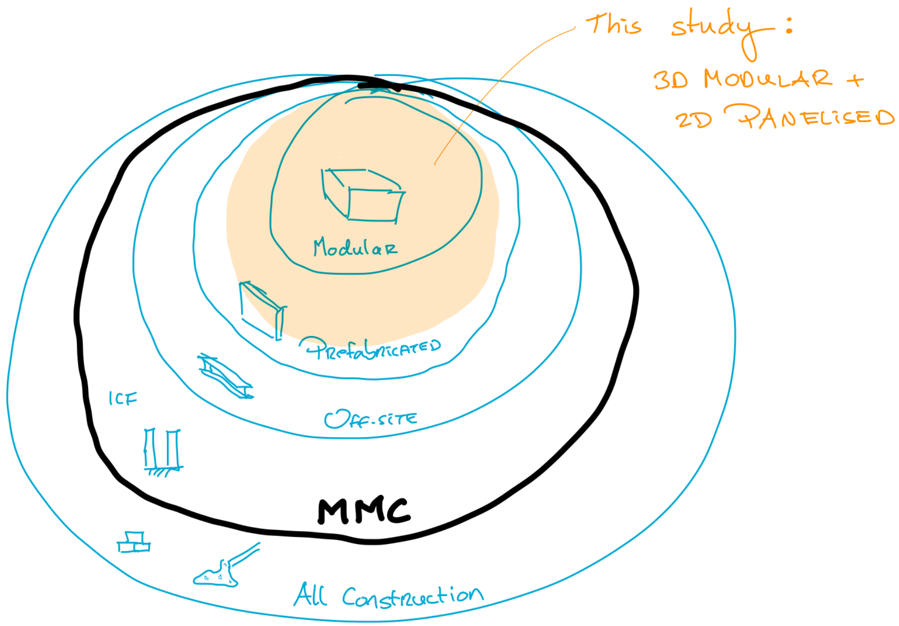


Figure 12. Conceptualising MMC relative to other terminology used e.g. "prefabricated" "off-site" etc.

The construction sector has, for many years, been criticized for its low level of innovation and slow productivity (Ahmad et al., 2020; Goodrum et al., 2002). This has led to a push for new ways to do things. MMC makes sense as an area of consideration, especially in the amidst of high global housing demand. This logic has seen government policy direct research to this area. From an academic perspective there are also some past and emerging studies, documented here.

Several studies reviewing the literature on MMC have been published recently. The work of Sánchez-Garrido et al. (2023) is perhaps the most comprehensive. The authors use machine learning to conduct a systematic literature review of 633 studies published between 1975 and 2022 – concluding that "*MMCs offer a promising solution to the building sector's low productivity, labour shortages, cost control issues while reducing uncertainty, minimizing waste, and promoting sustainability.*". Although a the sustainability-related conclusion is a bit ambiguous, Sánchez-Garrido et al. (2023) seems to imply a positive environmental impact when applying MMC. The evidence within the paper however is not clear, especially not in terms of MMC as a lower embodied carbon solution.

Teng et al. (2018) address this uncertainty in a preceding study which compiled embodied carbon data from 27 prefabricated case studies and reported that on average the prefabricated buildings resulted in a 15.6% reduction in embodied carbon. With values ranging from 105 – 864 $kgCO_2/m^2$ the authors were also quick to note that this does not necessarily mean prefabrication is better or worse and that ultimately there is "significant inconsistency in the embodied carbon emissions of prefabricated buildings.", calling for "consistent embodied carbon emissions analyses". Work is being prepared by the Platform 4 MMC group in UCD's School of Architecture to further advance these knowledge gaps.

The following sections touch briefly on some innovations in this space.

MMC by material

MMC is often used loosely to refer to timber frame and/or Light Gauge Steel (LGS) but MMC is material agnostic by definition. LGS and timber modularised and panelised systems are well covered online and throughout the MMC literature. Concrete is covered to a much lesser extent as it pertains to MMC.

Concrete sandwich panels for retrofit

Advantages of concrete include its durability, fire resistance, homogeneity among others. Its weakness however is its weight. An issue magnified when applied to existing buildings as illustrated in Figure 13. Tackling this issue was the focus of past research conducted by the authors of this work (O'Hegarty et al., 2020b; Richard O'Hegarty et al., 2021a, 2021b; O'Hegarty and Kinnane, 2020).

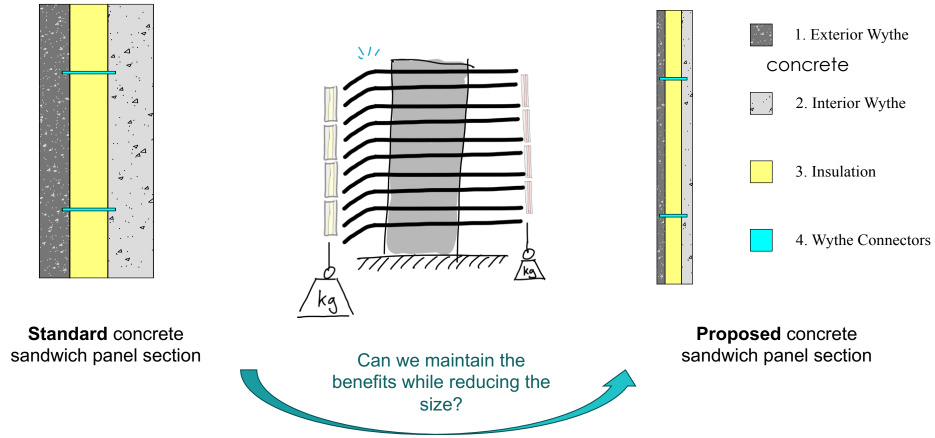


Figure 13. Concrete sandwich panels – standard and under development.

The authors used a number of material- and product-innovations to design a sandwich panel with reduced thickness, embodied carbon and equal thermal performance. Innovations included the use of vacuum insulated panels (Johansson, 2012), high performance low carbon concrete (Richard O'Hegarty et al., 2021b) and structural optimisation via Fibre reinforced polymer (FRP) shear connectors (Hodicky et al., 2014). A selection of results are presented in Figure 14.

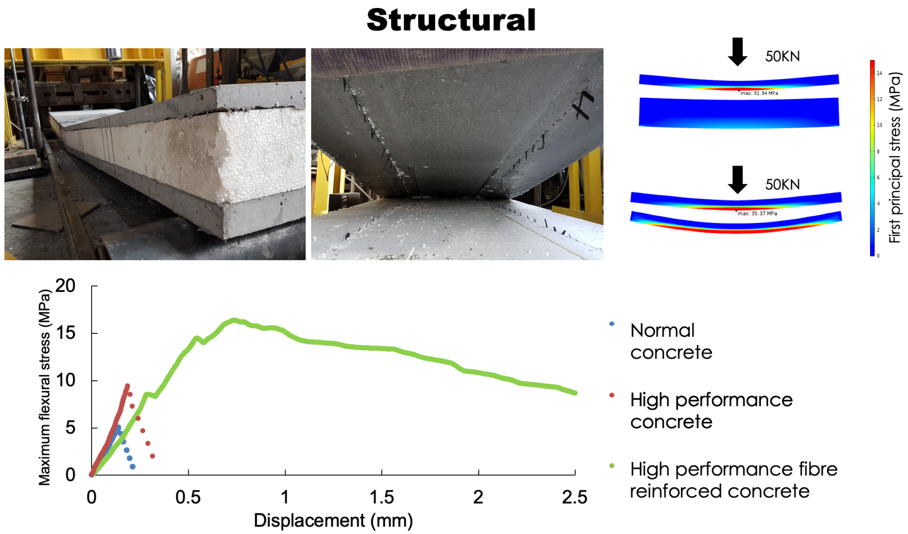


Figure 14. Experimental and finite element investigation of a concrete sandwich panel (Hegarty and Kinnane, 2020).

The embodied carbon question for MMC

As noted earlier, MMC is often cited for its sustainability advantages. The logic being that increasing the amount of offsite construction results in better quality control and waste reduction which is then implied to mean savings in other sustainability metrics such as embodied carbon.

The literature on this is in relatively high agreement although initial further investigation shows that in many cases apples are not being compared with apples. E.g. timber vs concrete. These results reflect the embodied carbon potential saving of timber rather than MMC. And in any case there are several uncertainty challenges associated to the accurate embodied carbon quantification of timber structures (Morris et al., 2021).

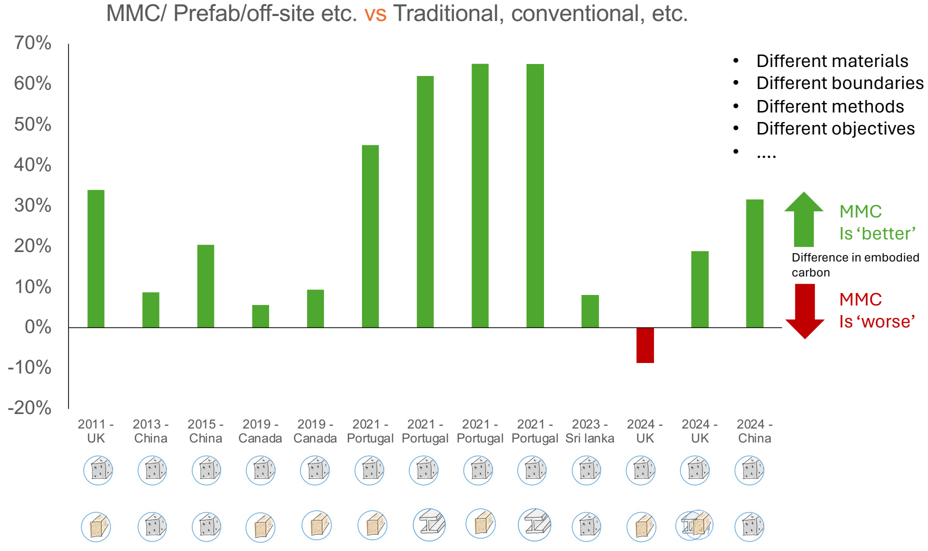


Figure 15. MMC vs traditional embodied carbon comparison

Concluding comments

- There is a requirement to enhance the speed of delivery and improve the efficiency within the construction sector.
- MMC is seen as the answer, which it might very well be, given the broad umbrella term that it is. In some ways MMC can be considered anything which isn't bricks, blocks or in-situ concrete. But for each of these techniques there are other benefits such as monolithic robustness and low skills requirement.
- The evidence surrounding the embodied carbon benefits are light and require deeper investigation.

3. What we build with?

Concrete

Understanding the carbon component of concrete

Figure 16. Concrete components by volume (top) and by carbon content (bottom)

Concrete is mostly sand and aggregate by volume. From a carbon emissions perspective, it is approximately 90% cement – that is more than 90% of concrete's emissions are associated to the cement in it. Decarbonising cement therefore decarbonises concrete.

The concrete and cement industries are under pressure to decarbonise and have been criticised for being "the most destructive material on the planet" . A provocative headline which lacks nuanced understanding. Concrete is probably the most polluting material on the planet but not on a per kg or m3 basis, simply because it is what we use most of as illustrated in Figure 17.

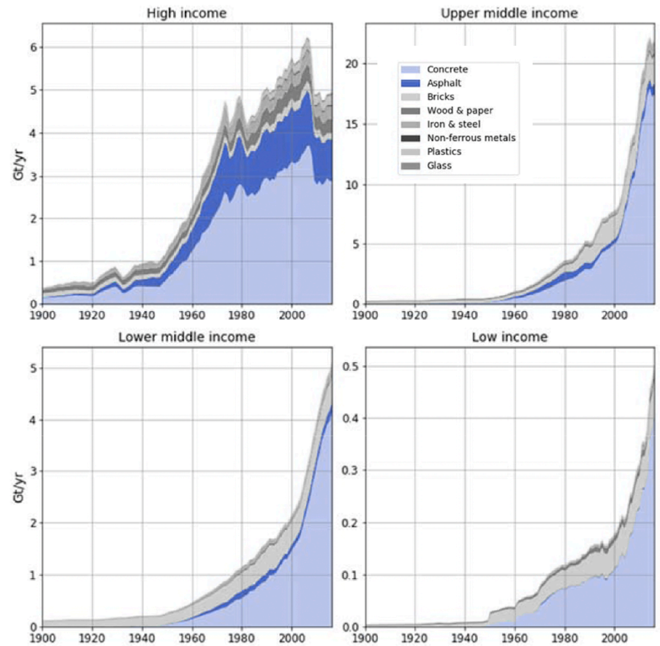


Figure 17. Overview of material consumption adapted from (Plank et al., 2022)

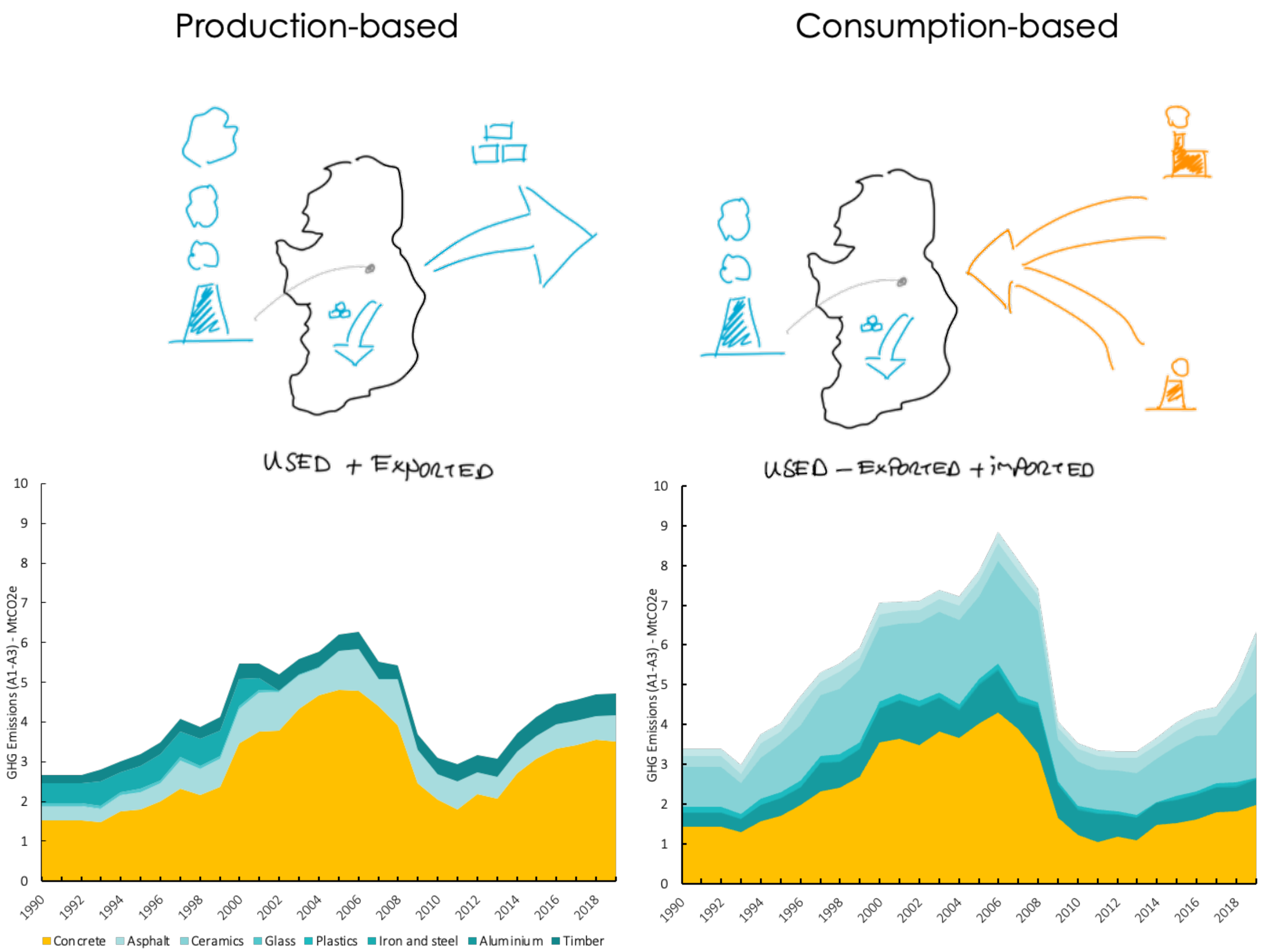


Figure 18. Production- vs consumption-based material-related emission accounting. Adapted from (O'Hegarty and Kinnane, 2022)

Ireland's material-related embodied carbon balance sheets are quite different when observed from a production (as per GHG inventories such as the EPA in Ireland) and consumption based accounting framework. The Production only lens could lead to policies which focus only on materials produced in Ireland and fail to address high pollutant materials produced overseas.

Solutions and challenges – Net zero viable

A live and relatively comprehensive low-carbon concrete tracker is accessible online via the Institute of Structural Engineers website[2]. Details of which can be found in the magazine's volume 102, issue 4 (The Institution of Structural Engineers, 2024).

An extract of some of the key technologies are presented in Figure 19 depicting the range in embodied carbon impact.

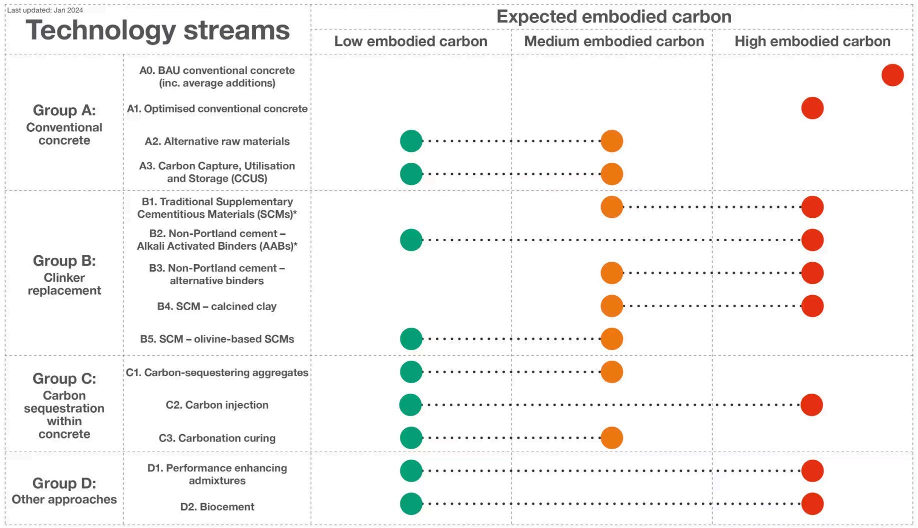


Figure 19. Breakdown of low carbon technologies by group, taken directly from https://www.istructe.org/resources/guidance/concrete-technology-tracker/

Several other key documents provide succinct overviews and reviews of cement and concrete's decarbonisation pathway. Hibbert et al. (2022) for example assess solutions in the UK, from an implementation perspective, looking at technology readiness levels of different solutions.

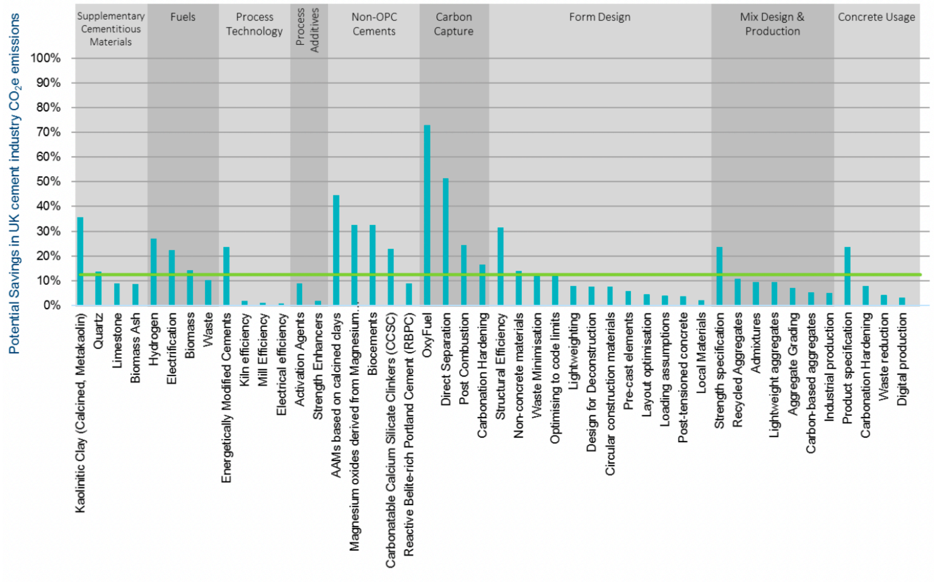


Figure 20. Low carbon cement solutions chart. Taken from (Hibbert et al., 2022)

From an academic perspective, there are several recent studies which have reviewed the different technologies from both a socio-technical perspective (Griffiths et al., 2023) as well as a policy perspective (Busch et al., 2022).

[2] https://www.istructe.org/resources/guidance/concrete-technology-tracker/

Discussion of some key emerging technologies

The search for a low-carbon drop-in replacement for OPC is on-going, with the likes of *Sublime-systems*^{TM} making a strong rationale for their electrolytic reactor derived cement and reaping the rewards of this transparent approach having recently received $87 million from the US Dep of Energy to cover half the cost of its first commercial plant (CNBC, 2024). The innovators of this particular cement (who's origins interestingly were as battery scientists) have published their process in 2019 (Ellis et al., 2020), and have since moved to 100 tonnes per year production with 1,000,000 tonnes targeted for 2028. The process entirely replaces the current thermochemical OPC process with a electrochemical process. It is flexible in the range of feedstock it can process including CO2 and non CO2 containing materials. The authors note that it can use limestone as is typical in a OPC kiln and while this does produce CO2, the form of CO2 is of a higher quality and hence requires less pre-processing to be captured.

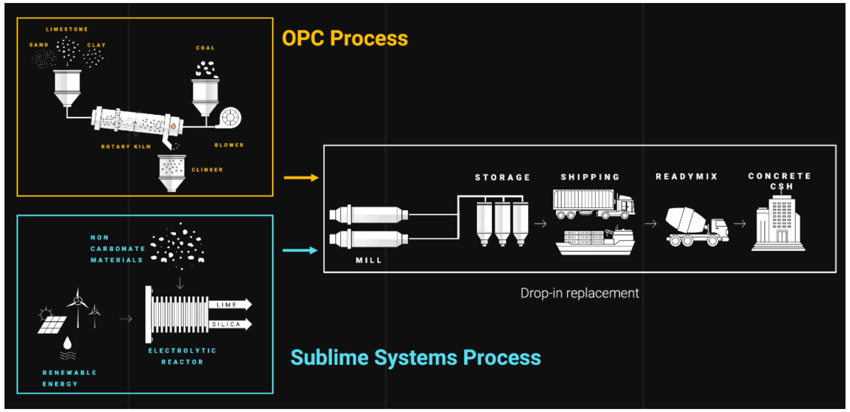


Figure 21. Sublime Systems' cement manufacturing process taken from Sublime-Systems' website

Another emerging innovative solution in the cement decarbonisation space is the *Cambridge Electric Cement (Cambridge Electric Cement, 2024)*. Similar to the Sublime Systems approach, it aims to replace clinker entirely and the process is very different to traditional cement manufacturing. The approach used by this solution is, however, very different.

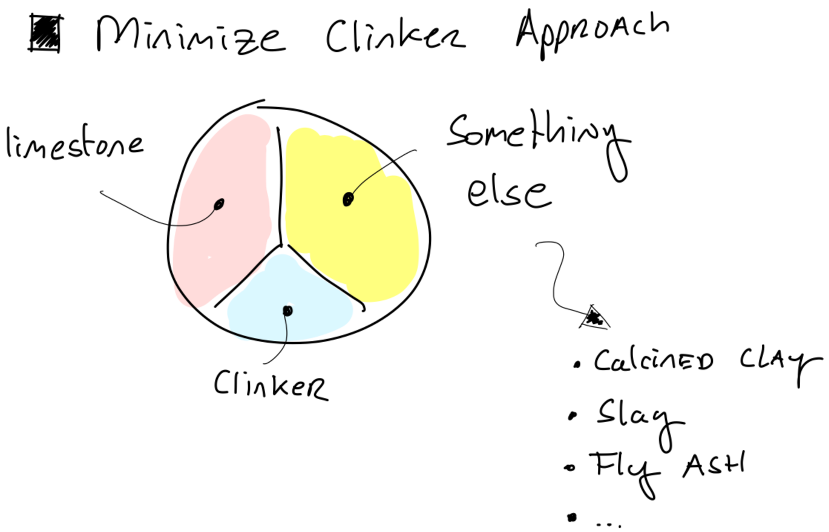
It uses recovered cement paste from waste concrete as its feedstock and taps into existing Electric Arc Furnace infrastructure which is used for steel recycling. Lime-flux, which is used to provide the required basicity and to protect the electrodes, is replaced with Recovered Cement Paste (RCP) during the recycled steel melting and processing phases. Making this substitution means the left over slag is similar in constitution to current clinkers (Dunant et al., 2024). The process is promising in that it taps into existing infrastructure and can be a direct clinker replacement.

There are a number of drawback however. The output is sensitive to the silica content of the RCP feedstock, and hence requires adequate quality control and source selection. Furthermore, RCP is not commercially available at scale. To arrive at RCP, the aggregates and sand in used concrete needs to be separated from the cement past. Past efforts have been driven by a focus to process high quality recovered aggregates, but the increase in quality has, to date, not warranted significant investment in the extra processing cost. The innovators of this electric cement argue that their research has helped incentivise a new market here.

Minimizing clinker

Other more traditional routes include the minimization of the clinker content through a combination of chemical (cement blends e.g. clinker, ash, slag, limestone etc) and physical (i.e. particle packing (Borges et al., 2014)) optimisation. The resultant pre-blended cements usually contain a portion of clinker, a reactive/pozzolanic material (e.g. calcinated clay, fly ash or

Within this “minimize clinker approach” the clinker and limestone portion typically remain constant providing the scalability and reactivity pieces of the puzzle. The final piece then needs to provide sufficient alumina and silica requirements.



Arriving at this slice has seen the emergence of two schools of thought - one which is chasing *the material* which will be sufficiently scalable. This approach is adopted by LC3 which has identified Calcined Clay as the most suitably abundant material for this equation. The developers also have a strong scientific foundation behind the approach (K. Scrivener et al., 2018; K. L. Scrivener et al., 2018) and make a convincing rationale for the use of calcined clays which are suitably located in parts of the world expecting to see development over the coming decades.

The other school of thought is more of a material agnostic approach which

Is currently deriving its material from well-tested replacements such as slag, but which considers this piece of the equation as dynamic and potentially geographically determined.

Ecocem’s ACT might land in this field which currently used GGBS as its “something else” portion but whom are actively investigating other available SCMS.

Of course this blending process can occur at the concrete producers facility provided sufficient plant has been installed to deal with the additional number of silos, chutes, controls and admixtures. The question for concrete producers here is whether the additional flexibility warrants the additional capital. This will depend on the concrete manufacturer’s market.

Snelling

German researchers Muller et al.

If, by looking at the bottom image of Figure 16, we observe that the carbon problem of concrete is a cement problem.

Another way of thinking is to observe the portion of aggregates and sand used in concrete as a carbon saving

Regulation tool - Green Procurement report

From a regulatory perspective, Ireland has made some positive steps forward in terms of ensuring a pathway to a lower carbon concrete industry.

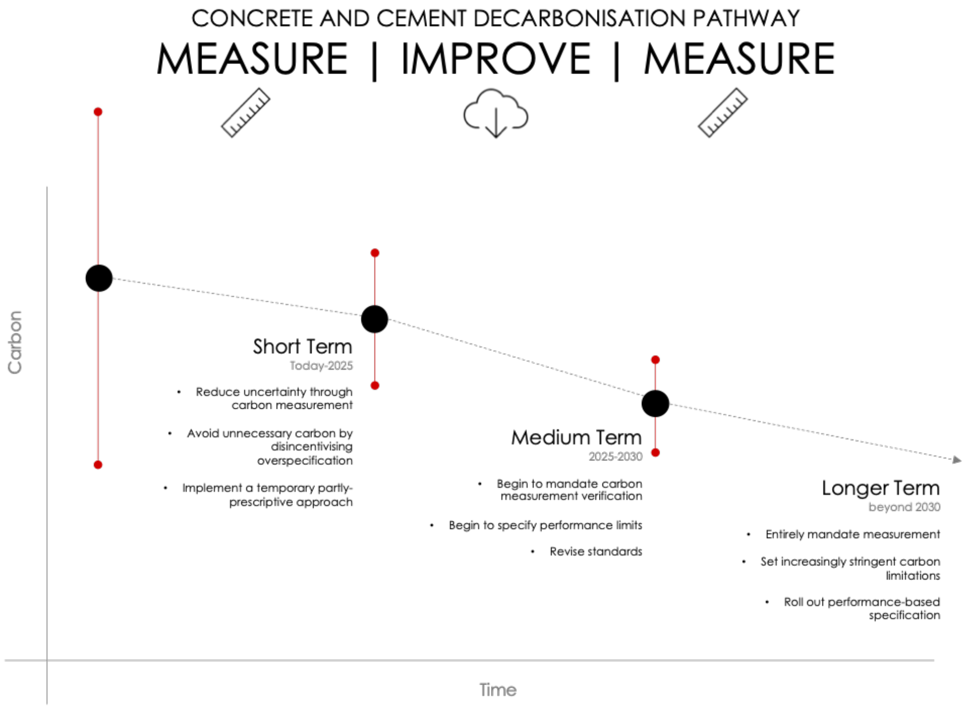


Figure 22. High level overview of decarbonisation pathway for Irish cement and concrete industry (Boland et al., 2024)

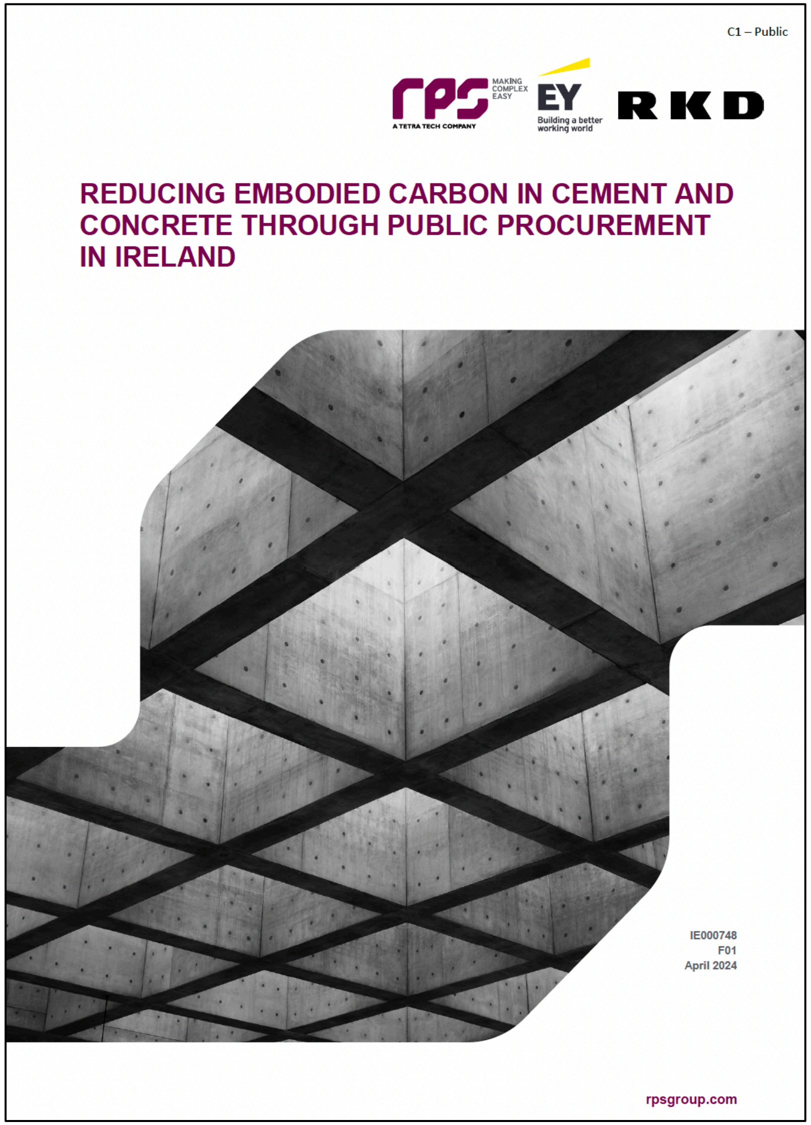


Figure 23. Cover of Irish government commissioned report (Boland et al., 2024)

4. What is left?

Carbon capture storage and utilisation

Overview

This section is included to present an understanding of what can be done with some of the remaining emissions from building-related activities. It is well documented that CCUS is in not an easy win in the world of decarbonisation (as depicted in the IPCC's comparison of solutions shown in Figure 24).

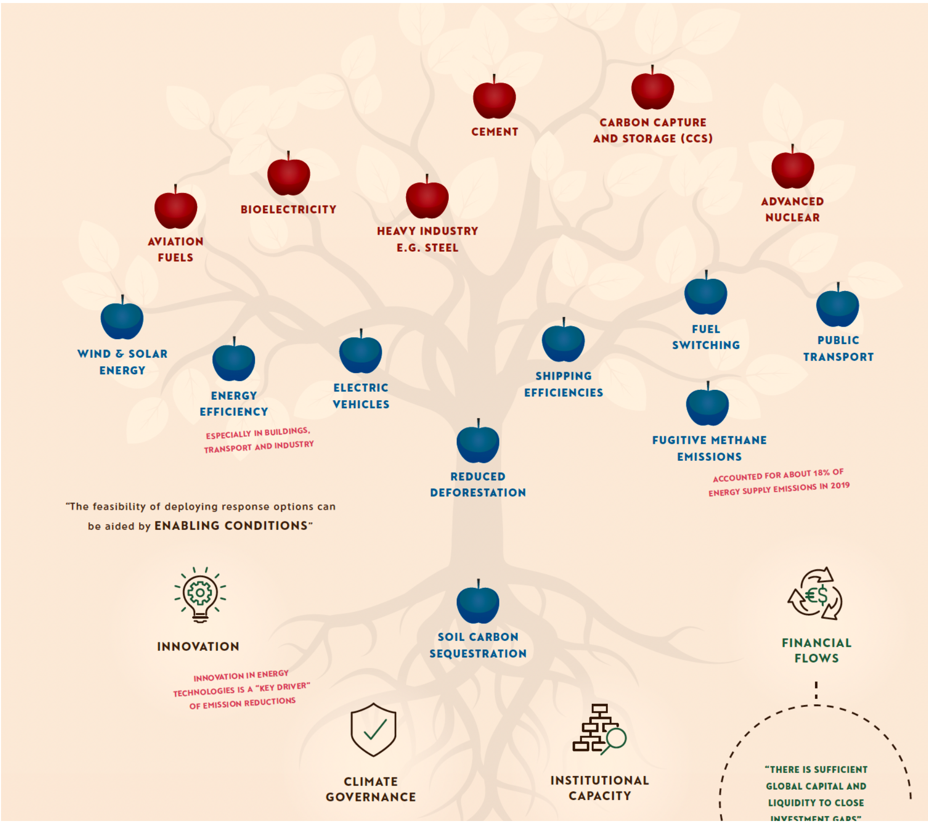


Figure 24. Hard to abate sectors compared to low-hanging-fruit. Image taken from the IPCC.

CCUS can be used by a particular industry such as the cement, chemical or steel sectors to reduce the specific industries' carbon footprint, or it can be used to make additional net negative contributions to the global decarbonisation challenge via Direct Air Capture (DAC). DAC is a form of Carbon Dioxide Removal and would be considered an additional contribution. Equally it is one of the most expensive forms of CCUS. The application of CCUS is not equal, and can be broadly grouped by the concentration of the CO2 from a given process as shown in Figure 26 with DAC as the outlier and most costly and with cement, power generation and steel production below that in the "low concentration" / more costly bracket of CCUS. This is covered in detail in the State of Carbon Dioxide Removal report (S. M. Smith et al., 2024).

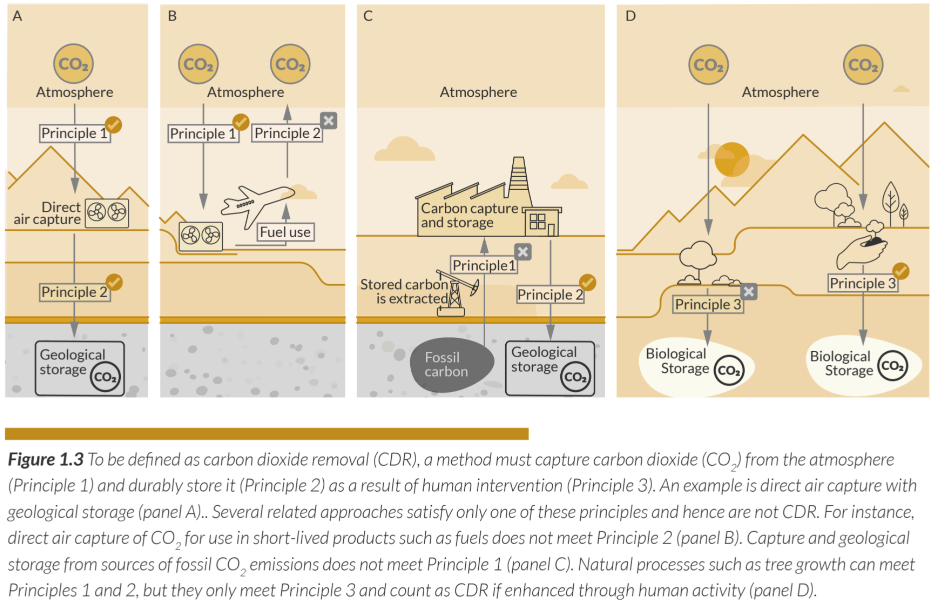


Figure 25. Figure 1.3 of (S. M. Smith et al., 2024)

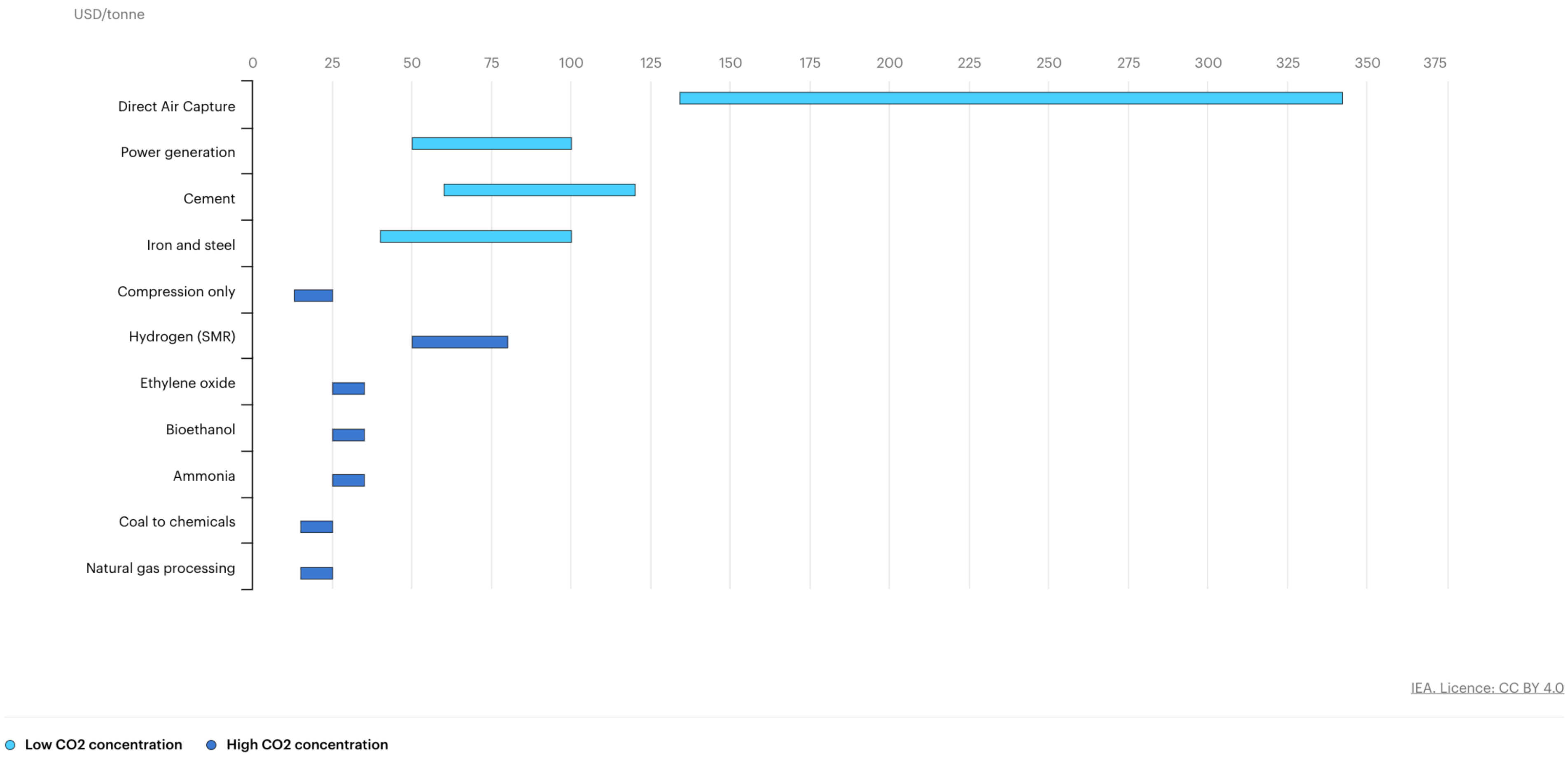


Figure 26. IEA (2020), Levelised cost of CO2 capture by sector and initial CO2 concentration, 2019, IEA, Paris https://www.iea.org/data-and-statistics/charts/levelised-cost-of-co2-capture-by-sector-and-initial-co2-concentration-2019, Licence: CC BY 4.0

The need for CDR and hence some form of CCUS is well documented in global and national policies. In a review of residual emission coverage in the long term national climate strategies, Smith et al. (2024) found that there was considerable disparity among different countries on how much residual emissions would be left. Ranging from 5 – 52% excluding land use and 21% of peak emissions on average.

Clearly, a form of CDR is required for net zero to be achieved. CDR includes, direct air capture, afforestation, Bioenergy with carbon capture and storage (BECCS) among others.

Carbon capture in the built environment

The residual emissions for the built environment are largely in the materials used i.e. cement and steel. In section 3 we covered some innovations relating to cement decarbonisation.

One route that is cited in some cement and concrete decarbonisation plans is the use of Carbon capture at various stages in the cement and concrete process. As noted earlier, CCUS is a part of the cement sector's decarbonisation roadmap during the production stage. But carbon capture also occurs naturally during the lifetime of concrete (Fitzpatrick et al., 2015) while other innovations have been explored which aim to add carbon during mixing (https://www.carboncure.com/), curing (https://www.carboclave.com/) and by combining material selection with curing (https://www.solidiatech.com/media.html).

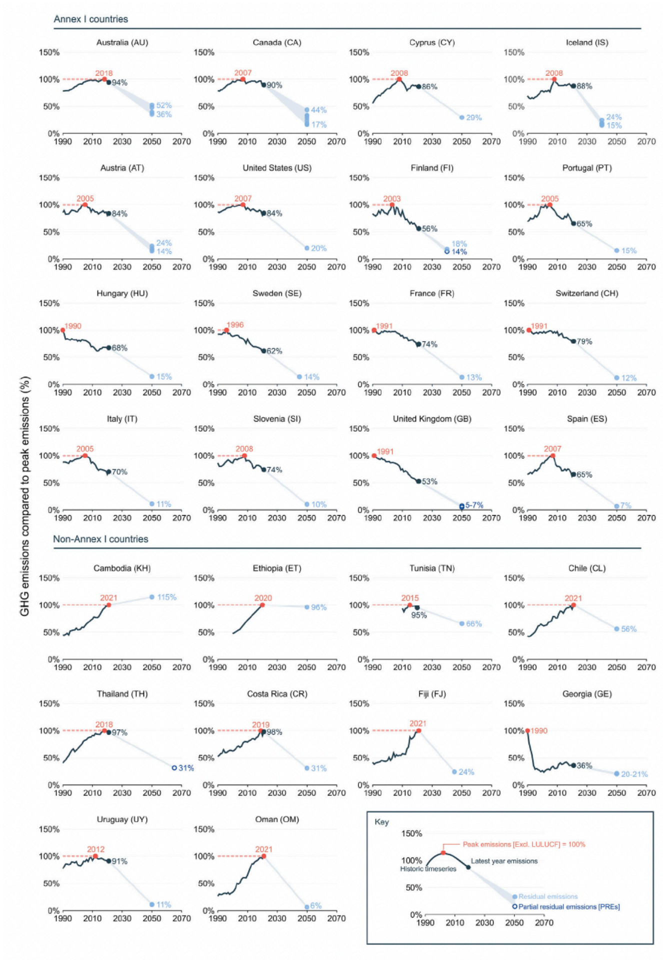


Figure 27. Residual emissions in different national policies. Figure taken from (H. B. Smith et al., 2024)

Concluding remarks

This document integrates past research from the current authors with state of the art research in relevant academic, policy and commercial literature pertaining to the decarbonisation of the built environment and the core focus areas:

- Retrofit and renovation
- Modern methods of construction
- Concrete
- Carbon capture storage and utilisation.

The research is non-exhaustive but highlights the intricate challenges associated decarbonising buildings and their materials while also showcasing some of the solutions required to get to full decarbonisation.

Part 1 of the report covers renovation and retrofit, arguably the biggest area of potential decarbonisation in developed parts of the world. Saving the buildings we already have by making them attractive and energy efficient also reduces the requirement for new floor space. Both insulation and heat pumps are covered, arguably the two biggest technologies required for residential building decarbonisation. The solutions are well tested but challenges associated with performance gaps between produced rated performance and actual performance persist. Likely due to inadequate installations, mass upskilling is required in this space.

Part 2 moves on from what we have built to what we will build going forward. A ramp up in the amount of construction is planned in countries where there are housing shortages. This, in conjunction with the decarbonisation of existing buildings and the insurance of low energy new buildings results in a potential scenario whereby the future of the built environment's annual emissions will be from the materials used in new construction. In terms of how building are put together there is a drive for more modern methods of construction to enhance both speed, efficiency and productivity. Sustainability is then often assumed to be a consequence of productivity and efficiency but such a conclusion is not yet substantiated by robust evidence.

Part 3 then focuses on the materials part of the embodied carbon equation, or more precisely *the material* we use most of i.e. concrete. This section navigates the pathways to zero carbon cement touching on the challenges ahead as well as some of the exciting new innovations in the space. The likely route for concrete's journey to zero will be multi-faceted with various innovations taking chunks out of the industries current 8% of global emissions.

In Part 4, we briefly touch on a solution touted to solve the left over emissions in the built environment. This section looks at both CCUS and CDR at a high level. It acknowledges the expectation for some form of carbon removal from almost every national policy and briefly describes some of the concrete-related carbon capture innovations.

Acknowledgments

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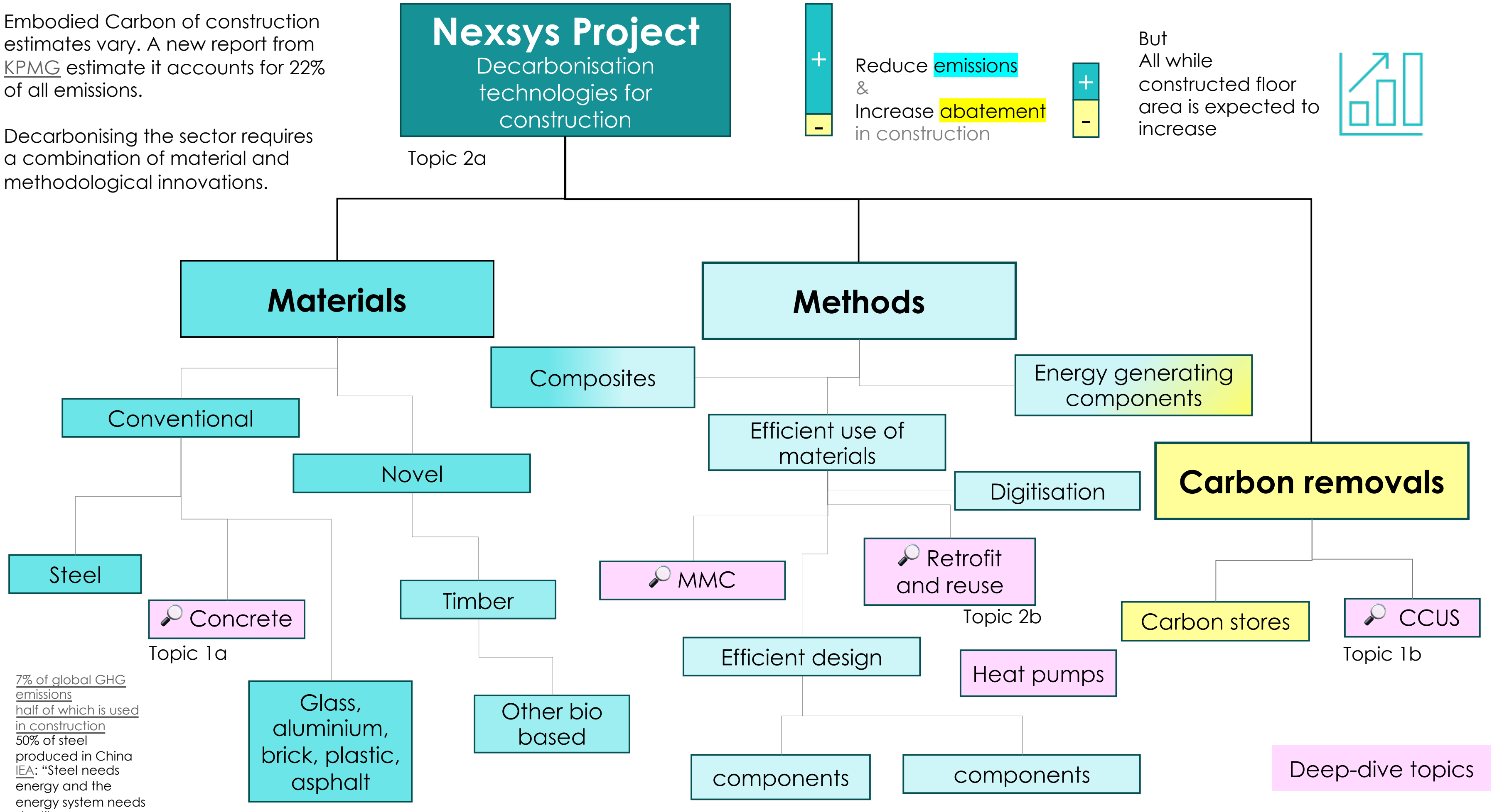
Appendix A – Project Map

Embodied Carbon of construction estimates vary. A new report from KPMG estimate it accounts for 22% of all emissions.

Decarbonising the sector requires a combination of material and methodological innovations.



- 7% of global GHG emissions
- half of which is used in construction
- 50% of steel produced in China
- IEA: "Steel needs energy and the energy system needs steel"

References

Ahmad, S.B.S., Mazhar, M.U., Bruland, A., Andersen, B.S., Langlo, J.A., Torp, O., 2020. Labour productivity statistics: a reality check for the Norwegian construction industry. International Journal of Construction Management 20, 39–52. https://doi.org/10.1080/15623599.2018.1462443

Allen, C., Oldfield, P., Teh, S.H., Wiedmann, T., Langdon, S., Yu, M., Yang, J., 2022. Modelling ambitious climate mitigation pathways for Australia's built environment. Sustainable Cities and Society 77, 103554. https://doi.org/10.1016/j.scs.2021.103554

Boland, C., Gil, O., Hughes, A., O'Hegarty, R., 2024. Reducing Embodied Carbon in Cement and Concrete through Public Procurement in Ireland. RPS RKD EY. Department of Enterprise, Trade and Employment (DETE).

Borges, P.H.R., Fonseca, L.F., Nunes, V.A., Panzera, T.H., Martuscelli, C.C., 2014. Andreasen Particle Packing Method on the Development of Geopolymer Concrete for Civil Engineering. Journal of Materials in Civil Engineering 26, 692–697. https://doi.org/10.1061/(ASCE)MT.1943-5533.0000838

Busch, P., Kendall, A., Murphy, C.W., Miller, S.A., 2022. Literature review on policies to mitigate GHG emissions for cement and concrete. Resources, Conservation and Recycling 182, 106278. https://doi.org/10.1016/j.resconrec.2022.106278

Cambridge Electric Cement, 2024. Product and technology – Cambridge Electric Cement [WWW Document]. URL https://cambridgeelectriccement.com/the-product/ (accessed 8.22.24).

Casini, M., 2020. Insulation Materials for the Building Sector: A Review and Comparative Analysis, in: Encyclopedia of Renewable and Sustainable Materials. Elsevier, pp. 121–132. https://doi.org/10.1016/B978-0-12-803581-8.10682-4

CNBC, 2024. Sublime Systems says cement is being made with zero carbon emissions [WWW Document]. URL https://www.cnbc.com/2024/07/10/sublime-systems-says-its-cement-made-with-zero-carbon-emissions.html (accessed 8.22.24).

Crowe, P., 2019. How data on vacancy is created and used: Case studies from Scotland, Denmark and Philadelphia. The Collaborative Working Group for Housing and Sustainable Living.

CSO, 2022. Non-Domestic Building Energy Ratings Q1 2022 - CSO - Central Statistics Office [WWW Document]. URL https://www.cso.ie/en/releasesandpublications/er/ndber/non-domesticbuildingenergyratingsq12022/ (accessed 7.28.22).

Drewniok, M.P., Azevedo, J.M.C., Dunant, C.F., Allwood, J.M., Cullen, J.M., Ibell, T., Hawkins, W., 2023. Mapping material use and embodied carbon in UK construction. Resources, Conservation and Recycling 197, 107056. https://doi.org/10.1016/j.resconrec.2023.107056

Dunant, C.F., Joseph, S., Prajapati, R., Allwood, J.M., 2024. Electric recycling of Portland cement at scale. Nature 1–7. https://doi.org/10.1038/s41586-024-07338-8

Ellis, L.D., Badel, A.F., Chiang, M.L., Park, R.J.-Y., Chiang, Y.-M., 2020. Toward electrochemical synthesis of cement—An electrolyzer-based process for decarbonating CaCO3 while producing useful gas streams. Proceedings of the National Academy of Sciences 117, 12584–12591. https://doi.org/10.1073/pnas.1821673116

Enkvist, P.-A., Klevnäs, P., Westerdahl, R., Åhlén, A., 2022. How a 'materials transition' can support the net-zero agenda. McKinsey 8.

Finnegan, S., Jones, C., Sharples, S., 2018. The embodied CO2e of sustainable energy technologies used in buildings: A review article. Energy and Buildings 181, 50–61. https://doi.org/10.1016/j.enbuild.2018.09.037

Fitzpatrick, D., Nolan, E., Richardson, M.G., 2015. Sequestration of carbon dioxide by concrete infrastructure: a preliminary investigation in Ireland. Journal of Sustainable Architecture and Civil Engineering 10, 66–77. https://doi.org/10.5755/j01.sace.10.1.8037

GeoDirectory, 2022a. GeoDirectory commercial Buildings Report Q2 2022.

GeoDirectory, 2022b. GeoDirectory Residential Buildings Report Q2 2022.

Goodrum, P.M., Haas, C.T., Glover, R.W., 2002. The divergence in aggregate and activity estimates of US construction productivity. Construction Management and Economics 20, 415–423. https://doi.org/10.1080/01446190210145868

Griffiths, S., Sovacool, B.K., Furszyfer Del Rio, D.D., Foley, A.M., Bazilian, M.D., Kim, J., Uratani, J.M., 2023. Decarbonizing the cement and concrete industry: A systematic review of socio-technical systems, technological innovations, and policy options. Renewable and Sustainable Energy Reviews 180, 113291. https://doi.org/10.1016/j.rser.2023.113291

Habert, G., Röck, M., Steininger, K., Lupisek, A., Birgisdottir, H., Desing, H., Chandrakumar, C., Pittau, F., Passer, A., Rovers, R., Slavkovic, K., Hollberg, A., Hoxha, E., Jusselme, T., Nault, E., Allacker, K., Lützkendorf, T., 2020. Carbon budgets for buildings: harmonising temporal, spatial and sectoral dimensions. Buildings & Cities 1. https://doi.org/10.5334/bc.47

Hibbert, A., Cullen, J., Drewniok, M.P., 2022. Low Carbon Concrete Technologies (LCCT): Understanding and Implementation. University of Cambridge.

Hodicky, K., Sopal, G., Rizkalla, S., Hulin, T., Stang, H., 2014. FRP Shear Transfer Mechanism for Precast Concrete Sandwich Panels 15.

Huang, Y., Wolfram, P., Miller, R., Azarijafari, H., Guo, F., An, K., Li, J., Hertwich, E., Gregory, J., Wang, C., 2022. Mitigating life cycle GHG emissions of roads to be built through 2030: Case study of a Chinese province. Journal of Environmental Management 319, 115512. https://doi.org/10.1016/j.jenvman.2022.115512

IEA, 2022. Technology and Innovation Pathways for Zero-carbon-ready Buildings by 2030, IEA, Paris https://www.iea.org/reports/technology-and-innovation-pathways-for-zero-carbon-ready-buildings-by-2030, License: CC BY 4.0. International Energy Agency.

IGBC, 2022. Building a zero carbon Ireland. A roadmap to decarbonise Ireland's built environment across its whole life cycle. The Irish Green Building Council.

IPCC, 2023. Intergovernmental Panel on Climate Change (IPCC), ed. Chapter 9 Buildings. In: Climate Change 2022 - Mitigation of Climate Change: Working Group III Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press; 2023:953-1048. 953–1048. https://doi.org/10.1017/9781009157926.011

Johansson, P., 2012. Vacuum Insulation Panels in Buildings. Chalmers University of Technology, Göteborg, Sweden.

Johnson, E.P., 2011. Air-source heat pump carbon footprints: HFC impacts and comparison to other heat sources. Energy Policy 39, 1369–1381. https://doi.org/10.1016/j.enpol.2010.12.009

Leti, 2023. Retrofit vs rebuild: Unpicking the carbon argument.

Morris, F., Allen, S., Hawkins, W., 2021. On the embodied carbon of structural timber versus steel, and the influence of LCA methodology. Building and Environment 206, 108285. https://doi.org/10.1016/j.buildenv.2021.108285
O'Callaghan, C., Stokes, K., 2022. Housing and Vacancy. Edited by Lorcan Sirr., in: Housing in Ireland: Beyond the Markets.
O'Hegarty, R., Colclough, S., Kinnane, O., Lennon, D., Rieux, E., 2020a. Operational and embodied energy analysis of 8 single-occupant dwellings retrofit to nZEB standard, in: CERAI. Presented at the CERAI 2020, Cork, p. 6.
O'Hegarty, R., Kinnane, O., 2023. A whole life carbon analysis of the Irish residential sector - past, present and future. Energy and Climate Change 4, 100101. https://doi.org/10.1016/j.egycc.2023.100101
O'Hegarty, R., Kinnane, O., 2022. Whole life carbon quantification of the built environment: Case study Ireland. Building and Environment 226, 109730. https://doi.org/10.1016/j.buildenv.2022.109730
O'Hegarty, R., Kinnane, O., 2020. Review of precast concrete sandwich panels and their innovations. Construction and Building Materials 233, 117145. https://doi.org/10.1016/j.conbuildmat.2019.117145
O'Hegarty, Richard, Kinnane, O., Grimes, M., Newell, J., Clifford, M., West, R., 2021a. Development of thin precast concrete sandwich panels: Challenges and outcomes. Construction and Building Materials 267, 120981. https://doi.org/10.1016/j.conbuildmat.2020.120981
O'Hegarty, R., Kinnane, O., Lennon, D., Colclough, S., 2021. Air-to-water heat pumps: Review and analysis of the performance gap between in-use and product rated performance. Renewable and Sustainable Energy Reviews 111887. https://doi.org/10.1016/j.rser.2021.111887
O'Hegarty, Richard, Kinnane, O., Newell, J., West, R., 2021b. High performance, low carbon concrete for building cladding applications. Journal of Building Engineering 43, 102566. https://doi.org/10.1016/j.jobe.2021.102566
O'Hegarty, R., Kinnane, O., Wall, S., 2022. Whole Life Carbon in Construction and the Built Environment in Ireland – Today & 2030 - Draft 4.0. Irish Green Building Council.
O'Hegarty, R., Reilly, A., West, R., Kinnane, O., 2020b. Thermal investigation of thin precast concrete sandwich panels. Journal of Building Engineering 27, 100937. https://doi.org/10.1016/j.jobe.2019.100937
Plank, B., Streeck, J., Virág, D., Krausmann, F., Haberl, H., Wiedenhofer, D., 2022. From resource extraction to manufacturing and construction: flows of stock-building materials in 177 countries from 1900 to 2016. Resources, Conservation and Recycling 179, 106122. https://doi.org/10.1016/j.resconrec.2021.106122
Reilly, A., Kinnane, O., O'Hegarty, R., 2020. Energy embodied in, and transmitted through, walls of different types when accounting for the dynamic effects of thermal mass. Journal of Green Building 15, 43–66. https://doi.org/10.3992/jgb.15.4.43
RKD, 2024. Maximising building use.
Robati, M., Oldfield, P., Nezhad, A.A., Carmichael, D.G., Kuru, A., 2021. Carbon value engineering: A framework for integrating embodied carbon and cost reduction strategies in building design. Building and Environment 192, 107620. https://doi.org/10.1016/j.buildenv.2021.107620
Sánchez-Garrido, A.J., Navarro, I.J., García, J., Yepes, V., 2023. A systematic literature review on modern methods of construction in building: An integrated approach using machine learning.

Journal of Building Engineering 73, 106725. https://doi.org/10.1016/j.jobe.2023.106725
Scrivener, K., Martirena, F., Bishnoi, S., Maity, S., 2018. Calcined clay limestone cements (LC3). Cement and Concrete Research, Report of UNEP SBCI WORKING GROUP ON LOW-CO2 ECO-EFFICIENT CEMENT-BASED MATERIALS 114, 49–56. https://doi.org/10.1016/j.cemconres.2017.08.017
Scrivener, K.L., John, V.M., Gartner, E.M., 2018. Eco-efficient cements: Potential economically viable solutions for a low-CO2 cement-based materials industry. Cement and Concrete Research, Report of UNEP SBCI WORKING GROUP ON LOW-CO2 ECO-EFFICIENT CEMENT-BASED MATERIALS 114, 2–26. https://doi.org/10.1016/j.cemconres.2018.03.015
Smith, H.B., Vaughan, N.E., Forster, J., 2024. Residual emissions in long-term national climate strategies show limited climate ambition. One Earth 7, 867–884. https://doi.org/10.1016/j.oneear.2024.04.009
Smith, S.M., Geden, O., Gidden, M.J., Lamb, W.F., Nemet, G.F., Minx, J.C., Buck, H., Burke, J., Cox, E., Edwards, M.R., Fuss, S., Johnstone, I., Müller-Hansen, F., Pongratz, J., Probst, B.S., Roe, S., Schenuit, F., Schulte, I., Vaughan, N.E. (Eds.), 2024. The State of Carbon Dioxide Removal 2024 - 2nd Edition. The State of Carbon Dioxide Removal. https://doi.org/10.17605/OSF.IO/F85QJ
Teng, Y., Li, K., Pan, W., Ng, T., 2018. Reducing building life cycle carbon emissions through prefabrication: Evidence from and gaps in empirical studies. Building and Environment 132, 125–136. https://doi.org/10.1016/j.buildenv.2018.01.026
The Institution of Structural Engineers, 2024. Lower-carbon concrete technologies. The Structural Engineer. The Structural Engineer 102, 12–17. https://doi.org/10.56330/RWIZ5191
UKGBC, 2021. Whole Life Carbon Net Zero Roadmap: A Pathway to Net Zero for the UK Built Environment.
United Nations Environment Programme, 2024. 2023 Global Status Report for Buildings and Construction: Beyond foundations - Mainstreaming sustainable solutions to cut emissions from the buildings sector. United Nations Environment Programme, Nairobi. https://doi.org/10.59117/20.500.11822/45095
WBCSD, Arup, 2023. Net-zero buildings Halving construction emissions today.
World Business Council for Sustainable Development (WBCSD), World Resource Institute (WRI), 2004. The Greenhouse Gas Protocol. A Corporate Accounting and Reporting Standard. Revised Edition.
Yang, X., Hu, M., Tukker, A., Zhang, C., Huo, T., Steubing, B., 2022. A bottom-up dynamic building stock model for residential energy transition: A case study for the Netherlands. Applied Energy 306, 118060. https://doi.org/10.1016/j.apenergy.2021.118060
Zhu, W., Feng, W., Li, X., Zhang, Z., 2020. Analysis of the embodied carbon dioxide in the building sector: A case of China. Journal of Cleaner Production 269, 122438. https://doi.org/10.1016/j.jclepro.2020.122438