IES

Digital Twin Modelling for Climate Resilient Housing

Integrated Environmental Solutions Ltd.

Comhairle Cathrach
Bhaile Átha Cliath
Dublin City Council

Our Public Service

An Roinn Caiteachais
Phoiblí agus Athchóirithe
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Executive Summary

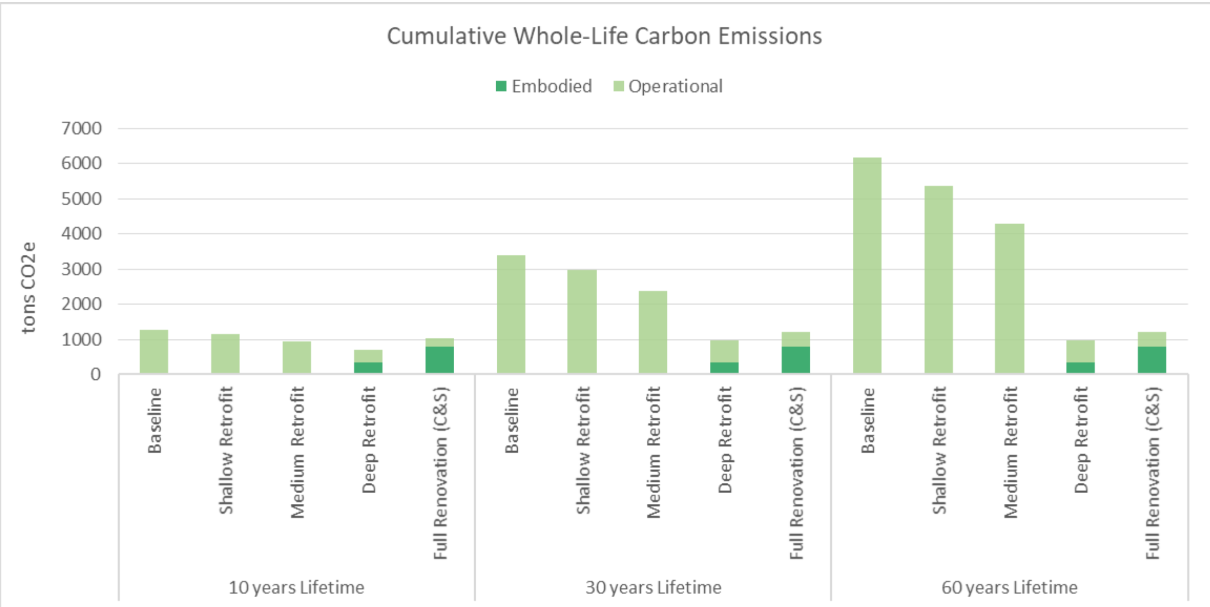
IES have carried out energy and carbon modelling of three residential blocks located on the West side of Dominick Street Lower, Dublin, with the aim of understanding their current ('Baseline') energy performance and the impact on energy and carbon emissions associated with different retrofit strategies, namely:

- Strategy 1: Shallow Retrofit
- Strategy 2: Medium Retrofit
- Strategy 3: Deep Retrofit
- Strategy 4: Full Renovation (reduce to Core & Shell and rebuild)

All results in this report (energy, carbon, costs) refer to Block B only, as it is estimated that the difference in energy use between the 3 blocks is lower than 1% (Section 2.2), hence they can be assumed to be the same for each block.

Each strategy consists of a package of measures, which are described more in depth in the body of this report. The Virtual Environment (VE) software was used to understand the impact on energy usage and operational carbon of each measure through dynamic, physics-based simulations. This allowed to understand which strategy would bring the biggest reduction in operational emissions, which, as expected, resulted to be Strategy 4.

In order to understand the whole-life cycle impact of the interventions, the integration between the VE and OneClickLCA was used to calculate the embodied carbon associated with each intervention. Once this is added to the operational emissions, and estimated at different life periods (20, 40 and 60 years), Strategy 3 outperforms Strategy 4 due to the high embodied carbon associated with a full renovation, as it can be seen in the Figure below.



Strategy 3 (**Deep Retrofit**) was hence selected as **the best option to optimize the whole-life carbon** of the building over all life-cycle periods assessed.

An indicative BER is also provided for each strategy, as based on the primary energy use of the building, as well as an indicative cost.

	Annual EUI [kWh/m²]	*Embodied Carbon[1] [tons CO_{2e}]*	*Indicative BER[2]*	*Indicative Cost[3]*
Baseline	380	0	F	0
Strategy 1	338	2	E2	1
Strategy 2	263	45	D2	2
Strategy 3	105	344	B2	3
Strategy 4	70	792	A3	4

[1]*Embodied carbon associated with changes applied to the building only, not to the existing structure*
[2]*BER Rating estimated based on primary energy use of the building*
[3]*Indicative costs from low (1) to high (4).*

1 Introduction

1.1 Building Overview

The three residential building blocks under assessment are located in Dominick Street Lower, Dublin. The building was built in the 1960s, but a significant refurbishment measure was conducted since construction through which existing window units have been replaced.

The existing building is referred to in this document as the 'Baseline Building'. The 'Proposed Building' is instead representative of a future scenario (the overall best performing in terms of whole-life carbon emissions) in which retrofit measures are applied to the Baseline Building such as building fabric, HVAC, and lighting improvements.

The impact of such measures on energy consumption and carbon emissions of the building is estimated through physics-based, dynamic energy modelling; the difference between final energy usage of the Baseline Building and that of the Proposed Building is referred to as 'energy savings', while 'carbon emission reductions' describes the achieved potential cut in carbon emissions.

1.2 Modelling Methods

The IES <VE> software has been used to carry out dynamic thermal simulation of the building. The software allows to evaluate and compare energy usage and carbon emissions between the Baseline Building and a number of Proposed Scenarios.

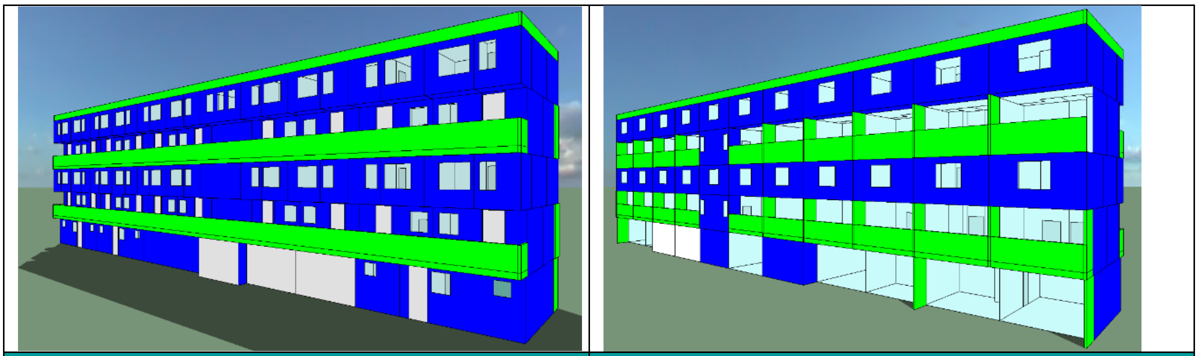
The baseline models are created based on information retrieved from the client as well as site surveys. No change or assumption has been made to the building orientation since the structure, as well as the surrounding site, is already existing rather than being a proposed new construction.

The weather file used for the energy simulation comes from the Dublin airport weather station, which is the closest one to the building site.

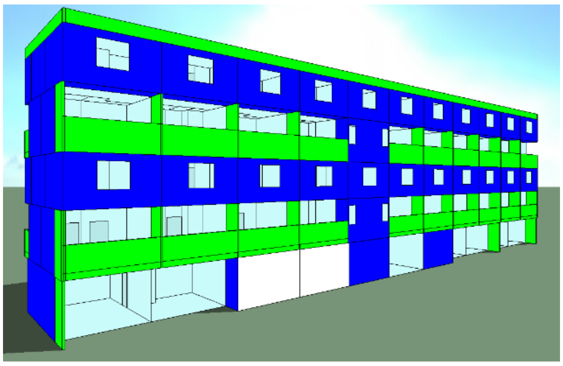
The geometry of the model has been created from floor plans and elevations/sections provided by Dublin City Council, as well as images and information gathered during the site survey.

The resulting building model features a total floor area of 1,641 m^2, excluding external walls, terraces, balconies and outside common access corridors.

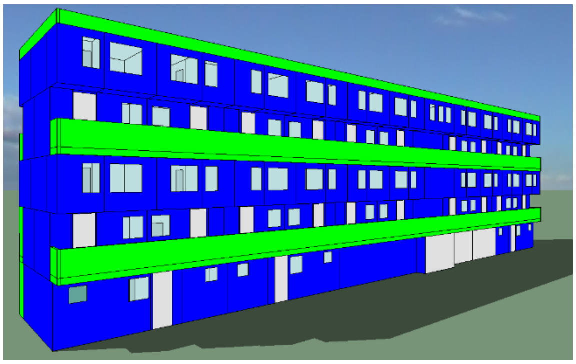
1.3 Model Images/Geometry



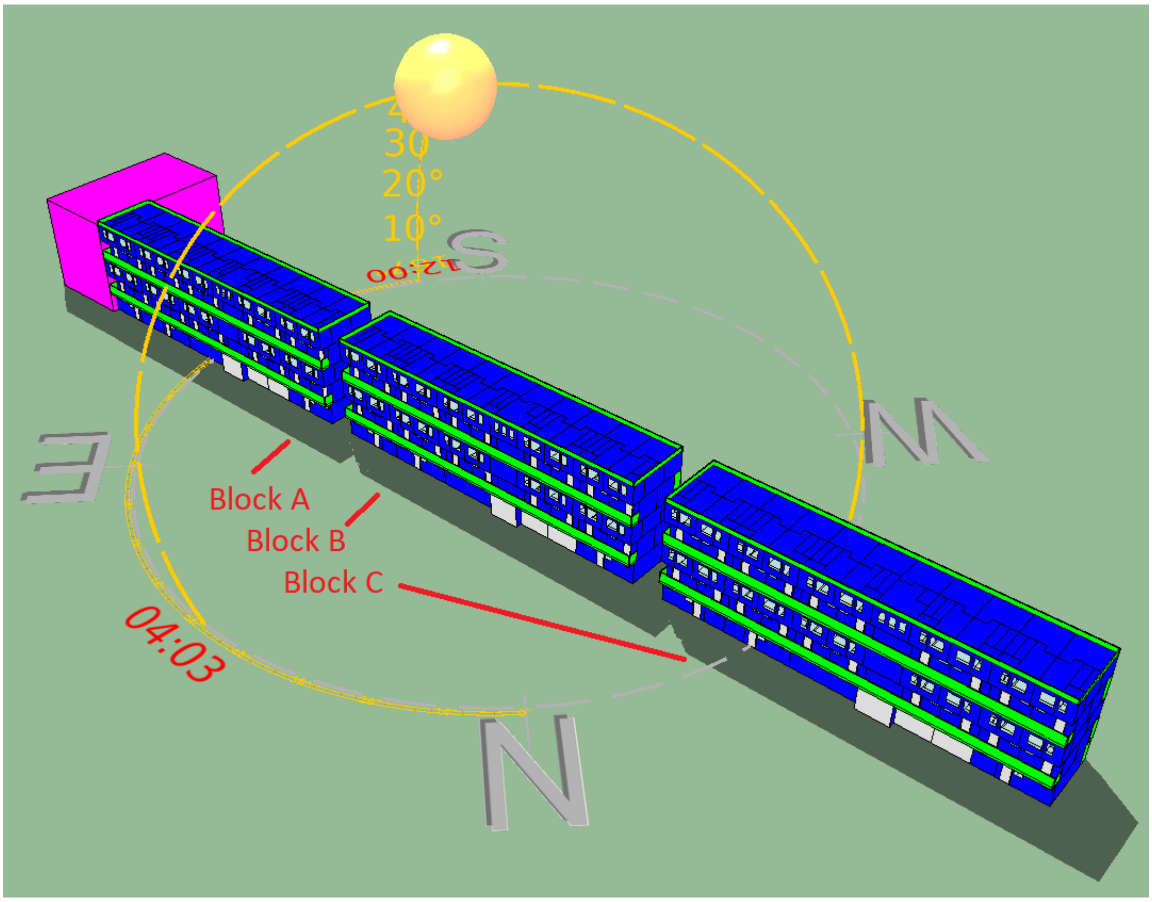
North View | South View



West View



East View



Full IESVE 3D model view

FIGURE 1: MODEL GEOMETRY

1.4 Report Overview

The main body of the report is broken into the following sections:

- Baseline Building Modelling
    - Benchmarking metrics
    - Baseline Building energy usage
- Proposed Strategies Results
    - Energy savings and carbon emission reductions through retrofit strategies
- Embodied Carbon analyses
    - Embodied carbon associated with each retrofit strategy
- Cost analysis
    - Overview
- Appendix A: Baseline Model Input Data
    - Provides an overview of the main model inputs and modelling methods
- Appendix B: Retrofit Strategies details
    - Provides details on the various measures considered within the 4 Strategy packages
- Appendix C: Embodied Carbon References
    - Provides insights on the references used for estimating embodied carbon emissions associated with each retrofit strategy

2 Baseline Building Modelling

2.1 Benchmarking metrics

After the energy model was created, the building model was benchmarked according to a building given in the TABULA WebTool* in similar condition, built in the same year range and location, and with similar building components.

The TABULA WebTool has been developed within the framework of the Intelligent Energy Europe projects TABULA and EPISCOPE.

* https://webtool.building-typology.eu/#bm

2.2 Benchmarking results

The energy model has been successfully validated according to the benchmark described in Section 2.1, as can be evinced from **Table 1** below. **Figure 2** shows the annual comparison between the simulated model and benchmark for total heating and service hot water, which is lower than 10% and hence within an acceptable range given the uncertainty of the existing building elements.

	Heating [kWh/m²]	***Service Hot Water [kWh/m²]***	***Total [kWh/m²]***
Benchmark	136	124	260
Baseline model	**145**	**134**	**279**
Difference	+6%	+7%	+7%

TABLE 1: BENCHMARK RESULTS

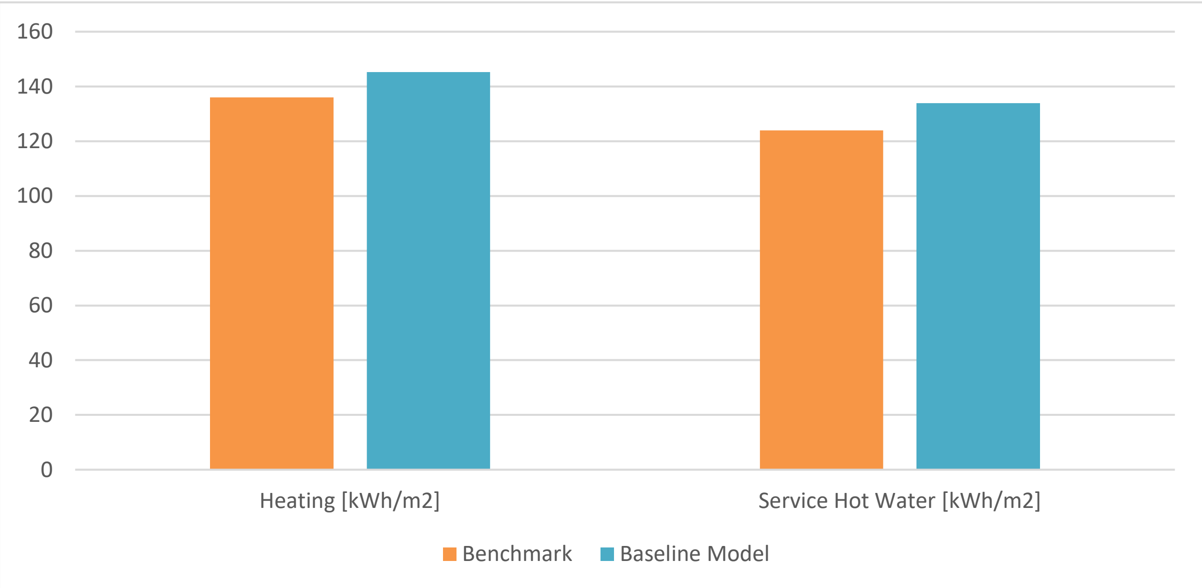


FIGURE 2: BASELINE CALIBRATION: BENCHMARK VS BASELINE HEATING AND SERVICE HOT WATER

Baseline models were created for A, B, and C Blocks. Electricity and natural gas consumptions for each can be seen in **Figure 3**. The studies within this report will be focused on block B only, since the difference between electricity and natural gas consumptions amongst all blocks is negligible; moreover, being Block B a standalone building with no adjacencies, it is best representative of a typical residential building block for replication studies. The small differences appreciated amongst the three blocks are due to slightly different expositions to solar radiation and adjacencies to nearby buildings.

	Electricity Consumption (MWh)	*Natural Gas Consumptions (MWh)*	*Total Consumption (MWh)*	*% Difference from Block B*
Block A	165	459	624	+0.2%
Block B	**165**	**458**	**623**	**0.0%**
Block C	165	463	628	+0.8%

TABLE 2: ELECTRICITY AND NATURAL GAS CONSUMPTIONS OF A, B, AND C BLOCKS

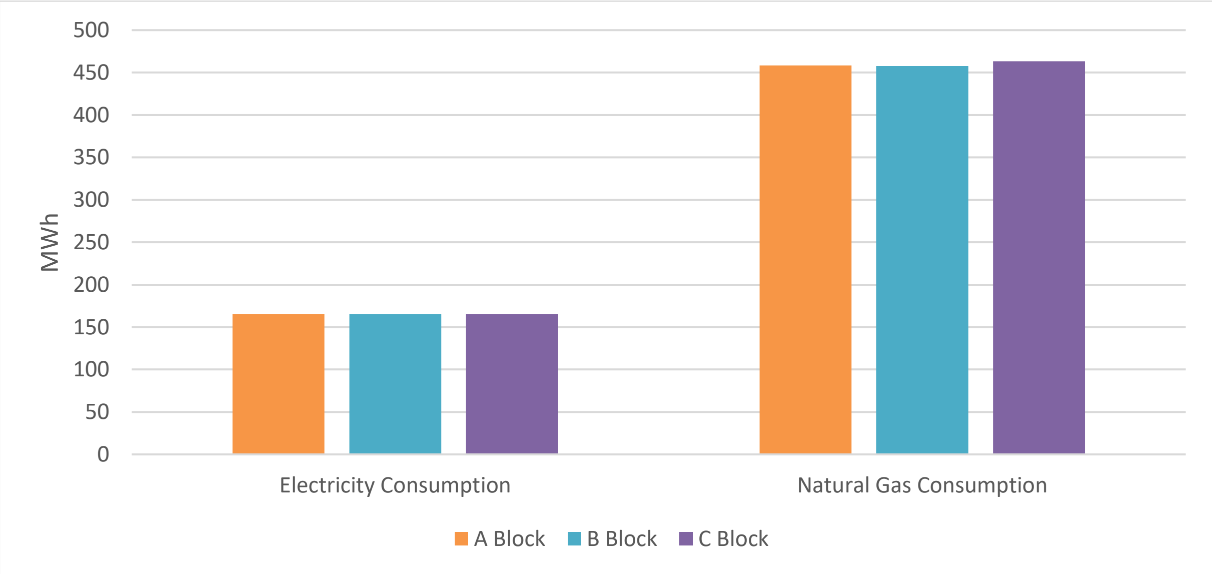


FIGURE 3: BASELINE MODEL – ELECTRICITY AND NATURAL GAS CONSUMPTIONS OF A, B, AND C BLOCKS

2.3 Baseline Building Energy Usage

The Virtual Environment (VE) software enables to break down energy by end uses, allowing to identify the main sources of energy consumption within the building. As we can see in **Figure 4**, the majority of the energy use is associated with space heating and service hot water; this is an important piece of information when looking at possible retrofit strategies, which will be focused at lowering as much as possible the carbon emissions associated with those end uses.

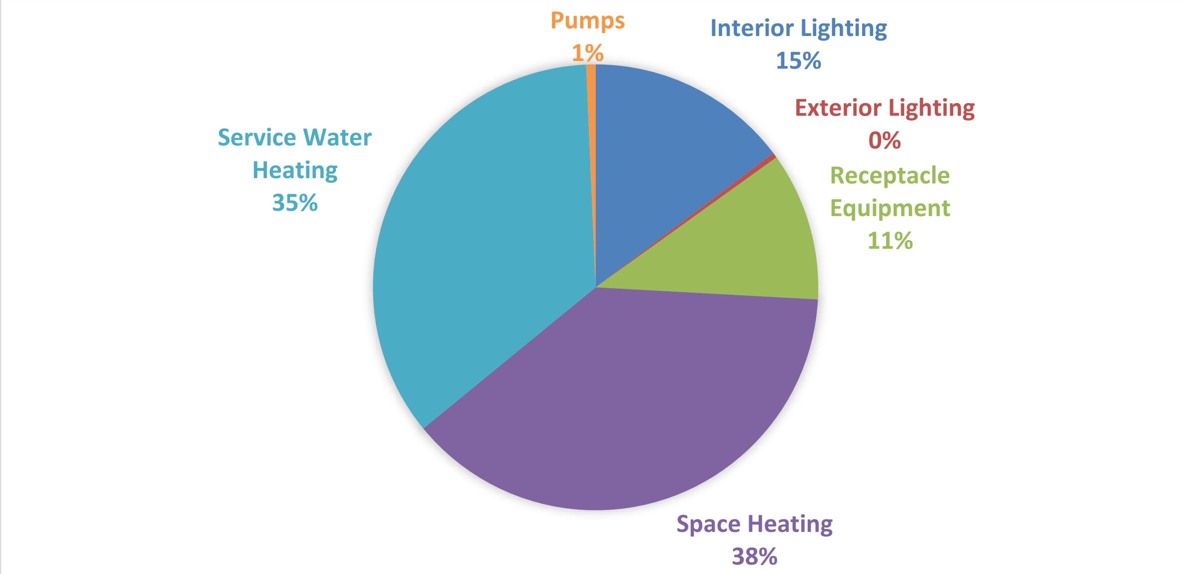


Figure 4: Baseline Building End-Use Energy Consumptions

Exterior lighting, which refers to street lighting, has not been considered within the energy use of the building; balcony lights as well as common areas lighting are included within the interior lighting.

The large share of energy for space heating indicates low efficiency in the current systems, as well as poor operational strategies (e.g. the absence of a zone control to avoid heating in unoccupied spaces) and poor conditions of the existing building envelope that lead to high dispersion of the generated heat to the outside of the building. Service hot water also has a large impact on the energy use, due to the need for storing hot water continuously at a high temperature to allow for immediate on-demand use.

3 Retrofit Strategies

3.1 Retrofit Strategies Summary

A number of renovation strategies have been evaluated and simulated through the use of the Virtual Environment (VE) software, some of which have been excluded due to the nature of the building or the minimal impact they would have on energy and carbon savings compared to their cost. The table below summarizes the potential measures that could enable the building to start its pathway towards Net-Zero carbon, with the impact being evaluated per single measure and summarized within this report at package level. A more detailed description of each measure can be found in Appendix B.

Strategy	*Measures considered*
Baseline Building	None (Existing building)
Strategy 1: Shallow Retrofit	a) Zoned heating controls b) Domestic hot water (DHW) setpoint optimization c) Passage areas lighting occupancy control
Strategy 2: Medium Retrofit	a) Zoned heating controls b) Domestic hot water (DHW) setpoint optimization c) Lighting upgrade (LED) + Daylight & Occupancy controls d) Windows/doors sealing & draft proofing e) Boiler replacement
Strategy 3: Deep Retrofit	a) Zoned heating controls b) Domestic hot water (DHW) setpoint optimization c) Lighting upgrade (LED) + Daylight & Occupancy controls (all areas) d) Windows/doors sealing & draft proofing e) External wall insulation f) Roof insulation g) Ground floor insulation h) Windows replacement i) Air-source Heat pump (ASHP) + low temperature radiators j) Energy-efficient elevator
Strategy 4: Full Renovation (C&S)	a) Rebuild to current standards, including ASHP & Mechanical ventilation with heat recovery (MHRV) b) PV panels on rooftop

Table 3: Description of Retrofit Strategies

Table 4 summarizes the benefit of each strategy. The impact of renewable energy has also been evaluated as part of Strategy 4: Full renovation; the installation of 195m^2 of photovoltaic panels on the roof of the building has been considered, which required the installation of a 300m^2 steel superstructure to elevate them above the existing plants and water storages on the roof. The self-consumption of electricity produced through green strategies has been maximized, to limit as much as possible, the reliance of the building on the electricity grid.

	Operational Energy			Operational Carbon	
	Electricity consumption [MWh]	*Natural gas consumption [MWh]*	*Building EUI [kWh/m2]*	*CO_2 emissions [ton/year]*	*CO_2 emissions reduction*
Baseline	165	458	**380**	142	**0%**
Shallow R.	160	394	**338**	127	**10%**
Medium R.	118	315	**263**	99	**30%**
Deep R.	173	0	**105**	51	**64%**
Full R. (C&S)	115*	0	**70***	34*	**76%***

Table 4: Operational energy and Carbon Impact of Renovation Strategies
**Includes PV contribution*

	Operational Carbon With Grid Decarbonisation			Operational Carbon Without Grid Decarbonisation		
	10 Years Life Period [tons CO2]	*30 Years Life Period [tons CO2]*	*60 Years Life Period [tons CO2]*	*10 Years Life Period [tons CO2]*	*30 Years Life Period [tons CO2]*	*60 Years Life Period [tons CO2]*
Baseline	1,284	3,385	6,171	1,418	4,255	8,510
Shallow R.	1,144	2,980	5,380	1,275	3,824	7,647
Medium R.	891	2,341	4,256	986	2,959	5,919
Deep R.	371	625	625	512	1,535	3,071
Full R. (C&S)	248	417	417	341	1,023	2,047

Table 5: Operational Carbon emissions for different life periods

According to the results in **Table 5,** the best performing retrofit strategy in terms of operational carbon emissions is Strategy 4: Full Renovation. This considers that the projected carbon emission factors from the Irish grid are met; for comparison purposes, Table 5 also shows what the impact would be if those targets were not to be met and assuming the emissions from the electricity grid would stay constant as today's ones.

In order to understand what the overall best solution in whole-life carbon terms is for different life stages (10, 30, and 60 years), however, we need to address the embodied carbon impact associated with each of the strategies under assessment, which will be discussed in Section 4.

4 Embodied Carbon Analysis

4.1 Embodied Carbon Overview

The embodied carbon associated with the deployment of each strategy was estimated. This was performed through One Click LCA, by taking advantage of the One Click LCA Integration feature of the IES Virtual Environment (VE) modelling platform, which enables a direct upload of VE model construction materials into the One Click LCA platform for further analysis. The embodied carbon analysis includes the additional materials required for the deployment of each strategy in terms of building structure and enclosure, finishing and other materials, as well as services. It excludes foundations and substructure as they are assumed to be constant across Baseline and all measures.

It must be noted that the embodied carbon analysis performed herein is focused on capturing the added embodied carbon for each strategy when compared against the embodied carbon estimated for the baseline VE model (i.e. no strategy deployed). Therefore, the baseline model is only used as a reference to calculate the added embodied carbon for each strategy; baseline embodied carbon is thus set to 0 ton of CO_2e, as detailed in **Table 6**, since no changes have been applied to the Baseline building.

Strategy	*Added Embodied Carbon (tCO_2e)*	*Added Embodied Carbon Intensity ($kgCO_2e/m^2$)*
Baseline	0	0
Shallow R.	2	1.3
Medium R.	45	27.7
Deep R.	344	209.4
Full R. (C&S)	792	482.8

TABLE 6: EMBODIED CARBON OF RETROFIT STRATEGIES

As detailed in **Table 6**, the results indicate an added embodied carbon intensity (i.e. embodied carbon expressed per square meter of floor area) that increases from 1.3 $kgCO_2e/m^2$ for Strategy 1, to 27.7 $kgCO_2e/m^2$ for Strategy 2, to 209.4 $kgCO_2e/m^2$ for Strategy 3, and to 482.8 $kgCO_2e/m^2$ for Strategy 4, thus translating the gradual increase in additional materials required for the deployment of each strategy when compared against the baseline, which is insignificant for strategy 1, limited for Strategy 2, significant for Strategy 3 and very significant for strategy 4.

The full list of added materials for each strategy is set out in ***Appendix C: Embodied Carbon References***, in line with the description of the measures considered for each renovation strategy, as detailed in **Table 3** and ***Appendix B: Proposed Scenarios Details***. It should be noted that the materials listed are used as a reference and IES does not intend to provide advice on specific manufacturer or product. Insulation and material types have been selected within the list of materials available from the One Click LCA database while reaching the target U-values, with the aim of providing a representative estimation of added embodied carbon for a fair comparison between the different strategies.

Where possible, materials with local or regional generic data were selected, as detailed in ***Appendix C: Embodied Carbon References***. Additionally, based on the source of materials, the added embodied carbon related to the life cycle stage A4 (Transport) has been calculated based on the distance and transportation mode from the material source to the construction site.

4.2 Embodied Carbon Elements

As illustrated in **Figure 5**, by comparing the embodied carbon for each strategy against that of the baseline, the difference becomes significant when considering the deployment of Strategies 3 (Deep Retrofit) and 4 (Full Renovation), whereas it remains negligible for the deployment of Strategies 1 (Shallow Retrofit) and 2 (Medium Retrofit).

By considering the energy conservation measures (ECMs) part of the deep retrofit strategy, the replacement of existing gas boilers and radiators with air-to-water heat pumps and low-temperature radiators represents the largest source of added embodied carbon, + 226 tCO_2e against the baseline, followed by the replacement of external windows, responsible for + 41 tCO_2e against the baseline.

For the ECMs related to the full renovation of the building, the refurbishment of internal ceilings and floors, + 166 tCO_2e against the baseline, closely followed by the installation of solar PV panels with associated superstructure on the roof (+ 157 tCO_2e), represent the largest sources of added embodied carbon.

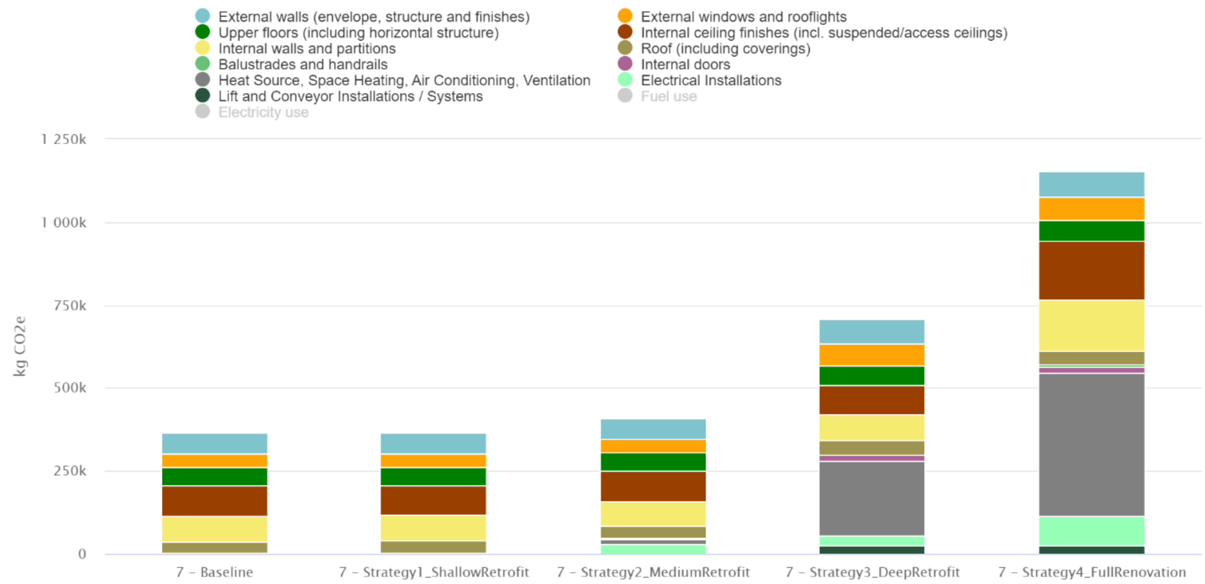


FIGURE 5: EMBODIED CARBON PER ELEMENT FOR EACH STRATEGY

4.3 Embodied Carbon Life Cycle Stages

In **Figure 6**, a breakdown of the impact of different renovation strategies based on the life cycle stage of the building is shown.

As mentioned in Section 4.2, the added embodied carbon impact from Strategy 1 and Strategy 2 is negligible, hence no particular insight has been highlighted in this breakdown.

By considering the deployment of energy conservation measures part of Strategy 3, life cycle stages B4-B5 (Material Replacement over the Building Technical Lifetime) represent the largest source of added embodied carbon, +208 tCO_2e against the baseline, followed by life cycle stages A1-A3 (Construction Materials Supply, Transport and Manufacturing), +127 tCO_2e against the baseline.

For Strategy 4, life cycle stages B4-B5 still represent the largest source of added embodied carbon, with +390 tCO_2e against the baseline, closely followed by life cycle stages A1-A3, responsible for +384 tCO_2e against the baseline.

However, when comparing the full renovation strategy against the deep retrofit strategy, it should be noted that the largest increase in added embodied carbon is represented by life cycle stages A1-A3, +257 tCO_2e, followed by life cycle stages B4-B5, +182 tCO_2e, due to the extensive installation of additional building equipment (e.g. solar-PV panels, mechanical ventilation, electrical appliances, etc.) that feature a lower technical lifetime compared to building envelope construction materials, and would thus require to be replaced at least once over the building lifetime.

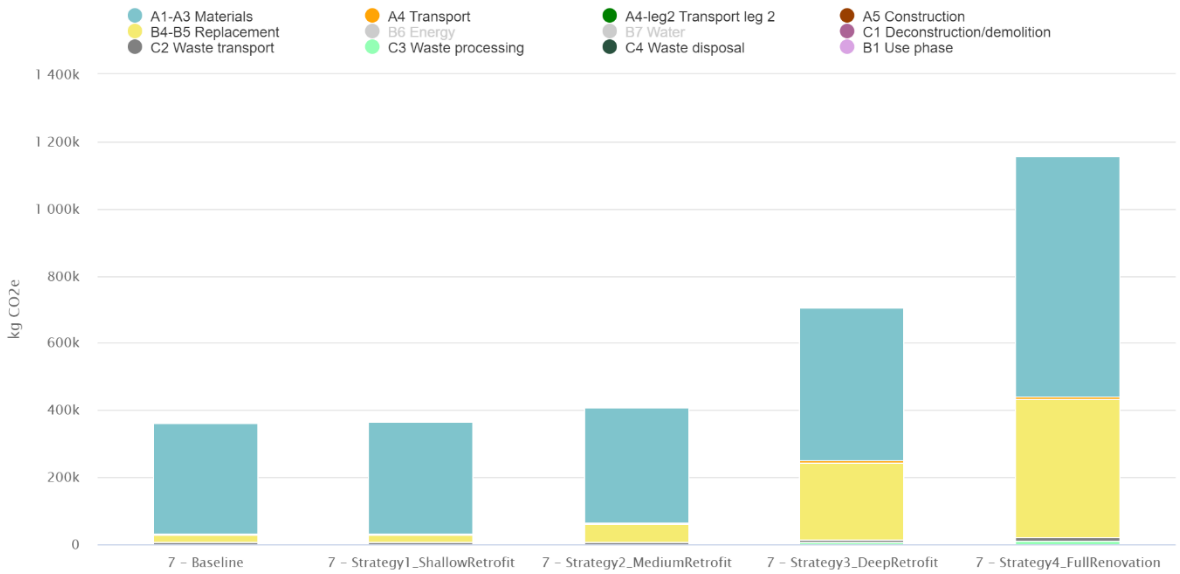


FIGURE 6: EMBODIED CARBON PER LIFE CYCLE STAGE FOR EACH STRATEGY

5 Cost Analysis

5.1 Cost Overview

Analysis was undertaken that quantified and measured the new materials and components that would be required for each retrofit strategy. This was used to rank the costs associated with each of the strategies from low to high (with 1 being the lowest and 4 being the highest). A comprehensive cost estimate encapsulating all works should be prepared on selection of preferred strategy.

6 Conclusions

The 4 retrofit strategies have been compared in terms of whole-life carbon impact as well as potential BER and indicative costs associated with the energy efficiency measures required by each strategy. As per **Table 7**, **the overall best performing strategy is Strategy 3: Deep Retrofit,** which whole-life carbon emissions are the lowest at every life period under assessment compared to any other strategy. Totally, over a 60-year life period, the block can achieve about **85% reduction** in cumulative emissions with a deep retrofit compared to the Baseline model.

This number would be reduced to about 60% if we were to ignore the decarbonisation of the grid and assume today's carbon emission factors for both natural gas and electricity would remain constant over the years. With that assumption, Strategy 4 would be the one obtaining the best (lowest) results in terms of whole-life carbon at 60 years and 40 years lifetime, while Strategy 3 would still be the best option at 20 years lifetime. This is due to the huge share of operational carbon compared to embodied emissions if the grid won't decarbonise over time.

	Whole-Life Carbon *With Grid Decarbonisation*			***Whole-Life Carbon*** *Without Grid Decarbonisation*		
	10 Years Life Period [tons CO2]	*30 Years Life Period [tons CO2]*	*60 Years Life Period [tons CO2]*	*10 Years Life Period [tons CO2]*	*30 Years Life Period [tons CO2]*	*60 Years Life Period [tons CO2]*
Baseline	1,284	3,385	6,171	1,418	4,255	8,510
Shallow R.	1,147	2,982	5,382	1,277	3,826	7,649
Medium R.	937	2,386	4,301	1,032	3,005	5,964
Deep R.	**715**	**969**	**969**	**855**	**1,879**	**3,414**
Full R. (C&S)	1,040	1,209	1,209	1,133	1,816	2,839

TABLE 7: WHOLE-LIFE CARBON EMISSIONS FOR DIFFERENT LIFE PERIODS

Figure 7 shows a comparison between cumulative emissions associated with the different strategies at each life stage under assessment. While Strategy 4 largest emissions come from embodied CO2, for the baseline as well as retrofit strategies 1-3 the operational emissions play the biggest role. This is under the assumption of grid decarbonisation projections as per ***Appendix A: Emission Factors & Model Input Data.***

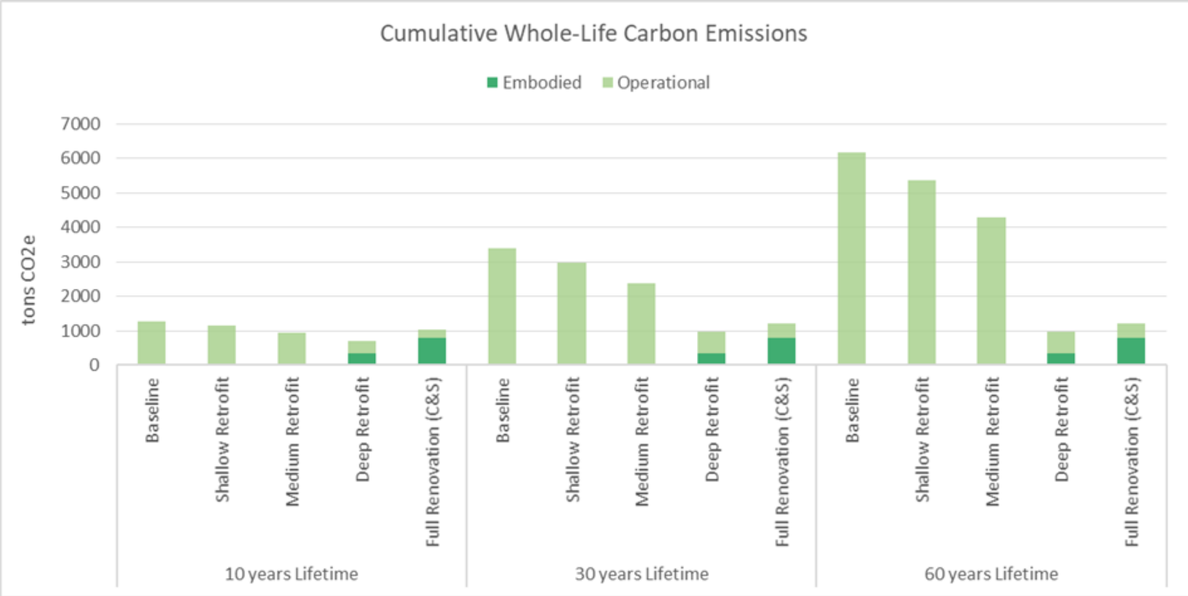


FIGURE 7: CUMULATIVE EMISSIONS COMPARISON AT DIFFERENT LIFE STAGES

The lower energy usage intensity of a full renovation is not enough to justify the additional costs of such an invasive intervention. Moreover, the analyses have shown that the carbon emissions over the whole lifetime of the building are even higher than those of a deep retrofit scenario.

	Annual EUI [kWh/m²]	*Embodied Carbon[1] [tons]*	*Indicative BER[2]*	*Investment Cost[3]*
Baseline	380	0	F	0
Strategy 1	338	2	E2	1
Strategy 2	263	45	D2	2
Strategy 3	105	344	B2	3
Strategy 4	70	792	A3	4

TABLE 8: RETROFIT STRATEGIES – COMPARISON SUMMARY

[1]Embodied carbon associated with changes applied to the building only, not to the existing structure
[2]BER Rating estimated based on primary energy use of the building
[3]Indicative costs from low (1) to high (4).

For the purposes of this exercise, it has been assumed that works proposed under Strategies 1 and 2 do not constitute a 'material alteration', while works proposed under Strategies 3 and 4 do, due to the extensiveness of the retrofit actions associated with those. This aspect will need further evaluation and consultation with Statutory Authority in order to assess the extent of potential additional Building Regulation compliance works required.

Through this energy and carbon modelling exercise, the best long-term scenario to optimize the whole-life carbon of the building has been identified. There is potential for this study to be scaled across different sites at either single building or block/community level, to estimate the carbon impact of renovation scenarios and/or new developments. The 3D model provided together with this report can be used as a way to visualize the impact of different projects across Dublin, or potentially at other locations too.

7 Appendix A: Emission Factors & Model Input Data

Carbon Emission Factors

The natural gas emission factor used for evaluating operational emissions has been taken from the SEAI website (Conversion Factors – 2021) as the most updated value publicly available and it has been considered constant over the years.

The carbon emission factors used for electricity are taken from the '*Supplementary Guidance – Measuring and Valuing Changes in Greenhouse Gas Emissions in Economic Appraisal*', part of the Public Spending Code published by the Irish Department of Public Expenditure and Reform; this document contains projected marginal emission factors for electricity based on the expected decarbonisation of the electric grid and is thus more relevant for a whole-life carbon study compared to using a constant factor. Marginal emission factors have been preferred to average ones since they are more representative of the carbon savings related to small-scale energy interventions.

	Electricity CO2 emission factor (kg CO2/MWh)	Natural gas CO2 emission factor (kg CO2/MWh)
2022	296.10	202.9
2023	285.20	202.9
2024	262.50	202.9
2025	228.70	202.9
2026	194.80	202.9
2027	189.00	202.9
2028	179.10	202.9
2029	178.60	202.9
2030	171.90	202.9
2031	163.31	202.9
2032	154.71	202.9
2033	146.12	202.9
2034	137.52	202.9
2035	128.93	202.9
2036	120.33	202.9
2037	111.74	202.9
2038	103.14	202.9
2039	94.55	202.9
2040	85.95	202.9
2041	77.36	202.9
2042	68.76	202.9
2043	60.17	202.9
2044	51.57	202.9
2045	42.98	202.9
2046	34.38	202.9
2047	25.79	202.9
2048	17.19	202.9

	Electricity CO_2 emission factor (kg CO_2/MWh)	Natural gas CO_2 emission factor (kg CO_2/MWh)
2049	8.60	202.9
2050	0.00	202.9
2051	0.00	202.9
2052	0.00	202.9
2053	0.00	202.9
2054	0.00	202.9
2055	0.00	202.9
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2070	0.00	202.9
2071	0.00	202.9
2072	0.00	202.9
2073	0.00	202.9
2074	0.00	202.9
2075	0.00	202.9
2076	0.00	202.9
2077	0.00	202.9
2078	0.00	202.9
2079	0.00	202.9
2080	0.00	202.9
2081	0.00	202.9

Table 9: Carbon Emission Factors *

**from Public Spending Code, Department of Public Expenditure and Reform, December 2019*

Internal Gains, Process Energy and Occupancy

Internal gains and occupancies were retrieved, where possible, through the site survey. Missing information, due to inaccessibility of the spaces, unknown values, or inconsistent occupancy, have been estimated based upon ASHRAE 90.1 standard values for the space type, or benchmark-based and then adjusted during the calibration process to best reflect the building operation. Summary values are outlined in the tables below.

Space type	***Type***	***Power density W/ m²***
Kitchen	Incandescent / fluorescent	15.984
Corridor	Incandescent / fluorescent	10.656
Living Room	Incandescent / fluorescent	17.922
Stairs	Incandescent / fluorescent	11.141
Bedroom	Incandescent / fluorescent	17.922
Plant Room	Incandescent / fluorescent	15.339
Bike Storage	Incandescent / fluorescent	10.172
Laundry	Incandescent / fluorescent	10.172
Storage	Incandescent / fluorescent	10.172
Bathroom	Incandescent / fluorescent	15.823
Guest rooms	Incandescent / fluorescent	17.92
Exterior Lightning	Incandescent / fluorescent	0.5 kW

TABLE 10: LIGHTING POWER

Space type	***Type***	***Power density W/ m² or W***
Corridor	*from ASHRAE 90.1*	2.153 W/m²
Plant Room	*from ASHRAE 90.1*	2.153 W/m²
Bedroom	TV	100 W
Living Room	TV	150 W
Kitchen	Fridge	250 W
Bathroom	*from ASHRAE 90.1*	5.382 W/m²
Stairs	*from ASHRAE 90.1*	10.764 W/m²
Laundry	Washing Machine and Dryer	1400 W
Waste Room	*from ASHRAE 90.1*	2.153 W/m²

Space type	***Type***	***Power density W/ m² or W***
Bike Storage	*from ASHRAE 90.1*	2.153 W/m^2

TABLE 11: RECEPTACLE POWER

Space type	***Number of people / People***
Kitchen	1 person for each space
Living Room	2 people for each space
Bedroom	1 person for each space

TABLE 12: OCCUPANCY

Building Envelope

Building envelope information have been taken from the site survey, where available. The U-values of the envelope elements for the Baseline Building are calculated by the software based on material properties and thickness, and are summarized in **Table 14**.

- Window to gross wall Ratio (WWR)

Room / Zone Type	***% Window to gross wall area***
Baseline	30.3 %

TABLE 13: BASELINE BUILDING WINDOW TO WALL RATIO

- Baseline Building Constructions Summary

Surface Description	***Description***	***U-Value***
Existing Roof	Membrane 0.1 mm (R1), Concrete Deck 200 mm (R2), Thermocrete 50 mm (R0.16), Plasterboard 12.5 mm (R0.21)	1.64 W/m2K
Existing External Wall	Brickwork 100mm (R0.84), Thermocrete 50 mm (R0.16), Concrete Block 100 mm (R0.51) Plasterboard 12.5 mm (R0.21)	1.21 W/m2K
Existing External Windows	Double glazed window	1.98 W/m2K, 0.50 SHGC

Registered in Scotland Number SC151456

Existing Ground /Exposed Floor	Reinforced 200 mm (R2.3), Thermocrete 50 mm (R0.16), Chipboard Flooring 20 mm (R0.13)	1.34 W/m²K

TABLE 14: BASELINE BUILDING CONSTRUCTIONS

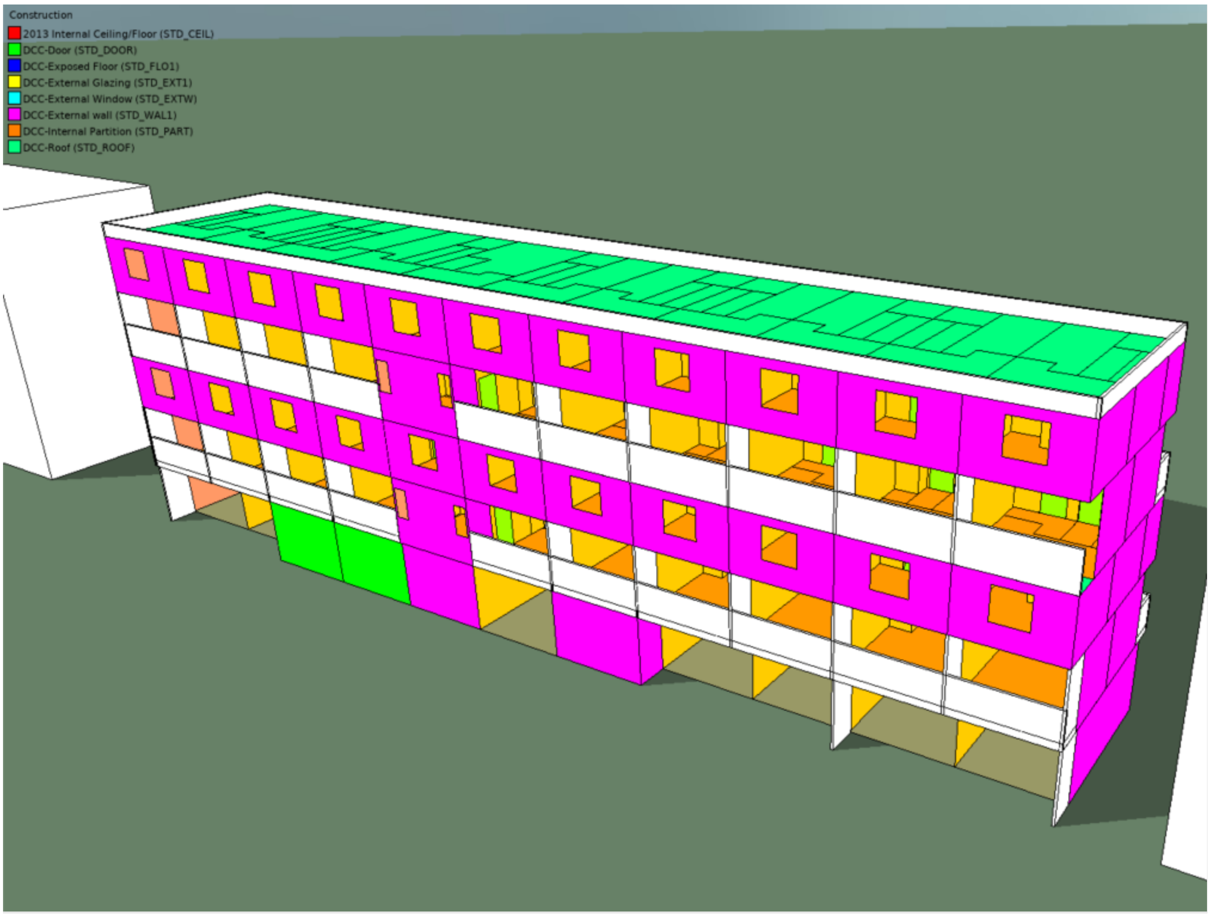

FIGURE 8: BASELINE BUILDING CONSTRUCTIONS FROM VE MODEL

System Schedules & Set-points

ASHRAE 90.1 Residential Building schedules were used. Thermostats set-points have been modelled according to the information collected on the site survey, where available, and adjusted through the validation process against benchmarks.

Space type	*Heating set-point*	*Cooling set-point*	*RH%*
Bedroom	19 °C	Unconditioned	n/a
Staircase	Unconditioned	Unconditioned	n/a
Corridor	21 °C	Unconditioned	n/a
Bathroom	21 °C	Unconditioned	n/a
Living Room	21 °C	Unconditioned	n/a
Kitchen	21 °C	Unconditioned	n/a

Plant Room	Unconditioned	Unconditioned	n/a
Waste Room	Unconditioned	Unconditioned	n/a
Laundry	Unconditioned	Unconditioned	n/a
Storage	Unconditioned	Unconditioned	n/a

Table 15: Baseline Building System Set-Points

HVAC Systems Summary

Service	*HVAC system(s) type*	*Efficiency / Schedule*
Heating	Individual Gas Boilers Radiators	Individual boiler heating efficiency (including delivery losses): 65%
Cooling	N/A	N/A
Ventilation	Natural ventilation	N/A
Energy Recovery	N/A	N/A
Service Hot Water	Individual Gas Boilers	DHW delivery efficiency: 80%

Table 16: Baseline Building HVAC Details

Service Water Heating

Service water heating systems have been evinced, where possible, from site survey. In absence of a fixture count spreadsheet, hot water demand has been estimated based on space types.

Item	*Description*
System type and fuel	Individual gas boiler
Efficiency (EF, SL, %, etc.)	80% delivery efficiency
Storage volume (L)	660 for each dwelling unit
Storage temperature (°C)	60
Peak hot water demand (L/s)	3.8125 l/(h.person)
Number of pumps	1 for each dwelling unit
Total pump power (kW)	0.2 kW for each dwelling unit

Table 17: Service Hot Water System Summary Performance

8 Appendix B: Proposed Scenarios Details

Energy Conservation Measure (ECM)	***Category***	***Description***
S1a: Zoned heating controls	Strategy 1: Shallow Retrofit	Install thermostatic radiator valves to control temperatures in individual zones. This will allow setpoints to be set independently in the various rooms and have different schedules.
S1b: DHW setpoint control	Strategy 1: Shallow Retrofit	Reduce domestic hot water (DHW) supply T to 50˚C. Research shows that a temperature above 45˚C is normally enough to avoid Legionellae bacteria formation. However, a temperature set at 50˚C would be a safer choice due to possible inaccurate controls. It is anyway advised to run periodic flushes at 60-65˚C (ideally once a month) to eliminate any potential bacteria formation.
S1c: Passage areas lighting occupancy control	Strategy 1: Shallow Retrofit	Install occupancy control sensors to switch off lights in passage areas when unoccupied.
S2a: Zoned heating controls	Strategy 2: Medium Retrofit	Install thermostatic radiator valves to control temperatures in individual zones. This will allow setpoints to be set independently in the various rooms and have different schedules.

Energy Conservation Measure (ECM)	Category	Description
S2b: DHW setpoint control	Strategy 2: Medium Retrofit	Reduce domestic hot water (DHW) supply T to 50˚C. Research shows that a temperature above 45˚C is normally enough to avoid Legionellae bacteria formation. However, a temperature set at 50˚C would be a safer choice due to possible inaccurate controls. It is anyway advised to run periodic flushes at 60-65˚C (ideally once a month) to eliminate any potential bacteria formation.
S2c: Lighting upgrade (LED) + Daylight & Occupancy controls (all areas)	Strategy 2: Medium Retrofit	Replace existing light bulbs (incandescent/CFL) with efficient LED bulbs in all areas. Install daylight & occupancy control sensors to dim/switch off lights in all areas based on daylight & occupancy.
S2d: Sealing & draft proofing	Strategy 2: Medium Retrofit	Draft proofing windows and doors to decrease infiltration rates (~7 m3/h.m2) ● Carry out a fan pressurization test to locate draughts that may not be immediately evident, via cupboards, ducts and window boards. ● Window draught proofing through compression seals or wiper seals; allowance might need to be made during installation to account for seasonal expansion and contraction of the frame materials. ● Shutters air leakages to be decreased through draught-stripping ● Draft excluders applied to all doors and windows.
S2e: Boiler replacement	Strategy 2: Medium Retrofit	Replace existing gas boiler (COP = 0.8) with modern gas boiler (COP = 0.91 as per Ireland cost-optimal report 2018). Insulate piping systems to increase delivery efficiency (decrease losses).

Energy Conservation Measure (ECM)	Category	Description
S3a: Zoned heating controls	Strategy 3: Deep Retrofit	Install thermostatic radiator valves to control temperatures in individual zones. This will allow setpoints to be set independently in the various rooms and have different schedules.
S3b: DHW setpoint control	Strategy 3: Deep Retrofit	Reduce domestic hot water (DHW) supply T to 50˚C. Research shows that a temperature above 45˚C is normally enough to avoid Legionellae bacteria formation. However, a temperature set at 50˚C would be a safer choice due to possible inaccurate controls. It is anyway advised to run periodic flushes at 60-65˚C (ideally once a month) to eliminate any potential bacteria formation.
S3c: Lighting upgrade (LED) + Daylight & Occupancy controls (all areas)	Strategy 3: Deep Retrofit	Replace existing light bulbs (incandescent/CFL) with efficient LED bulbs in all areas. Install daylight & occupancy control sensors to dim/witch off lights in all areas based on daylight & occupancy.
S3d: Sealing & draft proofing	Strategy 3: Deep Retrofit	Draft proofing windows and doors to decrease infiltration rates. (~5 m3/h.m2 - Part F) - below mechanical ventilation would be required to ensure appropriate ventilation of indoor spaces. ● Carry out a fan pressurization test to locate draughts that may not be immediately evident, via cupboards, ducts and window boards. ● Window draught proofing through compression seals or wiper seals; allowance might need to be made during installation to account for seasonal expansion and contraction of the frame materials. ● Shutters air leakages to be decreased through draught-stripping ● Draft excluders applied to all doors and windows. *Note: avoid draft proofing the existing windows* ***before*** *installing the secondary glazing to avoid condensation occurring* *Note: a lower infiltration rate compared to the medium retrofit can be obtained here thanks to the external wall insulation installation which will aid in reducing the air leakage*

Energy Conservation Measure (ECM)	Category	Description
S3e: Wall insulation	Strategy 3: Deep Retrofit	Add 70mm insulation layer to the exterior face of the existing wall structure. This will be done together with windows replacement and envelope sealing as it might require extension of roof eaves, replacement of window reveals and sills, gutters and downpipes. External wall insulation will not only reduce thermal transmittance but also ensure the heat is kept inside for longer thanks to the use of the thermal mass of the existing wall structure. The External wall insulation (EWI) will also reduce the risk of interstitial condensation compared to an internal solution and will not induce a loss in property price that could be caused from reduction of floor area if an internal layer were instead added. However, the EWI will impact the exterior appearance of the building. **New wall U-value ≤ 0.35 (Part L 2021 Existing Dwellings)**
S3f: Roof insulation	Strategy 3: Deep Retrofit	Create a warm roof system by insulating the roof from the outside. This will make sure that no structural change is needed to the bearing walls (due to windows height on the top floor apartments which could be impacted by the installation (150mm) of an internal insulation layer). Addition of a waterproof layer on the outside, covered by an anti-slip finishing for safe access to the roof for maintenance. **New roof U-value ≤ 0.25 (Part L 2021 Existing Dwellings)**
S3g: Ground floor insulation	Strategy 3: Deep Retrofit	Remove flooring and replace with solid insulation boards, e.g. aerogel insulation. 50mm. **New ground floor U-value ≤ 0.45 (Part L 2021 Existing Dwellings)**
S3h: Windows replacement	Strategy 3: Deep Retrofit	Replace existing windows (double-glazed PVC frames) with triple-glazed low-e windows. **New windows U-value ≤ 1.4 (Part L 2021 Existing Dwellings)**

Energy Conservation Measure (ECM)	*Category*	*Description*
S3i: Air-source Heat pump + low T radiators	Strategy 3: Deep Retrofit	Replace existing gas boiler (COP = 0.8) with an air-to-water heat pump (COP = 3.96 as per Ireland cost-optimal report 2018). Replace existing radiators with larger low-T radiators to maximize the heat pump efficiency.
S3j: Energy-efficient elevators	Strategy 3: Deep Retrofit	Install energy efficient elevators in the building
S4a: Rebuild to current standards, including ASHP & MHRV	Strategy 4: Full Renovation	**Maintain the core and shell only (foundations, bricks/cement & structural elements, roof, and glazing location) but improve the envelope and systems to reach:** Roof U-value ≤ 0.2 (Part L 2021 New Dwellings) Walls U-value ≤ 0.18 (Part L 2021 New Dwellings) Ground floor U-value ≤ 0.18 (Part L 2021 New Dwellings) Windows U-value ≤ 1.4 (Part L 2021 New Dwellings) Air permeability < 3 m3/h.m2 @50 Pa (Part L 2021 New Dwellings with MVHR) Mechanical Ventilation with Heat Recovery: Max SFP 0.6 W/l/s, Min HR efficiency 70% (Part L 2021 New Dwellings) Ventilation level is the greater of: 5l/s + 4l/s/p OR 0.3 l/s per m2 (Part F 2019 MVHR for Dwellings) Heating & Hot Water: ASHP, COP = 3.96 (Ireland cost-optimal report 2018) Insulated pipes, ducts & vessels (high delivery efficiency) Control of space heating based on room-by-room thermostat sensors (Part L 2021 New Dwellings) Lighting: LED + daylight & occupancy sensors Modern energy efficient appliances Energy-efficient elevator

Energy Conservation Measure (ECM)	*Category*	*Description*
S4b: PV panels on rooftop	Strategy 4: Full Renovation	Create a superstructure above the roof to enable placement of PVs. Total area of the structure will be approx. 80% of roof area. Building a raised substructure for the racking allows the panels to cover a larger portion of the roof instead of working around rooftop units. This has the added benefit allowing air to circulate around the panels, keeping them at a cooler, more optimal temperature. There is an added cost to developing an elevated system due to the superstructure, which self-weight (plus that of the PV units) will have to be evaluated at construction stage to ensure the roof will bear the weight. A total of 100 PV units is considered to maximise self-consumption and avoid self-shading between adjacent units.

9 Appendix C: Embodied Carbon References

ECM	One Click LCA resource name	One Click LCA data type	EPD number	Quantity	Unit	Notes
S1a	Thermostatic radiator valve (MDEGD)	Regional generic data	INIES_DROB20180223_160531, 7986	148	unit	1 unit per radiator
S1c	Motion sensor, French average	Regional generic data	INIES_DDÉT20170317_174334, 6407	93	unit	1 unit per common area / internal staircase / corridor
S2c	Indoor luminescent accent lighting, P=13W	Regional generic data	INIES_DENC20191220_142932, 32106	331	unit	1 unit per bedroom / staircase; 2 units per bathroom / kitchen / corridor; 3 units per living room
S2c	Indoor luminescent accent lighting, P=13W à 18W	Regional generic data	INIES_DENC20191220_142939, 32107	16	unit	Approx. 1 unit for 8 m^2
S2c	Indoor luminescent accent lighting, P=20W	Regional generic data	INIES_DENC20190710_155254, 13823	8	unit	2 units per external staircase
S2d	Joinery foam strip seal, impregnated	Regional generic data	INIES_CMOU20180529_143852, 8292	120	m	85m and 35m for draught-proofing of external windows and external doors, respectively
S2e	Gas condensing boiler, wall-mounted, 16 kW	Regional Manufacturer Specific Data	CHAP-00011-V01.01-FR, 27524	23	unit	1 unit per building unit
S2e	Polyethylene pipe insulation	Regional generic data	INIES_DMAN20180223_160910, 7989	1,000	m	Assumption based on floor plans and site visit

S3d	Door frame rubber seals	Other Manufacturer Specific Data	4787103471.125.1	46	unit	1 unit per external door
S3d	Rubber door thresholds	Other Manufacturer Specific Data	4787103471.127.1	46	unit	1 unit per external door
S3e	EPS insulation, R = 1.4 m2K/W, L = 0.035 W/mK	Local Manufacturer Specific Data	EPDIE-19-14	909	m^2	Wall insulation thickness: 70 mm
S3f	EPS insulation, R = 1.4 m2K/W, L = 0.035 W/mK	Local Manufacturer Specific Data	EPDIE-19-14	395	m^2	Roof insulation thickness: 150 mm
S3g	EPS insulation, R = 3.2 m2K/W, L = 0.031 W/mK	Local Manufacturer Specific Data	EPDIE-19-14	330	m^2	Exposed floor insulation thickness: 50 mm
S3h	Float glass, single pane, generic, 3-12 mm	Local Generic Data	One Click LCA	381	m^2	External windows replacement
S3h	Glass, clear, float, 4 mm	Regional Manufacturer Specific Data	S-P-00882	381	m^2	External windows replacement
S3h	Steel entrance door with mixed wood/metal	Regional Manufacturer Specific Data	INIES_IRCU20220310_182710, 29426	67	m^2	External windows replacement
S3i	Heat pump 5.80 kW AIR / WATER	Regional generic data	UNIC-00017-V01.01-FR, 8718	23	unit	1 unit per building unit

S3i	Water circulation radiator	Local Generic Data	One Click LCA	148	unit	1 unit per conditioned area
S3j	Elevator for residential buildings	Regional generic data	FASC-00001-V01.01-FR, 24297	1	unit	1 unit per building
S4a	Ventilation system for residential building	Local Generic Data	One Click LCA	1,418	m^2	Building conditioned floor area
S4a	Air exchanger + heat recovery	Local Generic Data	One Click LCA	23	unit	1 unit per building unit
S4a	Combined refrigerator-freezer	Local Generic Data	One Click LCA	23	unit	1 unit per building unit
S4a	Commercial electric hobs	Local Generic Data	One Click LCA	23	unit	1 unit per building unit
S4a	EPS insulation, R = 3.2 m2K/W, L = 0.031 W/mK	Local Manufacturer Specific Data	EPDIE-19-14	909	m^2	Wall insulation thickness: 150 mm
S4a	EPS insulation, R = 3.2 m2K/W, L = 0.031 W/mK	Local Manufacturer Specific Data	EPDIE-19-14	330	m^2	Exposed floor insulation thickness: 150 mm
S4a	Gypsum plasterboard, standard, 12.5 mm	Other Manufacturer Specific Data	S-P-00939	2,332	m^2	Internal walls full renovation
S4a	Red brick, average production, UK	Regional generic data	BREG EN EPD000002	2,332	m^2	Internal walls full renovation

S4a	Gypsum plasterboard, standard	Other Manufacturer Specific Data	EPD-RIGIPS-2014-1-GaBi	2,332	m^2	Internal walls full renovation
S4a	Gypsum plasterboard, 12.5 mm	Regional generic data	BREG EN EPD 000204	1,095	m^2	Internal ceilings/floors full renovation
S4a	Granite paving slabs	Other Manufacturer Specific Data	DAPc.004.004s	1,095	m^2	Internal ceilings/floors full renovation
S4a	Levelling screed, cement mortar	Regional Manufacturer Specific Data	EPD-QMX-20160208-IBC1-DE	1,095	m^2	Internal ceilings/floors full renovation
S4a	Chipboard, hollow core	Regional generic data	EPD-VHI-20130003-IBG1-DE	1,095	m^2	Internal ceilings/floors full renovation
S4b	Photovoltaic monocrystalline panel	Local Generic Data	One Click LCA	195	m^2	Available area & self-shading considerations
S4b	Steel floor grating, welded steel grid	Local Generic Data	One Click LCA	300	m^2	Approx. 75 % of roof area

TABLE 18: EMBODIED CARBON REFERENCE

Nomenclature

ASHRAE	*American Society of Heating, Refrigerating and Air-Conditioning Engineers*
ASHP	*Air Source Heat Pump*
CAV	*Constant Air Volume*
CHW	*Chilled Water*
CIBSE	*Chartered Institution of Building Services Engineers*
COP	*Coefficient of performances*
CV	*Constant Volume*
DHW	*Domestic Hot Water*
DT	*Digital Twin*
EER	*Energy Efficiency Ratio*
EPD	*Environmental Product Declaration*
EUI	*Energy Use Index*
FCU	*Fan Coil Unit(s)*
HVAC	*Heating, ventilation, and air conditioning*
IESVE	*Integrated Environmental Solutions "Virtual Environment"*
LCA	*Life Cycle Analysis*
LED	*Light Emitting Diode*
LPD	*Lighting Power Density*
LTHW/LPHW/HW	*Low Temperature Hot water / Low Pressure Hot water / Hot Water*
MVHR	*Mechanical Ventilation with Heat Recovery*
NMBE	*Normalized Mean Bias Error*
OA	*Outdoor Air*
SAT	*Supply Air Temperature*
SCSI	*Society of Chartered Surveyors Ireland*
SEER	*Seasonal Energy efficiency Ratio*
VAV	*Variable Air Volume*
VE	*Virtual Environment*
WWR	*Window to Wall Ratio*

An Roinn Caiteachais Phoiblí agus Athchóirithe
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