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Super-Insulate or use Renewable Technology? Life Cycle Cost, Energy and Global Warming Potential Analysis of Nearly Zero Energy Buildings (NZEB) in a Temperate Oceanic Climate

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Abstract

There are numerous strategies available to design and construct a low energy or nearly zero energy building (NZEB). However, the design strategy for a building depends on a high number of factors including location, climate, cost, available resources, etc. For instance, for countries like Ireland, which have a temperate oceanic climate, a key to achieving NZEB is a high thermal and air tightness performance of the building envelope, installing highly efficient space and water heating systems, and utilising renewable technologies for energy and heat generation. The challenge is to find the best combination of design strategies that would tackle the energy performance problems of a particular building. For example, is it better to design a super-insulated building with minimum heating requirements, or provide less insulation but install a large amount of renewable energy sources?

This paper presents the outcomes of a number of case study buildings in Ireland, which focus on the life cycle cost and environmental analysis (using energy and global warming potential as indicators) of NZEBs using various heat sources, such as a gas boiler, biomass boiler, a domestic gas fired combined heat and power unit, heat pump and renewable technology. With the de-carbonisation and increased efficiency of the electricity grid, the low global warming potential (GWP) emissions of biomass fuels and the depletion of fossil fuels, future buildings should be (i) designed and constructed to be super-insulated with high air-tightness performance, minimum heating requirements and (ii) operate with heating systems that have a low impact on the natural environment, such as a biomass boiler or heat pump.

Keywords: Nearly zero energy buildings; Life cycle energy; Life cycle greenhouse gas emissions; Life cycle cost; Embodied energy; Embodied global warming potential; Energy performance; Electricity grid; Energy prices; Renewable energy

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1 Introduction

The Paris Agreement (2015) contains a pledge from 195 countries to hold global temperatures to a maximum rise of 1.5ºC above pre-industrial levels [1]. As the building sector accounts for about 40% of the world's energy consumption and approximately a third of greenhouse gas (GHG) emissions [2], reducing the energy consumption and GHG emissions associated with buildings is key to meeting the pledge made in the Paris Agreement. The European Union (EU) has focused on reducing the impact of buildings on the natural environment through several directives and roadmaps for its member states [3–6]. One of the main requirements brought by the EU in the Energy Performance of Buildings Directive (EPBD) [4] was the introduction of nearly zero energy buildings (NZEB). A NZEB is a building with a very high energy performance. Starting from the end of 2020, all new buildings or those receiving significant retrofit must show a very high energy performance [4]. Similarly, this is a requirement for all public buildings from the end of 2018 [4]. The nearly zero or very low amount of energy required by NZEB should be produced, to a very significant extent, from renewable sources, including those on-site or nearby.

In order to achieve the energy reduction targets posed by the EU and achieve the NZEB standards, the majority of efforts focus on reducing the operational energy (OE) in buildings. This reduction in OE often requires an investment of materials into the building that can lead to an increase in the embodied energy (EE) impact of the building life cycle energy [7,8]. However, this is not always the case. The authors found in a previous study that if designed with a focus on achieving a high thermal and air tightness, a building with an embodied energy intensity less than a building that achieves compliance with 2011 Irish building energy performance regulations can achieve a NZEB standard [9]. As building life cycle assessments are becoming more common, engineers and architects must begin to quantify and reduce the impact of building materials on the natural environment.

The objective of this paper is to determine (for buildings in a temperate oceanic climate, such as Ireland) if it is better to design a NZEB to be a super-insulated building with minimum heating requirements, or to provide less insulation but install a large amount of renewable energy sources. This will be achieved by presenting the outcomes of a number of case study buildings in Ireland, which focus on the life cycle cost and environmental analysis (using two categories, life cycle energy and life cycle global warming potential) of NZEBs with various heat sources, such as a gas boiler, biomass boiler, gas-fired combined heat and power, heat pump and renewable technology. These case studies will be assessed using two different methodologies to determine the best solutions.

The first is the comparative framework methodology which is mandatory in all EU member states for calculating cost optimal levels of minimum energy performance requirements for buildings and building elements. The second is a methodology that incorporates the commonly known three pillars of sustainability: environmental, social and economic. In the analyses of both methods, account will be taken of (i) varying discount rates, (ii) future de-carbonisation and improved efficiency of the electricity grid and (iii) future energy prices. However, firstly a brief synopsis of environmental LCA studies of residential buildings available in the literature will be presented.

2 Environmental LCA Studies

There are numerous strategies available to design and construct a low energy or NZEB. However, the design strategy for a building depends on a high number of factors including location, climate, cost, available resources, etc. Since the design solution has a big impact on the environmental and economic life cycle of buildings, it is important to assess the effectiveness of those solutions in a comprehensive manner.

The life cycle assessment (LCA) is starting to be recognised as an important support method in the design of buildings. Table 1 summarises a broad range of published environmental LCA studies, in terms of the building type, location, climatic zone, heating system, installed renewable technologies, and the impact those aspects have on the building's operational energy (OE) and operational global warming potential (OC) [7–31]. Global warming potential (GWP) is a relative measure of how much heat a GHG traps in the atmosphere [32]. The OE in Table 1 accounts for the HVAC, hot water, lighting, appliance usage etc. depending on the individual study. The energy with regards to the maintenance, repair, replacement and refurbishment of materials during the operational phase is not included in the values given in Table 1.

Of the 25 reviewed studies, only three monitored the whole house energy consumption of the case study buildings [18,24,31], three simulated space heating [7,15,16], four simulated whole house energy consumption including appliances [11,26–28], seven simulated whole house energy consumption including appliances from multiple simulation/statistical sources [13,19,20,22,23,25,30], one simulated whole house energy consumption from multiple simulation/statistical sources without accounting for hot water requirements [14] , four simulated whole house energy consumption but did not explicitly state they accounted for appliances in electricity usage [8,10,12,29] and three simulated whole house energy consumption excluding appliances [9,17,21].

The contribution of EE to the overall energy consumption can be as low as 0% according to a case study on hypothetical building models in Finland [25]. In this study, 90% of the materials were assumed to be recycled at the end of the case study buildings life cycle and used for a secondary application. The results showed that for light weight timber and cross laminated buildings, more energy was saved in the recycling of materials and their secondary application than was initially invested into the buildings. Therefore, only the cradle to grave results were considered in this paper and this was applied to all case studies with a cradle to cradle system boundary for consistency in Table 1. Also, as the biogenic carbon content of wood was not used in the analysis of the case studies in this paper, the impact of biogenic carbon content assessed in the reviewed papers in Table 1 has been removed from the results shown.

The climatic regions are divided into five climate zones (A to E) with buildings in Zone A typically requiring high cooling and low heating needs and buildings in Zone E typically requiring low cooling and high heating needs. The criteria for each zone is based on the amount of heating degree days (HDD) and cooling degree days (CDD) experienced at the location [33]. HDD and CDD are a measure of how much (°Celsius) and for how long (days) outside air temperature was lower or higher than the base temperature. Using information gathered from an online degree day database [34] and taking 18°C as the base temperature for all climate types, climate zones were assigned to each of the case study locations.

Reviewed LCA studies concerned buildings with heating systems based on gas [7,9,14,17,19,21–23,30], electricity [8,11,13,15,16,22,30], ground and air source heat pumps [7,8,11,18,19,21,24,26–28], district heating [12,25–27,29,31] and renewable technologies [8,9,11,12,17–19,24,28].

Multiple studies on low energy and passive buildings are available in the literature [8,9,11–13,16,18,19,21,24,25,27,28,31]. Their annual operational energy and GWP usage ranged from -167 MJ/m^2 to 1025 MJ/m^2 and -9 kgCO$_{2e}$/m^2 to 51 kgCO$_{2e}$/m^2, respectively. Single residential building studies designed to latest building regulations or passive house standards generally had a lower operational energy (OE) contribution to their whole life cycle energy usage. Two notable exceptions were found in buildings constructed in Norway [8] and Sweden [31]. The minimum net energy demand requirement of residential buildings constructed to 2010 Norwegian Building Standards had an upper limit of 120 kWh/m^2/year plus 1600/(m^2 of heated floor area) kWh/m^2/year, which would equate to 135 kWh/m^2/year for a dwelling with a heated floor area of 106m^2 [35].

This was less onerous than the minimum requirements in the 2007 Irish Building Regulations [36] and would only achieve a Building Energy Rating (BER) of B3 in Ireland, which has a primary energy usage of between 125 and 150 kWh/m^2/year [37]. The BER assessment system was established due to the requirements of EPBD 2002 [3]. The BER in Ireland rates the energy performance of buildings on a simple 15-level scale of A1 (most efficient with ≤ 25 kWh/m^2/year of primary energy usage) to G (least efficient with > 450 kWh/m^2/year of primary energy usage). It is based on the characteristics of the building and is not dependent on the behaviour of the occupants [37]. The OE of the residential building constructed in Sweden was based on the results of the OE of two passive buildings monitored for a year [38]. The measured OE of the houses was found to be 27.5% to 32.4% higher than estimated, due to the behaviour of the inhabitants.

Among the other reviewed literature (Table 1), only three monitored the OE of the building [18,24,31]. The case study in Ref. [18] was a net-energy exporter residence which underestimated its predicted energy consumption by 14.4% [18], albeit it had the smallest OE and OC impact of the reviewed literature. This house was a net energy exporter as it produced more energy on-site than it imported from external sources due to a large amount of renewable technology installed. The space and water heating system of this house was based on an electric heat pump combined with mechanical ventilation, 6 m^2 of solar collectors and 68 m^2 of photovoltaics (PV).

In cold climates (e.g. Scandinavian countries), heating systems installed in the reviewed studies included electrical [8,11,26–28] or district heating [12,25–27,31] combined with mechanical ventilation and heat recovery (MVHR). In the UK studies [14,20], gas heating systems were used due to the availability of this resource. Gas has been the main source of fuel for domestic space and water heating in the UK, accounting for 84% and 80% of the energy consumption, respectively [20].

Table 1: Environmental LCA studies of residential buildings with OE and OC proportions.

Ref.	Building Type	Construction Type	Location	Climate Zone	Heating System	SC/PV	Ventilation	OE (MJ/m^2/year)	OC (kgCO$_{2e}$/m^2/year)	OE (%)	OC (%)
[10]	Prefabricated single detached units	WD	SWE	Zone E	Unk	-	MVHR	511	-	84	-
								533	-	84	-
								461	-	84	-
[11]	MT LEH Super-insulated building	TIM	NOR	Zone E	GSHP	PV (22m^2)	MVHR	227	-	72	-

		Current BR with SC				EL	SC	MVHR	409	-	90	-
		Current BR with EAHP				EL		EAHP	475	-	92	-
		Previous BR				EL		MV	605	-	95	-
		Architect ‘green’ BR				EL		MV	543	-	92	-
[7]	AP Block	Prior to EPBD	CON	North ITL	Zone B	GB	-	AC	486	-	86	-
		Current EPBD Standards				CGB	-	AC	360	-	81	-
		Borge Solare Standard				GHP	-	AC	101	-	53	-
[12]	PH	Original EE	TIM	SWE	Zone E	CHP DH	SC	MVHR	220	-	60	-
	TH	Min EE							220	-	64	-
		Max EE							220	-	59	-
[13]	BIAC Standard Single Storey House		TIM	NZL	Zone C	EL	-	Unk	126	-	74	-
			CON				-		115	-	71	-
			TIM				-		67	-	57	-
[14]	SD		TIM	South UK	Zone E	CGB	-	NV/MV	-	25-28	-	84-85
			CON				-		-	22-25	-	81-84
			CON				-		-	21-23	-	79-81
			CON				-		-	20-22	-	78-80
[15]	Singe-landed house		Clay & Bricks	IDN	Zone A	EL	-	AC	274	-	87	-
			CON				-		311	-	93	-
[16]	PH		Adobe	IND	Zone A	EL	-	NV	210	-	Unk	-
[17]	TH		CON	ESP	Zone B	GB	SC	AC	256	15	69	59
[8]*	Two-storey SFH	2010 BR	TIM	NOR	Zone E	EL	-	MVHR	1025	25	77	89
						EL & WD	-		846	23	75	86
						EL	SC		886	22	73	86
						EL & AWHP			748	20	71	85
		PR				EL			729	18	68	83
						EL & WD			665	17	66	81
						EL	SC		589	15	61	78
						EL & AWHP			561	15	61	78
[18]	PH		CON/STE/TIM	ITL	Zone B	EL HP	SC (6m^2), PV (68m^2)	MVHR	-173	-9	0	0
[19]	PH		Solid	AUT	Zone D	AAHP	-	MV	516	35.6	71	69
	LEH		TIM			Gas	-	-	806	50.8	82	81
	LEH		TIM			Gas	-	-	723	45.6	74	73
	LEH		Solid			Gas	SC (50m^2)	-	626	39.9	70	67
	LEH		Solid			Gas	SC (50m^2)	-	725	45.9	74	71
[31]*	PH		TIM	SWE	Zone E	DH & WD stove		MVHR	Unknown	Unknown	81	56

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[20]	Detached		CON	UK	Zone E	UK Domestic Energy use	-	Unk	678	62	99	88
	SD						-		809	74	99	89
	TH						-		1009	94	99	92
[21]	SFH		TIM	USA	Zone B	GB and ASHP	-	MVHR	740	33	79	79
	SFH		CON	CHE	Zone E	GSHP	-	MVHR	348	4	49	20
[22]	2 BD AP		CON	PRT	Zone A	EL and gas	-	Unk	269	14	20	80
	3 BD AP								214	11	20	77
	5 BD AP								136	7	27	69
[23]	Detached		CON	ITL	Zone B	Gas-fired	-	Unk	876	52	77	71
	Multi-dwelling					Gas-fired	-		640	40	79	75
	Office					AC	-		836	54	85	82
[24]	AP building		CON	ITL	Zone B	GSHP, GB	SC (10 m^2), PV (150 m^2)	MVHR	174	-	24	-
[25]	Detached house		TIM	FIN	Zone E	DH	-	MVHR	275	-	83	-
			TIM						274	-	75	-
			CON						97	-	52	-
			STE						99	-	58	-
	Row house		TIM	FIN	Zone E	DH	-	MVHR	220	-	83	-
			TIM						218	-	75	-
			CON						76	-	53	-
			STE						79	-	49	-
	Town house		TIM	FIN	Zone E	DH	-	MVHR	194	-	83	-
			TIM						193	-	74	-
			CON						68	-	54	-
			STE						70	-	58	-
	AP block		TIM	FIN	Zone E	DH	-	MVHR	150	-	81	-
			TIM						148	-	72	-
			CON						49	-	52	-
			STE						54	-	56	-
[9]	SD	2005 BR	CON	IRL	Zone E	GB	-	NV	473	26	89	81
		2008 BR					SC (3.23m^2)	NV	331	18	84	74
		2011 BR					SC (6.46m^2), PV (9m^2)	NV	218	11	75	60
		2011 BR					SC (3.23m^2)	MVHR	198	11	75	63
		NZEB BR					SC (6.46m^2), PV (16m^2)	NV	156	7	67	48
		NZEB BR					SC (6.46m^2), PV (3m^2)	MVHR	160	9	69	56
[26]	MSRB		CLT	SWE	Zone E	CHP & Heat Only Boiler	-	MVHR	673.2	-	91.8	-
						HP	-		633.6	-	92.2	-
			TIM, Beams & Column			CHP & Heat Only Boiler	-	MVHR	691.2	-	90.8	-
						HP	-		648	-	91.3	-
			TIM, Modular			CHP & Heat Only Boiler	-	MVHR	691.2	-	91.5	-
						HP	-		648	-	91.9	-
[27]	MSR B	Conventional	CLT	SWE	Zone E	CHP & Heat Only Boiler	-	MV	-	7.2	-	75

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	Low Energy					-	MVHR	-	6.3	-	70.3
	Conventional				HP		MV	-	8.4	-	77.8
	Low Energy						MVHR	-	6.8	-	71.8
	Conventional	TIM, Beams & Column			CHP & Heat Only Boiler	-	MV	-	7.2	-	69.4
	Low Energy					-	MVHR	-	6.3	-	65.6
	Conventional				HP		MV	-	8.4	-	72.5
	Low Energy						MVHR	-	6.9	-	67.6
	Conventional	TIM, Modular			CHP & Heat Only Boiler	-	MV	-	7.2	-	72.1
	Low Energy					-	MVHR	-	6.3	-	68.5
	Conventional				HP		MV	-	8.4	-	75.1
	Low Energy						MVHR	-	6.9	-	70.4
[28]	NZEB SFH	TIM	NOR	Zone E	AWHP	SC ($8.32 m^2$), PV	MVHR	-115	-4.2	0	0
[29]	MSRB	TIM	DEU	Zone E	DH CHP	-	Unk	372.1	22.4	58.1	68.3
[30] *	SD	Stone/Brick	PRT	Zone A	EL, Gas, LPG	-	Unk	270.7	19.7	80.9	77.9
	AP	Stone/Brick						254.8	18.6	82.5	79.8

AC= Air Conditioning
AAHP= Air-to-Air Heat Pump
AWHP= Air-to-water heat pump
AP= Apartment
BD= Bedroom
BR= Building Regulations
CLT= Cross Laminated Timber
CGB= Condensing Gas Boiler
CHP= Combined Heat and Power
CON= Concrete
DH= District Heating
EL= Electricity
EAHP= Exhaust Air Heat Pump
GB= Gas Boiler
GHP= Ground Heat Pump
GSHP= Ground Source Heat Pump
HP= Heat Pump
LEH= Low Energy House
LPG= Liquefied Petroleum Gas
MV= Mechanical Ventilation
MVHR= Mechanical Ventilation with Heat Recovery
NV= Natural Ventilation
PH= Passive House
PR= Passive Regulations
PV= Photovoltaics
SC= Solar Collectors
SD= Semi-Detached
SFH= Single Family House
STE= Steel
TH= Terraced House
TIM= Timber
WD= Wood

*Total primary energy, non-renewable energy

As different space and water heating strategies suit buildings at different geographical locations, it is important to assess the impact of different heating systems on the energy and GWP emission life cycle usage and production (together with their economic feasibility), in order to achieve a NZEB standard. Among the reviewed studies (Table 1), only one had investigated the impact different fuel source heating strategies had on the life cycle energy and GWP usage of the building [8]. However, the economic feasibility of the design solutions was not evaluated.

The EPBD recast [4] requires member states to use a comparative framework methodology for calculating cost optimal levels of minimum energy performance requirements for buildings and building elements. This methodology [39] has been used to determine the cost optimal energy performance levels for Irish residential nZEBs [40] and is used in this study to determine the optimal solution which offered the minimum life cycle cost for energy performance levels.

The comparative framework methodology for calculating cost optimal levels of minimum energy performance only considers two indicators; energy and cost. Numerous tools have been developed, and are in operation across Europe, that use multiple indicators to evaluate the sustainability of a building, such as the Home Quality Mark (HQM) [41], DNGB Certificate System [42], Leading the Environment for Sustainable Construction (LiderA) [42], Sustainability Assessment Tool (SBTool) [42] and the High Quality Environmental Standard (HQE) [42]. Each tool has varying types of indicators. Each of the tools indicators can be grouped under, what are commonly considered, the three pillars of sustainability: environment, social and economic. Other research has used the three pillars of sustainability to rank how green a material is (see, for example, [43]).

The objective of this paper is to determine, for buildings in a temperate oceanic climate, such as Ireland, if it is better to design a NZEB to be a super-insulated building with minimum heating requirements, or to provide less insulation but install a large amount of renewable energy sources. The proposed case studies will be assessed using two different methodologies to determine the best solutions. The first is the comparative framework methodology which is mandatory in all EU member states for calculating cost optimal levels of minimum energy performance requirements for buildings and building elements [39]. The second is a methodology that incorporates the commonly known three pillars of sustainability: environmental, social and economic. In the analyses of both methods, account will be taken of (i) varying discount rates, (ii) future de-carbonisation and improved efficiency of the electricity grid and (iii) future energy prices.

3 Methodology

The case study of NZEB dwellings presented in this paper demonstrate the future impact that the residential built environment may have on life cycle energy, GWP emissions and monetary cost. NZEBs are predicted to be economically viable to the Irish public at a BER of 'A2' [37,44]. The economic affordability of reaching a more efficient BER is deemed, in general, to be unviable according to Irish government evidence [44]. In this paper, residential dwellings are designed to achieve a rating of A2.

Utilising a standardised approach [45,46], environmental and economic LCA is conducted on various building designs, stressing the impact of different design strategies over an entire building's life cycle. The life cycle stages evaluated are identified according to the modularity principle of a building life cycle [47].

3.1 Material Production Stage (Module A1-A3)

Primary energy consumption and GWP emissions during the material production stage of all materials/components (excluding appliances, fixtures and fittings) in the construction of the case study buildings are assessed using the Inventory for Carbon and Energy (ICE) V.2.0 [48]. This stage is also known as a cradle to gate system boundary.

Embodied energy (EE) and embodied carbon (EC) are values which represent the energy consumed by, and emissions caused by extracting, processing and manufacturing of materials. EC considers the global warming potential (GWP) of various greenhouse gas emissions based on the relative amounts of heat trapped in the atmosphere by greenhouse gas. These calculations can be expressed mathematically as:

$$EE = \sum_1^n V_i \rho_i E_i \qquad (1)$$

$$EC = \sum_1^n V_i \rho_i C_i \qquad (2)$$

where V_i (m^3) is volume, ρ_i (kg/m^3) is density, E_i (MJ/kg) is EE intensity and C_i ($kgCO_{2e}/kg$) is EC intensity of material i. EC is taken as the greenhouse emissions released and is measured in CO_2 equivalents (CO_2eq), found by multiplying the mass of the greenhouse gases by their associated 100-year global warming potential [32].

Spon Construction Price Book [49] is utilised for the economic evaluation of the net construction costs (NCC) of the components in the case study buildings. The NCC accounts for the labour, plant and material economic costs of the components in the case study buildings. Economic construction costs are updated to current values using relevant consumer price indices [50] and do not include Value Added Tax (VAT). If EE, EC and economic construction values are unobtainable from the ICE database [48] and Spons Construction Price Book [49], data is sourced from other available databases and literature, as noted in the relevant sections of the paper.

3.2 Use Stage: Building Operation (Module B6)

Operational primary energy, GWP and economic cost of the case study buildings are estimated using the Dwelling Energy Assessment Procedure (DEAP) [51], together with current energy prices [52]. The DEAP methodology is the basis of determining the BER (Building Energy Rating) certificate to be awarded in Ireland. A life cycle of 60 years is taken as the life span of a residential building in Ireland. OE and EC are values which represent the primary energy consumed and GWP emissions generated during the operational phase of the building. This accounts for the energy consumed and GWP gases generated for the lighting, ventilation, central and water heating purposes. Due to the limitations of DEAP [51], the energy consumed and GWP emissions generated by building appliances (e.g. kitchen appliances, laundry equipment, TVs, etc.) is not accounted for. Of the reviewed studies in Table 1, four simulated whole house energy consumption, including appliances [11,26–28], and seven simulated whole house energy consumption, including appliances from multiple simulation/statistical sources [13,19,20,22,23,25,30], to assess the impact of building appliances in their case study buildings operational energy usage and GWP impact. Thus seven of the studies use other sources for estimating gaps in their simulations of whole building energy consumption. Estimations have been made on the impact building appliances have on the end use of Ireland's residential electricity consumption [53] by SEAI (Sustainable Energy Authority of Ireland). However, the accuracy of these estimations were questioned in the report and were thus, not used in combination with the DEAP software in the analysis of this paper. In this study, the OE and OC can be expressed mathematically as:

$$OE = \sum_{i=1}^{Y}\left[\sum_{j=1} PE_{j,i}\, F_j\right] \qquad (3)$$

$$OC = \sum_{i=1}^{Y}\left[\sum_{j=1} PC_{j,i}\, F_j\right] \qquad (4)$$

where PE_i (MJ_{prim}/MJ_{del}) is the primary energy conversion factor of fuel type j in year i of the building lifespan Y, F_j (MJ_{del}/m^2/year) is the delivered energy per heated floor area per year of fuel type j and PC_j ($kgCO_2/MJ_{prim}$) is primary GWP conversion factor of fuel type j in year i of the building lifespan.

The primary energy conversion factors of electricity, gas and wood pellets are taken as 2.37 MJ_{prim}/MJ_{del}, 1.10 MJ_{prim}/MJ_{del} and 1.10 MJ_{prim}/MJ_{del} [51], respectively, throughout the 60 year life cycle of the building. The GWP intensity conversion factors of electricity, gas, and wood pellets are taken as 0.145 $kgCO_2$/MJ, 0.056 $kgCO_2$/MJ and 0.0069 $kgCO_2$/MJ [51], respectively, throughout the 60 year life cycle of the building. Using the delivered energy of the respective fuels to each of the case study buildings and current Irish residential energy prices [52], operational costs of the case study buildings are determined. 2015 Irish residential electricity, gas and wood pellet prices of 5.77 c/MJ, 1.83 c/MJ and 1.47 c/MJ are assumed for this study [52] and do not include Value Added

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Tax (VAT). Standing charges, which are a combination of the fixed charges associated with providing electricity and gas network services and a share of the supply costs in servicing a costumer's account, are not included in the estimation of operational energy costs. These charges are applied at a fixed rate per day to a customer's account. Using the total values of EE, OE, EC, OC, NCC and operational economic costs (OEC), life cycle energy, GWP emissions and economic costs of the case study buildings are evaluated.

3.3 Life Cycle Cost Optimal

The EPBD recast [4] requires member states to use a comparative framework methodology for calculating cost optimal levels of minimum energy performance requirements for buildings and building elements. This methodology has been used to determine the cost optimal energy performance levels for Irish residential nZEBs [40] and is used in this study to determine the cost optimal solution. However, the EE of the materials invested into a building is accounted for in the current study despite not being required as part of the comparative framework methodology set out by the EPBD. The life cycle cost part of this methodology can be expressed mathematically as:

$$LCC(Y) = NCC + \sum_j \left[\sum_{i=1}^{Y} \left(OEC_i(j) R_d(i) + C_{c,i}(j) \right) - V_{f,Y}(j) \right] \tag{5}$$

where LCC is the life cycle cost, Y is the lifespan of the building (60 years), *NCC* is the net construction cost or initial investment costs (€), OEC_i (j) is the annual cost during year i for heating system j, $V_{f,Y}$ (j) is the residual value of heating system j at the end of the building lifespan, $C_{c,i}$(j) is the carbon cost during year i for heating system j based on the sum of the annual OC emissions and R_d (i) which is the discount factor for year i based on discount rate r which is determined using:

$$R_d(t) = \left(\frac{1}{1+r/100} \right)^t \tag{6}$$

where t is the number of years from the starting period and r means the real discount rate. As the environmental life cycle stages in this study accounts for the materials production (module A1-A3) and building operation (module B6) of a building, the cost associated with maintaining/repairing a building (module B2-B5) and recycling/selling/disposing of materials/systems (module C1-C4) are not considered in the LCC analysis.

In this analysis, a discount rate (4%) and cost per tonne of carbon produced by a building are assumed to be that used to determine the cost optimal NZEB energy performance standards for residential buildings in Ireland [40].

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As the analysis in the study for determining the NZEB energy performance standards is for 30 years, the cost per tonne of carbon in the final year of their analysis is assumed to remain constant for the remaining 30 years of this study. The energy prices for the different fuel types are the same as described in section 3.2.

3.4 Sustainability Index Factor

The comparative framework methodology for calculating cost optimal levels of minimum energy performance requirements for buildings and building elements only considers two indicators; energy and cost. In this paper, it is examined whether there is a need to start moving away from using the cost optimal energy performance method, which incorporates only energy and cost as indicators, to a method that incorporates the 3 pillars of sustainability which are commonly known as economic, social and environment. The methodology used in this paper is termed the Sustainability Index Factor (SIF) and can be expressed mathematically as:

$$SIF_j = \frac{aECO_j + bSOC_j + cENV_j}{k} \tag{7}$$

where a, b and c are weighting factors; k is Σ(a,b,c); ECO_n is the economic impact of case study n; SOC_n is the social impact of case study n; and ENV_n is the environmental impact of case study n and can be expressed mathematically as:

$$ECO_n = \frac{\left[\frac{\sum_{m=1}^{q} eco_{m,n} w_m}{\sum_{m=1}^{q} w_m}\right]}{\sum_{n=1}^{p}\left[\frac{\sum_{m=1}^{q} eco_{m,n} w_m}{\sum_{m=1}^{q} w_m}\right]/p};\; SOC_j = \frac{\left[\frac{\sum_{m=1}^{q} soc_{m,n} w_m}{\sum_{m=1}^{q} w_m}\right]}{\sum_{n=1}^{p}\left[\frac{\sum_{m=1}^{q} soc_{m,n} w_m}{\sum_{m=1}^{q} w_m}\right]/p};\; ENV_j = \frac{\left[\frac{\sum_{m=1}^{q} env_{m,n} w_m}{\sum_{m=1}^{q} w_m}\right]}{\sum_{n=1}^{p}\left[\frac{\sum_{m=1}^{q} env_{m,n} w_m}{\sum_{m=1}^{q} w_m}\right]/p} \tag{8}$$

where $eco_{m,n}$ is the impact of economic category m for case study n, $soc_{m,n}$ is the impact of social category m for case study n, $env_{m,n}$ is the impact of environmental category m for case study n, w_m is the weighting applied for each category depending on the categories importance, q is the number of categories evaluated in each of the economic, social and environmental indicators and p is the number of case studies evaluated. The sum of the weightings for each category must add up to one. As can be seen from Equation (7), each of the three indicators for the SIF can be given a different weighting depending on the importance each of the three indicators.

This SIF methodology can be used for assessing the SIF impact of a set of buildings which are representative of a countries national building stock for a number of economic, social and environmental categories.

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3.5 Sensitivity Analysis

The life cycle cost optimal and SIF results are influenced by the assumptions made with regards to the discount rate, energy prices and efficiency of the electricity grid. A baseline 4% discount rate is assumed in addition to the static energy prices and electricity grid efficiency for the lifespan of the building. Therefore, a sensitivity analysis is carried out to see what influence the assumptions made in terms of the discount rate, energy prices and efficiency of the electricity grid have on the results.

3.5.1 Discount rate

The discount rate effects the annual energy costs of the buildings in this papers analysis. Therefore, an analysis is done to determine the impact a varying discount rate has on the annual energy costs using the present value of annuity (PVA) formula which can be shown mathematically as:

$$PVA = \frac{OEC_i}{r}\left(1 - \frac{1}{(1+r)^Y}\right) \quad (9)$$

where OEC_i is the annual operational energy cost (€/year), r is the discount rate (%) and Y is the number of years in the building's life cycle (taken here as 60 years).

The impact of a varying discount rate on the equivalent annual cost (EAC) of constructing and operating the building over its lifespan is also assessed. The EAC can be expressed mathematically as:

$$EAC = {(NCC).r}\Big/{\left(1 - \frac{1}{(1+r)^Y}\right)} + \mathrm{OEC_i} \quad (10)$$

where NCC is the net construction cost (€), $\mathrm{OEC_i}$ is the operational energy cost per annum (€/year), r is the discount rate (%) and Y is the number of years (taken here as 60 years).

3.5.2 Energy Costs

For the baseline analysis, the energy prices are assumed to remain constant for the lifespan of the buildings. In reality, throughout a buildings 60-year lifespan, energy prices are not going to remain constant and may have a significant impact on the hierarchy of the case studies' life cycle economic costs. Therefore, a sensitivity analysis is carried out using projected future energy costs.

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This study predicts future energy prices, based on the average annual growth rate of electricity and gas prices from 2007 to 2015 and from 2005 to 2015 for wood pellet prices [52]. Future energy prices are predicted assuming an annual growth rate of 3.27%, 2.62% and 3.79% for electricity, gas and wood pellets, respectively. Prices for exporting electricity back onto the national electricity grid are assumed to remain at 2.5 c/MJ, in both the static and dynamic pricing scenarios [54].

3.5.3 Decarbonising and increasing efficiency of electricity generation

For the baseline analysis, the efficiency of the electricity grid and its GWP intensity is assumed to remain constant for the buildings life cycle. However, the electricity grid is expected to become more decarbonised as we move into the future. Therefore, a sensitivity analysis is carried out to determine what impact an electricity grid becoming more decarbonised and efficient has on the results.

The impact of a national electricity mix on a buildings' environmental life cycle impact had been highlighted in the reviewed case studies of [8,21] in Table 1, but only one had considered the impact of future grid decarbonisation [28]. This study took an average yearly carbon impact of an EU electricity grid assuming the grid would become decarbonised by reaching the 90% carbon reductions target of 2050 [28]. Other non-environmental life cycle assessment publications examining future decarbonisation of the electricity grid have used published reports projecting the source of electricity generation up to 2020, 2030, 2050 and 2070 to estimate the carbon impact of the electricity grid [55–60].

A similar approach is used in the analysis of this paper. To predict the impact decarbonising of electricity generation in Ireland would have on the life cycle GWP emissions of the case study buildings, the 'Energy Forecasts for Ireland to 2020, 2011 Report' [61] was utilised. In this report, the Economic and Social Research Institute's Irish Dispatch of Electricity Model (IDEM) model was used to produce the electricity sector projections. IDEM is a least-cost economic dispatch model that optimises the electricity system on a half-hourly basis to meet demand in that period of time. This economic dispatch is based on the various characteristics of generation unit. A more in-depth discussion of this model is contained in [62]. The total amount of fuel inputs for electricity generation remains static over the period from 2010 to 2020. Electricity generation is predicted to increase by 15% over this period, due to an increase in domestic demand and exports. On the other hand, an increase in the efficiency of electricity generation means less fuel will be required to meet electricity demand.

Based on targets set in the Irish Government's National Energy Efficiency Action Plan (NEEAP) [63] and National Renewable Energy Action Plan (NREAP) [64], the predicted shift from natural gas to renewable sources of energy for electricity generation (i.e. 62% to 43% and 8% to 28% of fuel share, respectively, from 2010 to 2020), increase in fuel share of coal (18% to 21%) and slight decrease in fuel share of peat (10% to 9%) lead to an 18.8% reduction in global warming potential (measured by CO_{2e}) of electricity generation from primary fuel inputs over the period 2010 to 2020 (Table 2).

Taking account of change in fuel source and improved system efficiencies, the average annual growth rates of GWP emissions intensity and primary energy factor of electricity generation from 2010 to 2020 are estimated to decrease by approximately 4.2% and 2.3% annually, respectively (Table 2). At this rate, it would take until 2065 to decarbonise electricity generation by 90% from the 2010 levels and approximately 100 years to reduce GWP emissions intensity of electricity generation to approximately zero.

These forecasts depend on, not only the fuel mix for electricity generation, but the demand side as well. Published data on the fuel mix of electricity generation in Ireland in 2014 [65] showed that the total primary fuel demand was less than what has been predicted in the 'Energy Forecasts for Ireland to 2020, 2011 Report' [61] for 2016. Due to this demand reduction, the amount of renewables accounting for the electricity fuel mix was not as high as predicted for 2016 and caused the average annual reduction rate to decrease to 3.5%, assuming the same fuel mix and demand would be required in 2020. However, with the small reduction in the annual reduction rate and the emphasis on countries to work towards a decarbonised grid, the reduction rates of 4.2% and 2.3% are used in the analysis presented in this papers.

Table 2: Global warming potential of electricity generation from primary fuel inputs 2010-2020 based on targets set in the Irish Government's NEEAP [63] and NREAP [64]

Fuel	**CO_{2e} related to gross electricity generation (Mt CO_{2e})**			**Growth (%)**	**Average annual growth rate (%)**			**CO_{2e} related to fuel share (%)**		
	2010	**2016**	**2020**	**2010-2020**	**2010-2020**	**2010-2016**	**2016-2020**	**2010**	**2016**	**2020**
Coal	3.455	4.000	3.988	15.4%	1.4%	2.5%	-0.1%	26%	33%	37%
Oil	0.422	0	0	-100%	-100%	-100%	0%	3%	0%	0%
Gas	7.208	5.427	4.915	-31.8%	-3.8%	-4.6%	-2.4%	54%	45%	46%
Peat	2.184	2.532	1.877	-14.1%	-1.5%	2.5%	-7.2%	16%	21%	17%
Renewables	0	0	0	0%	0%	0%	0%	0%	0%	0%
Total generation (Mt CO_{2e})	**13.269**	**11.960**	**10.780**	**-18.8%**	**-2.1%**	**-1.7%**	**-2.6%**			

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Total fuel inputs (ktoe)	4886	4880	4830	-1.1%	-0.1%	0.0%	-0.3%
Efficiency (%)	44.2	52.0	56.0	25.9%	2.3%	2.6%	1.9%
Total generation (kgCO$_{2e}$/kWh)	**0.528**	**0.405**	**0.343**	**-35.1%**	**-4.2%**	**-4.3%**	**-4.1%**
Primary Energy Factor (MJ$_{prim}$/MJ$_{del}$)	**2.261**	**1.922**	**1.785**	**-21.0%**	**-2.3%**	**-2.7%**	**-1.8%**

For the case studies which exported electricity to the grid, the GWP savings are assumed to have the same GWP intensity of the electricity grid for that given year, based on an annual reduction of 4.2% in the GWP intensity of the electricity grid. Other studies have suggested using the same GWP intensity as the electricity grid initially, before plateauing due to the GWP intensity of the marginal power plant supplier. Eventually the GWP intensity of the electricity supply would start declining again due to the increasing decarbonisation of the electricity fuel supply [66]. This would have minimal impact on the total GWP results of the case studies as the GWP intensity would reach the same intensity at some point in the future in these scenarios. Therefore, the exported electricity is assumed to have the same GWP intensity as the electricity grid. The same assumption is made with regards to the electricity primary energy factor.

The GWP and primary energy savings made through the installation of renewable technology vary throughout the year. The savings made by the ETSCs and MCPVs depend mainly on the varying energy demands of the case study buildings throughout the year, the varying energy production levels caused mainly by the levels of global radiation in Ireland throughout the year, and the GWP and primary energy factor for the main grid electricity generation during the year.

Combing the total CO$_2$ emissions and energy demand of the electricity grid (sourced from Eirgrid [67], the company that manages and operates the transmission grid across the island of Ireland), the GWP impact of the Irish electricity grid for the months during 2014 and 2015, together with their average monthly emissions intensities for 2014 and 2015, are given in Figure 1. As can be seen from Figure 1, the GWP intensity of the electricity grid in Ireland is similar throughout the year with a maximum of 20% difference in average monthly values throughout the year and standard deviation of 0.008 kgCO$_{2e}$/MJ in the average monthly values. The average global radiation (sourced from Met Éireann [68], the Irish National Meteorological Service) of five weather stations in Ireland (Mace Head, Malin Head, Cork Airport, Dublin Airport and Mullingar) for 2014 and 2015, together with monthly averages for the period 2013 to 2015, are given in Figure 2. The large variability in the

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global radiation for the different months of the year does not significantly affect the GWP intensity of the electricity grid in Ireland, as PV is a very small contributor of electricity supplied to the grid (i.e. < 0.001% as of 2013) [69]. Comparing the use of average yearly and monthly factors in determining both the GWP and operational energy of the case study buildings, it was found that the largest percentage difference was less than 5%. As this was minimal, an average yearly GWP and primary energy factor for the electricity grid is assumed for the remainder of the paper, as outlined in Section 3.2.

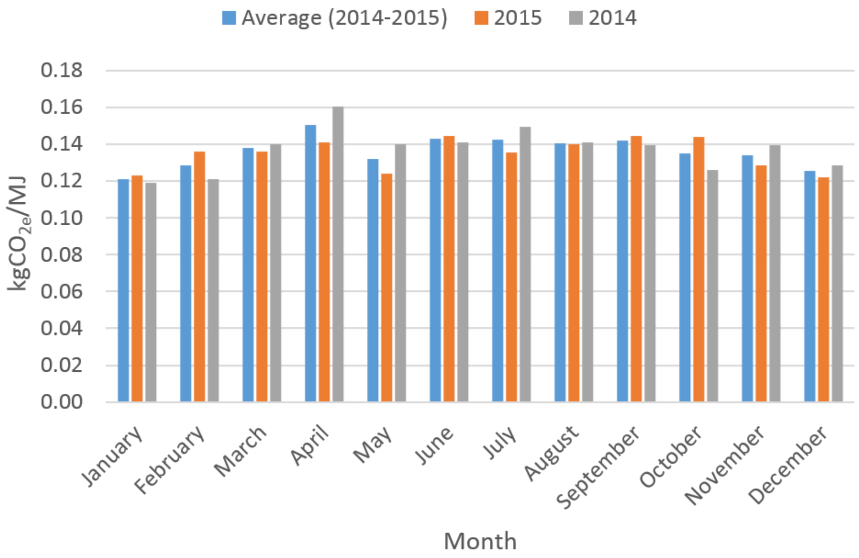

Figure 1: GWP impact of the Irish electricity grid for the months 2014 and 2015

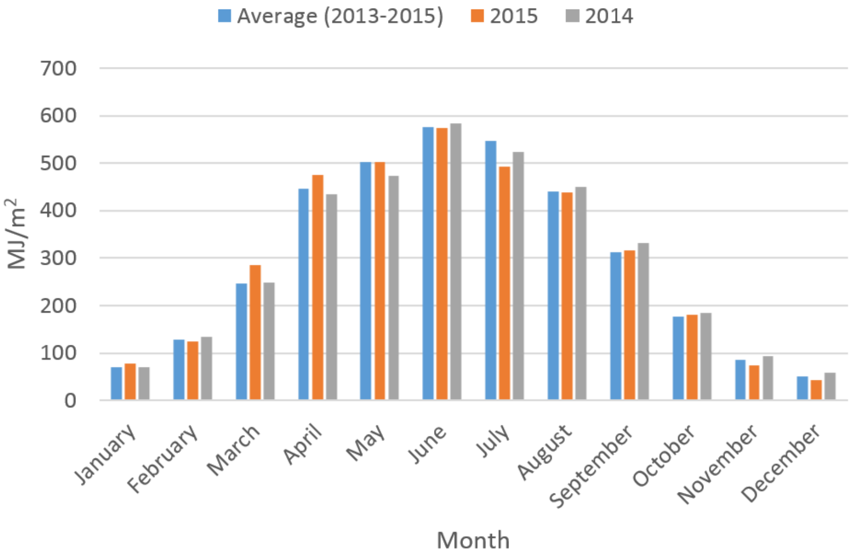

Figure 2: The average global radiation of five weather stations in Ireland (Mace Head, Malin Head, Cork Airport, Dublin Airport and Mullingar) for 2014 and 2015 along with their average for 2013-2015

3.6 Case study buildings

A south orientated residential semi-detached two storey masonry house (106 m^2 heated floor area) with features typical to Irish residential construction practice [70] was chosen as the case study design template (**Error! Reference source not found.**). Eight different versions of this semi-detached house were investigated with two different building fabrics, airtightness and ventilation strategies employed. Case studies one to four achieved the expected NZEB standard in terms of their BER [44], while also adhering to current Irish residential building regulation requirements for building fabric, airtightness and ventilation [71,72]. Natural ventilation (i.e. trickle and purge ventilation) was used in the living room and bedrooms. Kitchen, bathrooms and utility room were mainly ventilated with the help of mechanical extract fans with an extract rate of 10 m^3/h each. However, the practice of ventilating the house through opening windows is generally not welcomed by the occupants in all seasons, due to Ireland's temperate oceanic climate with cold and humid winters. People can be reluctant to open windows to allow the cold fresh air inside. Trickle vents in windows and walls are often closed or blocked-off by building occupants, especially if they are facing towards the prevailing wind in an exposed site or on northerly façade of the building, from which the colder winds come.

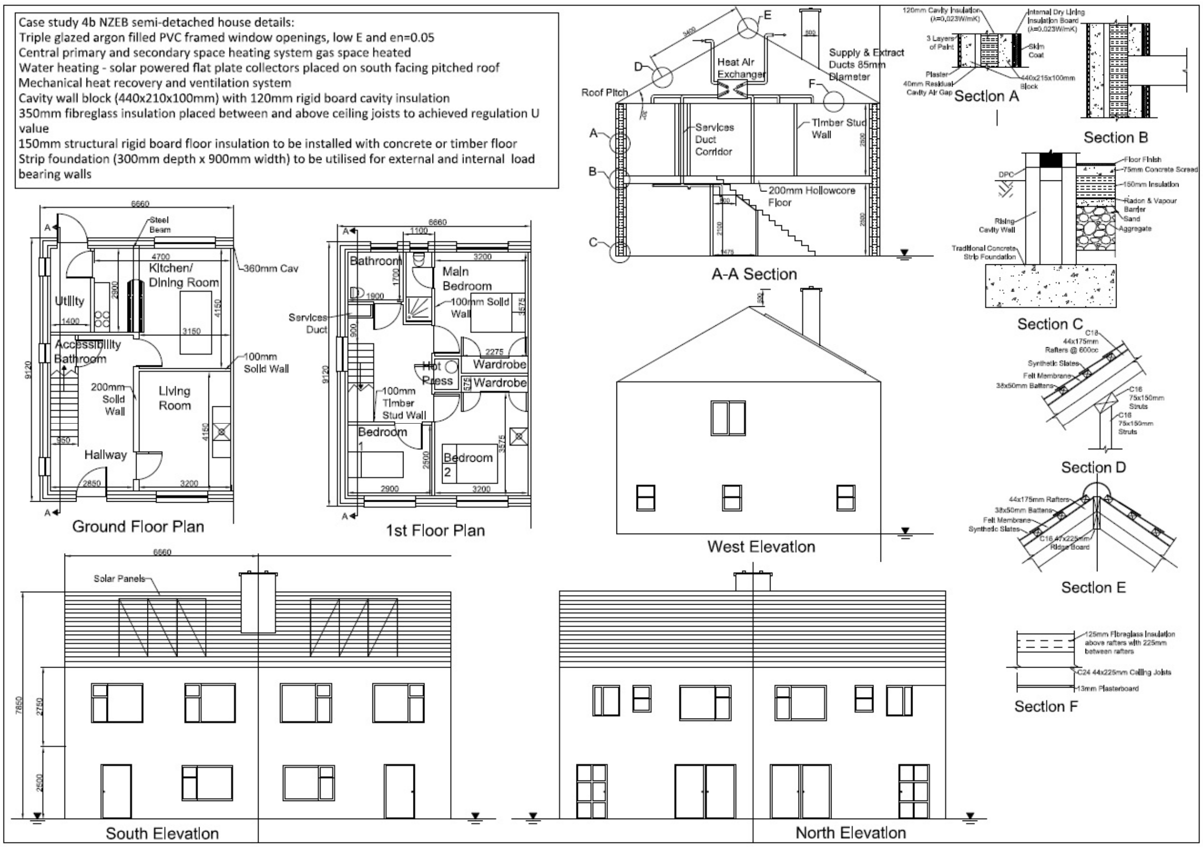

Figure 3: Design plans and elevations for the case study semi-detached houses.

Case studies five to eight complied with passive house building fabric, air-tightness and ventilation standards in order to achieve a NZEB status [73]. Table 3 summarises the differences in the case study buildings in terms of building fabric, airtightness and ventilation method. Refer to [9] for more details on the building elements used in the construction of the case study buildings. A breakdown of the embodied intensities of the materials used for the construction of case study buildings and their source is given in Appendix A.

Table 3: General characteristics of the building envelope and ventilation systems for the eight case studies

Case Study	External Wall	Roof	Floor	Window	Airtightness	Ventilation	Mechanical Ventilation System Characteristics	
No.	U-Value (W/m^2/K)				(ac/hr @ 50 Pa)		SPF (W/l/s)	HRE (%)
1-4	0.20	0.14	0.18	1.40	5.44	NV and MV	N/A	N/A
5-8	0.17	0.12	0.15	0.80	0.45	MVHR	0.89	90

NV= Natural Ventilation (Purge Ventilation via windows in habitable rooms and open flue (20 m^3/h) in living room)
MV=Mechanical Ventilation (Extract Fan of 10 m^3/h in kitchen, utility room and bathrooms)
MVHR=Mechanical Ventilation with Heat Recovery, SPF: Specific Fan Power, HRE: Heat Recovery Efficiency

Each of these case studies utilised different strategies for providing space and water heating needs, including a condensing gas boiler, a biomass boiler for wood pellets, a domestic gas fired combined heat and power (CHP) unit, a heat pump system covering 75% of the total water heating demand (the remaining is covered by electricity) and varying amounts of renewable technology. As it is a common practice in Ireland, a secondary space heating system, i.e. a wood stove, was installed in the living room of each of the case study buildings. The open flue for the wood stove was assumed to have a ventilation rate of 20 m^3/h. Each of the heating sources worked in tandem with varying amounts of renewable energy technology installed. The renewable energy technologies employed included evacuated tube solar collectors (ETSC) and multi-crystalline photovoltaics (MCPV). One ETSC had an aperture area of 3.23 m^2 and 0.727 zero loss collector efficiency. The MCPV had an efficiency of 13.2%. For a south orientated building in Ireland, annual solar radiation of 3866 MJ/m^2 was assumed [51].

ETSC's were used in tandem with the main heating system for the generation of hot water for domestic purposes. MCPV panels were used to generate electricity for the pumps, ventilation and lighting requirements of the case study buildings. However, the case study buildings with a building fabric adhering to the current building regulations (i.e. case studies 1 to 4) required a significant amount of additional capacity from the MCPV renewable energy system to achieve a BER of A2, which is the minimum rating expected for a NZEB new-build in Ireland (see **Error! Reference source not found.**). The use of domestic appliances was not accounted for due to the limitations of DEAP [51]. The MCPV system allowed generated electricity not consumed by the case study buildings to be exported back to the electricity grid.

Error! Reference source not found. summarises the differences in the case study buildings in terms of space and water heating systems, system efficiency and renewable energy technology employed. Energy and global warming potential (GWP) intensity values, together with economic costs, for the space and water heating systems, renewable technologies and ventilation methods were sourced from Refs.[49,74–83]. The EE and EC of the wood stove was not accounted for in the analysis.

Table 4: General characteristics of the heating systems and renewable technologies for the eight case studies

Case Study No.	Heated Floor Area (m^2)	Main heating system	*Secondary space heating system	Efficiency Heating System	Renewable Technology ETSC (m^2)	MCPV (m^2)
1	106	Gas boiler	Wood Stove	Main: 91.3%, Sec: 60%	6.46	16
2	106	Biomass Boiler	Wood Stove	Main: 82.7%, Sec: 60%	6.46	19
3	106	CHP	Wood Stove	Main: 76% heat & 7% electrical, Sec: 60%	6.46	16
4	106	Heat pump	Wood Stove	Main: SPF 300%, Sec: 60%	6.46	14
5	106	Gas boiler	Wood Stove	Main: 91.3%, Sec: 60%	6.46	3
6	106	Biomass Boiler	Wood Stove	Main: 82.7%, Sec: 60%	6.46	4

7	106	CHP	Wood Stove	Main: 76% heat & 7% electrical, Sec: 60%	6.46	3
8	106	Heat pump	Wood Stove	Main: SPF 300%, Sec: 60%	6.46	2

ETSC= Evacuated Tube Solar Collector, MCPV= Multi-crystalline Photovoltaics, SPF=Seasonal Performance Factor

*Secondary heating systems account for 10% of space heating requirements

4 Results

4.1 Life cycle energy, GWP and cost

In the life cycle analysis (LCA) and life cycle costing (LCC) presented in this section, it was assumed that emissions and efficiency, associated with production of electricity supplied through the mains grid, would remain constant over the lifetime of the building. In addition, static pricing of energy was assumed over the lifetime of the building. There was a significant amount of uncertainty associated with these variables and so the effects of changes to these variables on determining the rank order of case study buildings, in terms of their environmental and economic impacts over their lifetime, were investigated in Sections 4.4. Furthermore, the results presented in this section did not account for the time value of money, which was also considered in Section 4.4.

Error! Reference source not found.(a)-(c) demonstrate the estimated EE, OE, EC, OC, net construction and operational costs of each of the case studies analysed. In terms of EE, super-insulated houses (case studies 5-8) outperformed those with a high level of renewables installed (case studies 1-4). The design with the lowest EE impact was the super insulated house with a heat pump as the main source of heating (case study 8). The design with the highest EE impact was the house using biomass and a large amount of renewables as the main source of heating (case study 2), in addition to having the fourth highest net construction costs. On the other hand, this strategy had the lowest operational cost of all the strategies due to its large installation of renewables. In fact, due to the large amount of MCPV installed, this design exported electricity into the grid. With consumers currently being offered 2.5 c/MJ to export electricity into the grid in Ireland [54], this house generated 124 €/yr. Case studies 1 and 3 were also exporters of electricity. In spite of having a very high efficiency heating system and large installation of renewable energy sources, case study 4 had the second highest operational costs, due to the current high cost per MJ of electricity for domestic customers, compared to gas and wood pellets in Ireland [84].

A similar pattern followed for EC, whereby the houses designed to be super-insulated outperformed those with a large installation of renewables. The two houses designed using a biomass boiler (case study 2 and 6) had the lowest OC impact of all the eight designs, due to the low GWP impact of wood pellets. Furthermore, due to the

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large installation of MCPV in case study 2, 306 $kgCO_2/m^2$ was saved during the building's operational phase. The third lowest generator of GWP emissions (case study 3) generated 147 $kgCO_2/m^2$ more than the super-insulated house with a biomass boiler (case study 6) during the operational stage. This was 22% of the total amount that case study 6 produced over its lifespan. For the case studies which exported electricity to the grid, the GWP savings were assumed to have the same GWP intensity of the electricity grid for the lifespan of the building (0.145 $kgCO_2/MJ$). In this analysis, the exported electricity was considered avoiding electricity generation. Thus, the GWP and primary energy usage was reduced accordingly and included as part of the use stage of the case study buildings life cycle assessment (Module B6). Due to the GWP savings associated with the large amount of renewables installed on case studies 1-4, in terms of OC, the NZEBs designed to have a large amount of renewables outperforms those which are designed to be super-insulated.

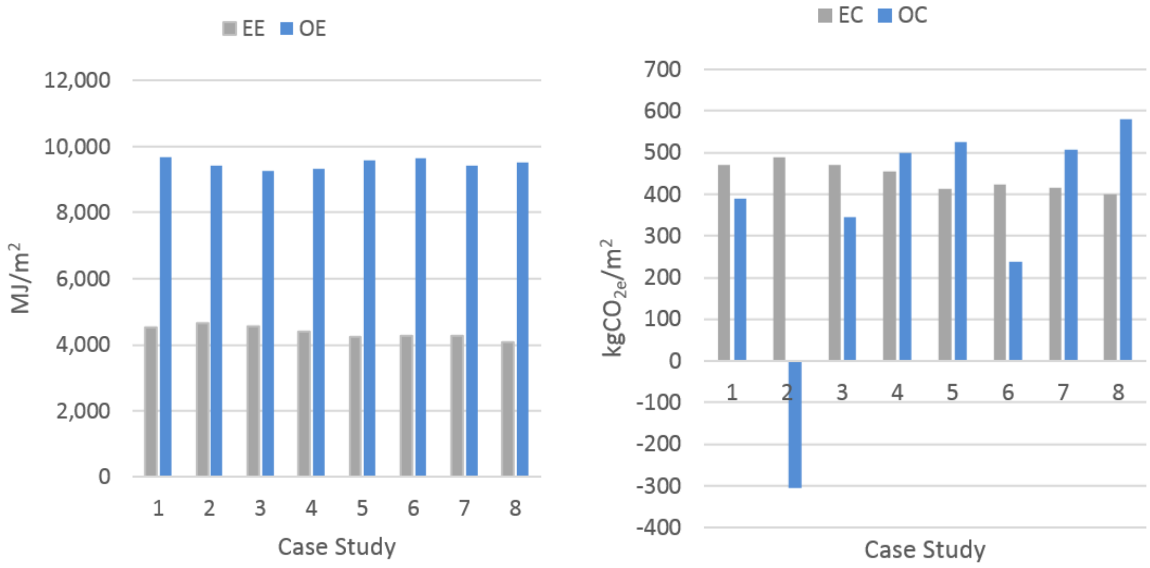
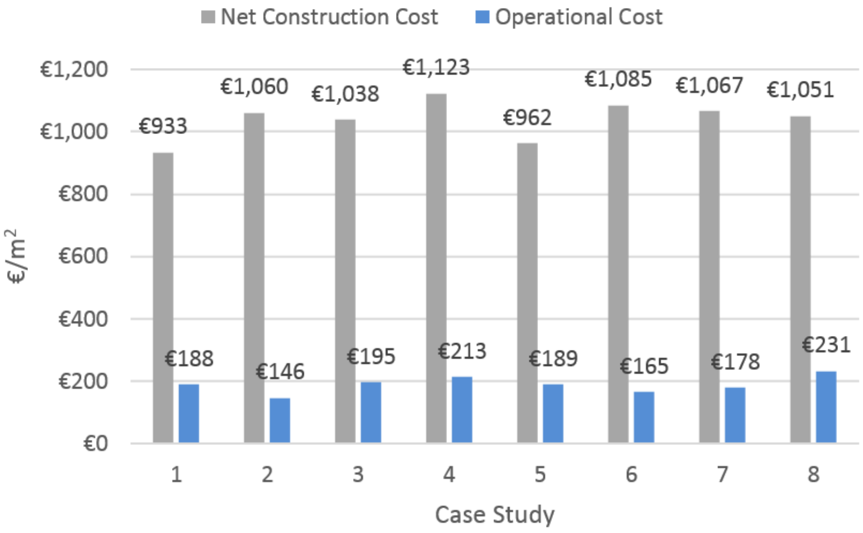


Figure 4(a): Estimated embodied energy (EE) and operational energy (OE) and Error! Reference source not found.**(b)**: embodied global warming potential (EC) and operational global warming potential (OC) of a typical semi-detached home in Ireland over a 60-year lifespan



Error! Reference source not found.**(c):** Estimated net construction and operational primary energy costs of a typical semi-detached home in Ireland over a 60-year lifespan

4.2 Life cycle cost optimal

Figure 5 demonstrates the life cycle costs vs life cycle energy of each of the analysed case studies. The design with the lowest life cycle cost was the building with gas as the main source of heating and a large amount of renewables installed (case study 1). The cost optimal in terms of energy performance was the building designed to be super-insulated with gas as its main heating source (case study 5). Even though case study 8 and 4 had the most efficient heating systems employed (i.e. lowest net secondary energy), the high cost of electricity used by the heat pump resulted in case study 8 and 4 being among the highest of the case studies in terms of life cycle costs. The cost of gas was higher than wood pellets, but the efficiency of the gas boiler was greater than that of the biomass boiler (**Error! Reference source not found.**) resulting in case study 5 being the optimal solution.

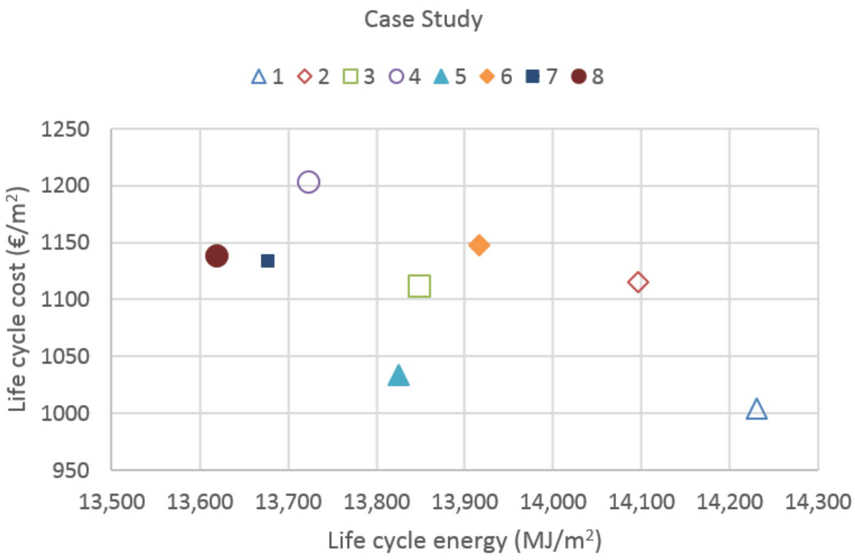


Figure 5: Life cycle cost versus life cycle energy of the eight different building designs

4.3 Sustainability Index Factor

Three of the top four designs in terms of both life cycle GWP emissions and life cycle economic cost focused their design on having a large amount of renewables installed (see Table 5). Three of the top four designs in terms of life cycle energy focused their design on having a super insulated building (see Table 5). Therefore, each case study had its strengths and weaknesses in terms of (i) life cycle cost, (ii) life cycle energy and (iii) life cycle GWP emissions. Thus, using the SIF as described in section 3.4, each of the case studies were evaluated based on the economic and environmental categories evaluated in this study. No social categories were evaluated in this papers analysis.

The economic category (life cycle cost) was giving a weighing of one with each of the environmental categories given a weighting of 0.5. Both the economic and environmental indicator were each given a weighting of one.

The indicators were averaged for each case study to give them a SIF as shown in Table 5. The case study with the lowest SIF was case study 2. Based on the cost optimal methodology, case 5 is the best solution. However, when using the SIF, which considered only one more category for evaluating the optimal solution, case study 5 was the 5th best design. This was primarily caused by the impact case study 5 had in terms of life cycle GWP. Life cycle GWP experienced the largest variability of the three categories evaluated. This was due to the large variability in the GWP impact of fuel sources [51] in addition to the GWP savings associated with case study 1-3 which were exporters of electricity to the grid due to their large installation of MCPV. For the case studies which exported electricity to the grid, the GWP savings were assumed to have the same GWP intensity of the electricity grid

Table 5: SIF of the eight case studies

	Economic		Environmental				Sustainability
Case Study	Life Cycle Cost		Life Cycle Energy		Life Cycle GWP		SIF
	€/m^2	Impact [-]	MJ/m^2	Impact [-]	kgCO$_{2e}$/m^2	Impact [-]	[-]
1	1,121	0.91	14,231	0.51	858	0.54	0.99
2	1,207	0.98	14,096	0.51	183	0.12	0.80
3	1,233	1.00	13,849	0.50	816	0.52	1.01
4	1,336	1.09	13,724	0.49	952	0.60	1.09
5	1,151	0.94	13,825	0.50	939	0.60	1.02
6	1,250	1.02	13,917	0.50	661	0.42	0.97
7	1,245	1.01	13,677	0.49	921	0.58	1.05
8	1,282	1.04	13,620	0.49	980	0.62	1.08
Average	1,228	1.00	13,867	0.50	789	0.50	1.00
STDEV	69	0.06	209	0.01	265	0.17	0.09

4.4 Sensitivity analysis

The life cycle cost optimal and SIF results were influenced by the assumptions made with regards to the discount rate, energy prices and efficiency of the electricity grid. Therefore, a sensitivity analysis is carried out to see what influence the assumptions made in terms of the discount rate, energy prices and efficiency of the electricity grid have on the results.

4.4.1 Decarbonising and increasing efficiency of electricity generation

A rate of -4.2% and -2.3% was used for the average annual growth rate of GWP emissions intensity and primary energy factor for electricity consumption in the case study buildings over their full life cycle of 60 years. The resulting impact on life cycle GWP emissions is given in Figure 6 and life cycle primary energy usage given in Figure 7. Decarbonising the electricity grid and its increasing efficiency had a significant impact on the hierarchy of case studies life cycle GWP emissions and primary energy usage.

Case studies 4 and 8 had the highest GWP emissions, assuming a static GWP intensity of electricity generation. Moreover, assuming an annual decrease of 4.2%, case studies 8 and 4 had the 3rd and 4th lowest life cycle GWP

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emissions (Figure 6). The annual reduction caused a reduction in life cycle GWP of 32 % and 37% in both case studies 4 and 8.

Even though the case study using a biomass boiler as the main heating system with a large amount of renewables (case study 2) still outperformed its super-insulated counterpart (case study 6), the design focusing on the use of renewables (case study 2) had a life cycle GWP emission impact only 17% less than case study 6. This was compared to 59% using a static GWP intensity factor. For all other case studies, the super-insulated designs outperformed their large renewable energy counterparts due to the minimising impact of the MCPV installation.

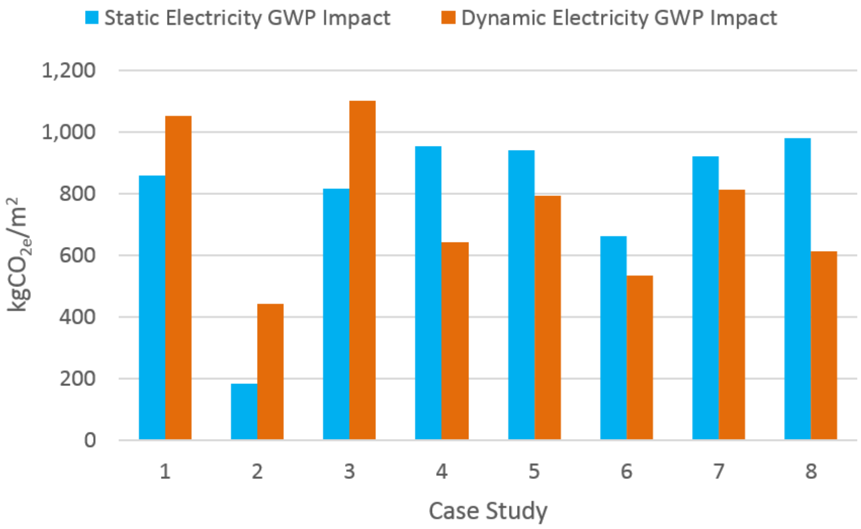

Figure 6: Impact of accounting for de-carbonisation of electrical grid over 60 years on case studies life cycle GWP emissions

Apart from the case studies using a CHP as the main heating system, the super-insulated designs outperformed their large renewable energy counterparts, assuming a static electricity grid efficiency throughout the buildings' lifespan. Accounting for increasing efficiency of the electricity grid, all the super-insulated designs outperformed their large renewable energy counterparts.

Case studies 1, 2 and 3 were all electricity exporters to the grid. Due to the diminishing savings of the MCPV in terms of GWP and primary energy caused by the decarbonisation and improved efficiency of the electricity grid, all these case studies had a larger life cycle GWP impact and primary energy usage compared to their static GWP electricity grid intensity and efficiency scenarios.

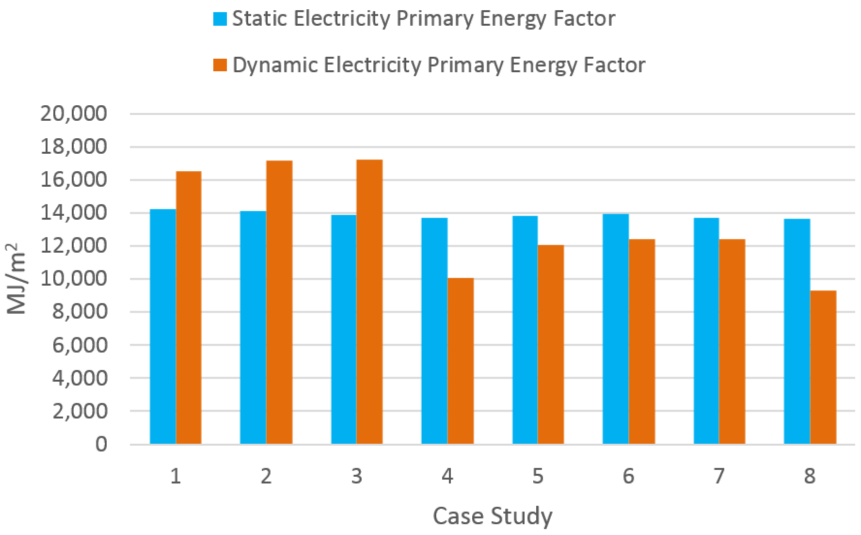

Figure 7: Impact of improving electricity grid efficiency over 60 years on case studies' life cycle energy usage

In fact, as the primary energy factor for the electricity grid improved due to improved generation efficiencies, the impact of exporting electricity to the grid from on-site electricity generation reduced. This meant that case studies 1, 2 and 3 did not achieve the required A2 BER rating, in order to be considered a NZEB building when annualising their life cycle primary energy usages. They achieved an A3 rating instead, which would meet the current Irish building energy regulation requirements [71]. Of course, this assumed that the efficiency of the on-site generation was constant over the life of the building. The rating of case study 8 improved to an A1, which was required to use less than 90MJ/m^2/year. All other case studies remained an A2 rated dwelling.

4.4.2 Discount rate

In the case studies' cost optimal results presented in this paper (Figure 5), the discount rate of 4% was assumed which effected the operating costs of the building. An analysis was done to determine the impact a varying discount rate had on the annual energy costs using the present value of annuity (PVA) formula, with the results given in Figure 8. For all discount rates, a building designed with gas boiler as its main heating system, with a large amount of renewable technology (case study 1) and super-insulated (case study 5) had the lowest and second lowest total life cycle cost, respectively.

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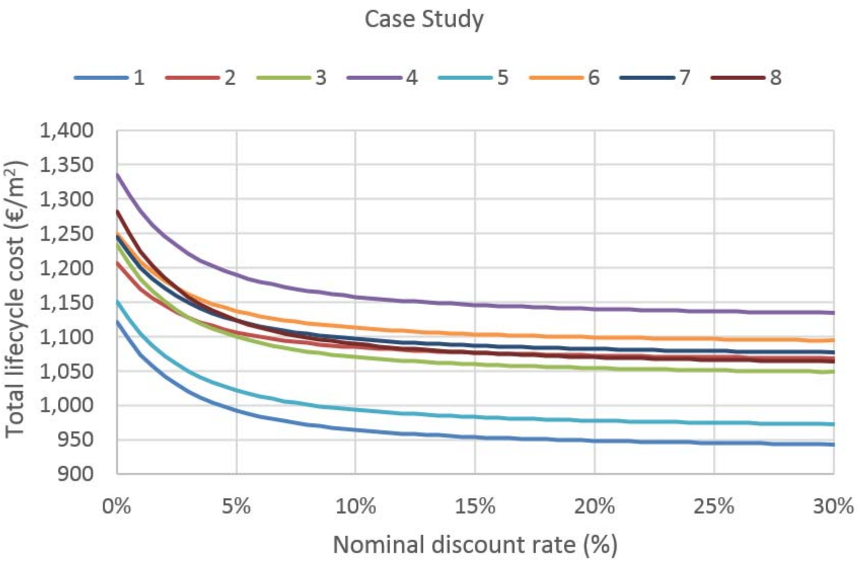

Figure 8: Relationship between the total life cycle cost and nominal discount rates for the investigated case study houses.

Figure 9 shows the equivalent annual cost (*EAC*) of constructing and operating the case study buildings at various discount rates, where the operation costs are based on primary energy usage only. As seen in Figure 9, similar to the PVA results, a building designed with gas boiler as its main heating system with a large amount of renewable technology (case study 1) and super-insulated (case study 5) had the lowest and second lowest EAC, respectively.

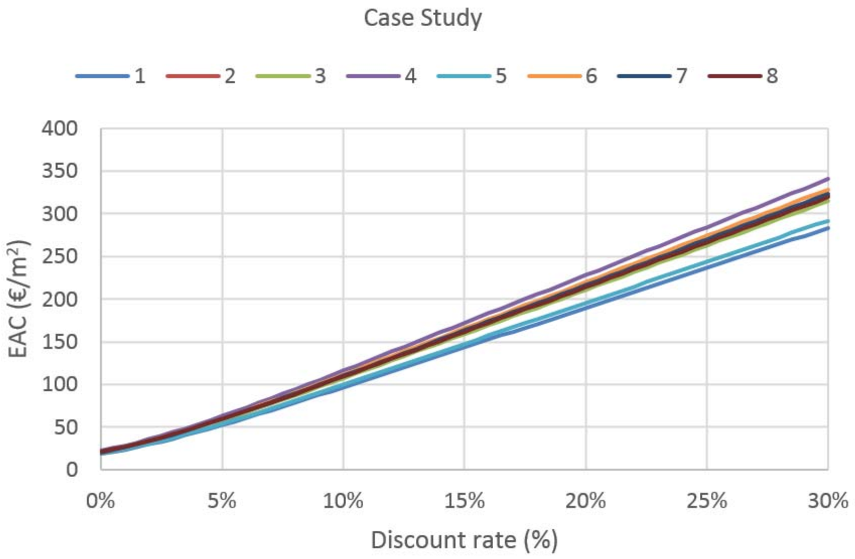

Figure 9: Equivalent annual cost (EAC) of constructing and operating the case study buildings at various discount rates (Note: operation costs are based on primary energy usage only).

4.4.3 Energy Costs

For the operational costs given previously (**Error! Reference source not found.**(c), Figure 5, Figure 8 and Figure 9), energy prices were assumed to remain constant throughout the buildings' lifespan. Table 6 compares the life cycle cost (LCC) of the eight case studies, based on a constant energy price (static pricing) and 0% discount rate, to that accounting for annual increases in energy price using the average annual growth rate in fuel energy prices (dynamic pricing). Prices for exporting electricity back onto the national electricity grid were assumed to remain at 2.5 c/MJ, in both the static and dynamic pricing scenarios [54].

Table 6: Difference in life cycle cost of case studies assuming an annual growth rate in energy prices

	Static Pricing				Dynamic Pricing			
Case Study	Electricity (€/yr.)	Gas (€/yr.)	Biomass (€/yr.)	Total (€/yr.)	Electricity (€/yr.)	Gas (€/yr.)	Biomass (€/yr.)	Total (€/yr.)
1	-93	394	31	332	-93	931	114	952
2	-124	0	382	258	-124	0	1394	1270
3	-136	450	31	345	-136	1063	114	1041
4	345	0	31	376	1033	0	114	1147
5	163	168	2	333	488	398	7	893
6	139	0	152	291	418	0	554	971
7	120	192	2	314	361	454	7	822
8	406	0	2	408	1219	0	7	1225
Average	102	301	79	332	396	712	289	1040
STDEV	208	142	132	47	519	335	481	160

As shown in Table 6, the case studies using a biomass boiler as their main heating source had the lowest annual cost over the building's life cycle with static pricing. However, with an assumed annual growth rate of 3.79% in wood pellet prices, these two case studies had the 1st and 4th highest annual cost over the buildings' life cycle. From the cost perspective, the two scenarios involving heat pumps (i.e. case study 4 and 8) remained among the worst options (i.e. ranked 6th and 7th out of 8), and the scenarios involving the condensing gas boilers (i.e. case studies 1 and 4) become the best options.

4.4.4 Life cycle cost optimal

Increasing energy prices had a significant impact on the hierarchy of case studies' life cycle economic costs (Figure 10). With dynamic pricing, three of the top four case studies (case study 5, 6 and 7) focused on having a super insulated building fabric and high air tightness performance. This was compared to the static pricing scenario

(Figure 5) where three of the top four case studies (case study 1, 2 and 3) focused on having a large amount of renewables installed. In the dynamic pricing scenario, the design with a gas boiler focusing on having a building fabric with high thermal and air tightness performance (case study 5) remained the cost optimal solution in addition to the design with a CHP and focusing on having a building fabric with high thermal and air tightness performance (case study 7)

By accounting for increasing efficiency to the electricity grid, the two case studies with heat pumps as their main heating source were the two optimum designs in terms of life cycle energy, but second and third worst designs in terms of life cycle cost (Figure 10). The case study designed with a gas fired CHP unit and a large installation of renewables (case study 3) was the worst design in terms of life cycle energy.

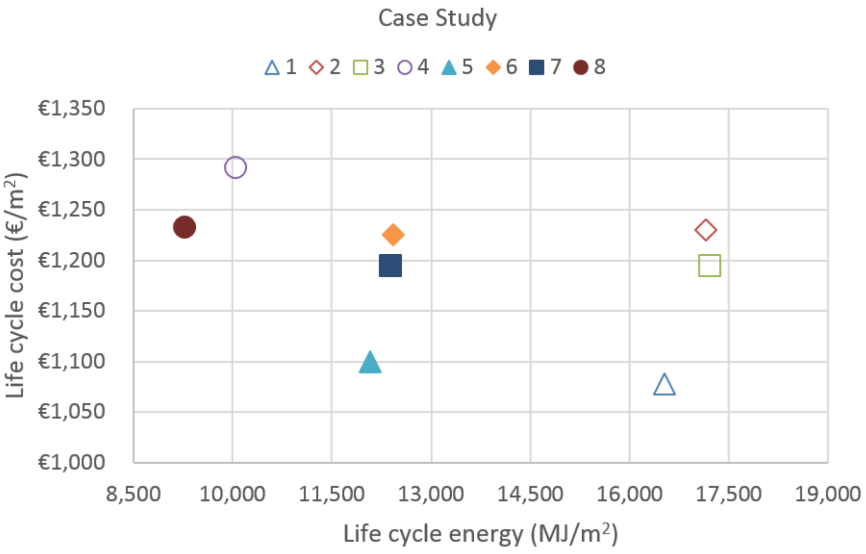

Figure 10: Life cycle cost, which accounts for increasing energy costs, versus life cycle energy, which accounts for increasing efficiency of the electricity grid, of the eight different designs

Accounting for both increasing energy costs and varying discount rates, the building designed with gas as the main heating system and a large amount of renewables installed (case study 1) and to be super-insulated (cased study 5) remained the best solutions in terms of PAV and EAC.

4.4.5 Sustainability Index Factor

Accounting for increasing energy prices, increasing electricity grid efficiency and grid decarbonisation, the SIF of the eight case studies are given in Table 7. The case study with the lowest SIF was case study 6. Based on the cost optimal methodology, case 5 and 7 were the best solutions. However, when using the SIF, which considered only one more category for evaluating the optimal solution, case study 5 is the 3rd best design and case study 7 is the 5th best design.

The super-insulated designs outperformed each of its renewable energy focused counterparts in terms of their respective SIF when increasing energy prices and increased electricity grid efficiency and decarbonisation was taken into account. Based on the three categories evaluated, buildings in a temperate oceanic climate (such as Ireland), should be designed to be super-insulated with minimum heating requirements and operate with heating systems that have a low impact on the natural environment, such as a biomass boiler or heat pump.

Table 7: SIF of the eight case studies accounting for increasing energy prices, increasing electricity grid efficiency and grid decarbonisation

	Economic		Environmental				Sustainability Index Factor	
Case Study	Life Cycle Cost		Life Cycle Energy		Life cycle GWP		SIF	
	Dynamic Pricing, Grid GWP and Primary Energy Impact						Static Pricing and Grid GWP Impact	Dynamic Pricing, Grid GWP and Primary Energy Impact
	€/m^2	Impact [-]	MJ/m^2	Impact [-]	kgCO$_{2e}$/m^2	Impact [-]	Impact [-]	Impact [-]
1	1885	0.91	16,651	0.62	1,052	0.70	0.99	1.11
2	2330	1.12	17,310	0.64	441	0.29	0.80	1.03
3	2079	1.00	17,381	0.64	1,099	0.73	1.01	1.19
4	2270	1.09	9,854	0.38	642	0.43	1.09	0.95
5	1855	0.89	11,997	0.45	792	0.53	1.02	0.94
6	2057	0.99	12,351	0.46	535	0.36	0.97	0.91
7	1889	0.91	12,324	0.46	813	0.54	1.05	0.96
8	2276	1.09	9,058	0.35	614	0.41	1.08	0.93
Average	2080	1.00	13365	0.50	748	0.50	1.00	1.00
STDEV	194	0.09	3324	0.12	236	0.16	0.09	0.10

5 Conclusions

One of the main requirements brought by the EU in the Energy Performance of Buildings Directive (EPBD) [4] was the introduction of nearly zero energy buildings (NZEB). A NZEB is a building with a very high energy performance. Starting from the end of 2020, all new buildings or those receiving significant retrofit must show a very high energy performance [4].

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The objective of this paper was to determine (for buildings in a temperate oceanic climate, such as Ireland) if it is better to design a NZEB to be a super-insulated building with minimum heating requirements, or to provide less insulation but install a large amount of renewable energy sources. The case studies involved in the analysis were assessed using two different methodologies to determine the best solutions. The first was the comparative framework methodology which is mandatory in all EU member states for calculating cost optimal levels of minimum energy performance requirements for buildings and building elements [39]. The second was a methodology termed the Sustainability Index Factor (SIF) that incorporates the commonly known three pillars of sustainability: environmental, social and economic. In the analyses of both methods, account was taken for varying discount rates, future de-carbonisation and improved efficiency of the electricity grid and future energy prices.

Based on the SIF methodology using static energy prices and electricity grid efficiency, NZEB buildings with a focus on renewable technology outperformed their super-insulated design counterparts. Assuming future electricity, gas and wood pellet energy prices would increase with an annual growth rate of 3.27%, 2.62% and 3.79%, respectively, in addition to an annual reduction rate of 4.2% and 2.3% in the GWP intensity and primary energy factor, both the cost optimal energy performance and SIF methodologies showed the super-insulated designs outperformed their renewable energy focused counterparts.

This was primarily due to the improved efficiency and decarbonisation of the electricity grid, and resulted in the energy and GWP savings associated with the MCPV installed on the buildings minimising overtime. This suggests that buildings should not be designed to be the exporters of electrical energy, in order to compensate for the use of other forms of energy during their operational phase. The results found that more focus should be placed on (i) minimising the space heating requirements through a building envelope with high thermal and air tightness performance and (ii) covering the remaining energy demand, to a very significant extent, by renewable sources that compensate for buildings' specific energy source during their operational phase.

However, the cost optimal energy performance and SIF results showed different optimum design solutions. The cost optimal results suggested that the super-insulated buildings with a gas boiler (case study 5) and with a CHP (case study 7) were the cost optimal designs. The SIF results showed the super-insulated buildings with a biomass boiler (case study 6) and a heat pump (case study 8) to have the lowest SIF due to evaluating another category in its assessment, GWP. There is a need for a more robust assessment methodology for evaluating the sustainability of residential buildings, rather than relying on the cost optimal level based on energy performance. There are many tools already established across Europe for evaluating the sustainability of a building using economic, social and economic indicators, e.g. HQM [41], DNGB Certificate System [42], LiderA [42], SBTool [42] and HQE [42]. However, there is a need for a framework to develop a tool for assessing the sustainability of a building using common categories for cross comparison in EU countries. However, further categories could be included for the sustainability evaluation depending on the specific circumstances of the building itself. The SIF methodology used in this paper, can be used for assessing the SIF impact of a set of buildings which are representative of a countries national building stock for a number of economic, social and environmental categories.

The hierarchy of the life cycle cost results were dependent on the assumptions made with regards to the annual increase of energy costs. However, predicting future energy prices was difficult due to numerous variables that impacted those prices. For instance, a report from the Sustainable Energy Authority of Ireland had predicted a range of scenarios for the trade price of wood pellets across the EU from 2010 to 2030 [85]. From 2010 to 2015, the average EU annual growth rate had been predicted to fall by 4.61% annually. However, in reality, the average annual price of wood pellets in Ireland increased at a growth rate of 5.68% annually for the same period [52]. Thusm the life cycle cost of each of the case studies may vary significantly in the future, compared to what the results suggested here, and may have a big impact in terms of the hierarchy of which case study would be the cost optimal and have the lowest SIF. Particularly with the electricity. 2015 Irish residential energy prices [52] used in this study showed electricity, gas and wood pellet prices to be 5.77 c/MJ, 1.83 c/MJ and 1.47 c/MJ, respectively. This shows the cost of gas and wood pellets to be 32% and 25% that of electricity. If the difference in these prices was to reduce overtime, heat pumps would become a more cost effective solution, given their high efficiencies.

The SIF results showed the super-insulated building with a biomass boiler (case study 6) to have the lowest SIF. This is despite the biomass boiler having the lowest operational efficiency (82.7%) of the four heating systems employed.

Based on the three categories evaluated (life cycle cost, life cycle energy and life cycle GWP) using the SIF methodology and accounting for increasing energy prices and increasing electricity grid efficiency, heating systems that have a low impact on the natural environment, such as a biomass boiler or heat pump, should be installed in NZEB buildings in Ireland. If the difference between the price of electricity per kWh in comparison to the price of gas and wood pellets per kWh can be reduced and more efficient biomass boilers are installed in

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residential buildings, heat pumps and biomass boilers would become a more sustainable heating system solution for NZEB residential buildings

The emergence of the environmental impact of building materials and products (e.g. their embodied energy (EE) and embodied carbon or GWP (EC) as a dominant construction design variable) is vividly noticeable as buildings move towards the NZEB standard. The life cycle EE and EC ranged from 30% to 33% and from 41% to 100%, respectively, for the eight case studies presented in this article (assuming static GWP intensity and primary energy factors for the lifespan of the case study buildings). Accounting for grid decarbonisation and increased efficiency, the life cycle EE and EC ranged from 27% to 44% and from 43% to 100%, respectively, for the eight case studies presented. Thus, the importance of a designer's role in sustainably selecting appropriate 'green' materials is highly stressed.

In summary, the results of this research suggest that:

- For designing a residential semi-detached NZEB, more focus should be placed on (i) minimising the space heating requirements through a building envelope with high thermal and air tightness performance, and (ii) covering the remaining energy demand, to a very significant extent, by renewable sources that compensate for buildings' specific energy source during their operational phase.
- Based on the three categories evaluated (life cycle cost, life cycle energy and life cycle GWP) using the SIF methodology and accounting for increasing energy prices and increasing electricity grid efficiency, heating systems that have a low impact on the natural environment, such as a biomass boiler or heat pump, should be installed in NZEB buildings in Ireland.
- There is a need for a more robust assessment methodology for evaluating the sustainability of a residential building, rather than relying on the cost optimal level based on energy performance. The SIF methodology used in this paper, can be used for assessing the SIF impact of a set of buildings which are representative of a countries national building stock for a number of economic, social and environmental categories.
- The embodied energy and embodied carbon of a residential NZEB, which consider the impacts associated with the materials production of building's life cycle, can account for up to 44% and 100% of its life

cycle energy and GWP impacts, respectively. Thus, the importance of a designer's role in sustainably selecting appropriate 'green' materials is highly stressed.

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Appendix A

Material	EE Intensity (MJ/kg)	EC Intensity (kgCO$_{2e}$/kg)	Source

Please cite: Moran, P., Goggins, J. & Hajdukiewicz, M., 2017. Super-insulate or use renewable technology? Life cycle cost, energy and global warming potential analysis of nearly zero energy buildings (NZEB) in a temperate oceanic climate. *Energy and Buildings*, 139(2017), pp.590–607. Available at: http://dx.doi.org/10.1016/j.enbuild.2017.01.029.

Aggregate	0.083	0.0052	[48]
Aluminium Coil	155	9.18	[48]
Cast Aluminium	159	3.1	[48]
Concrete Block 10 MPa	0.67	0.078	[48]
Copper	57	3.81	[48]
Cotton	30.66	3.28	[86]
Evacuated Tube Solar Collectors* (per m^2)	1689.2	111.6	[76]
Expanded Polystyrene	88.6	3.29	[48]
Fibre Cement Panel	10.4	1.09	[48]
Fibreglass	28	1.35	[48]
General Concrete	0.75	0.107	[48]
General Plastic	80.5	3.31	[48]
General Purpose Polystyrene	86.4	3.43	[48]
Glass Fibre	44.4	2.64	[86]
High Density Polyethylene	76.7	1.93	[48]
Iron	25	2.03	[48]
Lead	25.2	1.67	[48]
Low Density Polyethylene	78.1	2.08	[48]
Low Density Polyethylene Film	89.3	2.6	[48]
Mastic Sealant-Synthetic Rubber	91	2.85	[48]
Mineral Wool	16.6	1.28	[48]
Mortar (1:1:6 Cement:Lime:Sand mix)	1.11	0.174	[48]
Mortar (1:3 Cement:Sand mix)	1.33	0.22	[48]
Multi-crystalline Photovoltaics* (per m^2)	3908.9	553.8	[75]
Nickel Pigment Coating	85	5.63	[86]
Nylon 6	120.5	9.14	[48]
Oriented Strand Board	15	0.45	[48]
Paint (Double Coat)	21	0.87	[48]
Paint (Triple Coat)	31.5	1.31	[48]
Plaster	1.8	0.13	[48]
Plasterboard	6.75	0.39	[48]
Plywood	15	0.45	[48]
Polyethylene	83.1	2.54	[48]
Polyisocyanurate	55.11	2.48	[87]
Polypropylene Orientated Film	99.2	3.43	[48]
Polyurethane Rigid Foam	101.5	4.26	[48]
Precast Concrete (32/40 MPa)	1.48	0.19	[48]
Precast Concrete (40/50 MPa)	1.5	0.18	[48]
Precast Concrete (8/10 MPa)	1.15	0.13	[48]
Primary Glass	15	0.91	[48]
PVC General	77.2	3.1	[48]
PVC Pipe	67.5	3.23	[48]
Rockwool	16.8	1.12	[48]

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Sand	0.0081	0.0051	[48]
Sawn Hardwood	10.4	0.24	[48]
Sawn Softwood	7.4	0.2	[48]
Stainless Steel	56.7	6.15	[48]
Steel	20.1	1.46	[48]
Steel Bar	17.4	1.4	[48]
Steel Section	21.5	1.53	[48]
Steel Wire	36	3.02	[48]
UPVC Film	69.4	3.16	[48]
Vinyl Flooring	65.64	2.29	[48]
Vitrified Clay Pipe DN 100 & DN 150	6.2	0.46	[48]

Acronyms and symbols

a= Weighting Factor for Economic Indicator of Sustainability Index Factor
AAHP= Air-to-Air Heat Pump
AP= Apartment
AWHP= Air-to-water heat pump
b= Weighting Factor for Social Indicator of Sustainability Index Factor
BER=Building Energy Rating
BD= Bedroom
BR= Building Regulations
c= Weighting Factor for Environmental Indicator of Sustainability Index Factor
C= Embodied Carbon Intensity of a Material
C_c= Carbon Cost due to Annual OC Emissions (€)
CDD= Cooling Degree Days
CLT= Cross Laminated Timber
CGB= Condensing Gas Boiler
CHP= Combined Heat and Power
CON= Concrete
DEAP= Dwelling Energy Assessment Procedure
DH= District Heating
DGNB=Deutsche Gesellschaft für Nachhaltiges Bauen (German Sustainable Building Council)
EAC= Equivalent Annual Cost (€/year)
EAHP= Exhaust Air Heat Pump
E= Embodied Energy Intensity of a Material (MJ/kg)
EC= Embodied Global Warming Potential (kgCO$_2$,eq)
$eco_{m,n}$ = impact of economic category m for case study n
ECO_j = economic impact of case study j
EE= Embodied Energy (MJ)
$env_{m,n}$ = impact of environmental category m for case study n
ENV_j = environmental impact of case study j
EPBD= Energy Performance Building Directive
ETSC= Evacuated Tube Solar Collectors
EU = European Union
F= Delivered energy per heated floor area per year of a fuel type (MJ/m^2/year)
GB= Gas Boiler
GHG= Greenhouse Gas
GHP= Ground Heat Pump
GSHP= Ground Source Heat Pump
GWP= Global Warming Potential (kgCO$_2$,eq)
HDD= Heating Degree Days (days)

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HP= Heat Pump
HQE= High Quality Environmental Standard
HQM= Home Quality Mark
i = year
ICE= Inventory of Carbon and Energy
IDEM= Irish Dispatch of Electricity Model
j = heating system
k= sum of the weightings a, b and c
LCA= Life Cycle Assessment
LCC= Life Cycle Cost (€)
LEH= Low Energy House
LiderA= Leading the Environment for Sustainable Construction
LPG= Liquefied Petroleum Gas
m = category number
MCPV= Multi-crystalline Photovoltaics
MV= Mechanical Ventilation
MVHR= Mechanical Ventilation with Heat Recovery
n = case study number
NCC= Net Construction Costs (€)
NEEAP= National Energy Efficiency Action Plan
NREAP= National Renewable Energy Action Plan
NZEB= Nearly Zero Energy Building
OC= Operational Global Warming Potential (kgCO$_2$,eq/m^2/year)
OE= Operational Energy (MJ/m^2/year)
OEC= Operational Energy Costs (€)
p= number of case studies
PC= Primary Global Warming Potential Conversion Factor
PE= Primary Energy Conversion Factor
PH= Passive House
PR= Passive Regulations
PV= Photovoltaics
PVA= Present Value of Annuity (€)
q = number of categories
ρ = Density (kg/m^3)
r = discount rate (%)
R_d= Discount factor
SBTool= Sustainability Assesment Tool
SC= Solar Collectors
SD= Semi-Detached
SEAI= Sustainable Energy Authority of Ireland
SFH= Single Family House
SIF= Sustainability Index Factor
$soc_{m,n}$ = impact of social category m for case study n
SOC_j = social impact of case study j
STE= Steel
t = number of years from the starting period (years)
TH= Terraced House
TIM= Timber
VAT= Value Added Tax (%)
V= Volume (m^3)
V_f = the residual value of heating system (€)
w= weighting applied for each category for the indicators of the SIF
WD= Wood
Y= Lifespan (years)