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Achieving net zero life cycle primary energy and greenhouse gas emissions apartment buildings in a Mediterranean climate

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Abstract

The operation of buildings alone represents 30-40% of the total energy use and associated greenhouse gas emissions, globally. Efforts to reduce operational energy use have significantly driven energy efficiency levels, reaching so-called 'Net Zero Energy Buildings'. However, NZEBs do not consider the increased embodied energy and greenhouse gas emissions of building materials which are needed to achieve that performance.

The aim of this paper is to evaluate the feasibility of achieving net zero life cycle primary energy and greenhouse gas emissions (NZLCPEGHG) buildings. We use a case study apartment building in Sehaileh, Lebanon and conduct a life cycle cost, energy and greenhouse gas emissions analysis over 50 years of a business-as-usual building and its NZLCPEGHG counterpart. We rely on the systemically complete hybrid analysis technique to quantify embodied energy and greenhouse gas emissions and conduct a broad sensitivity analysis. Life cycle costs are quantified using the net present value technique.

Results show that a 6.5 kW_p solar photovoltaic array, combined with solar hot water, an improved operational energy efficiency, an all-electric operational energy demand, and a reduced embodied energy, can achieve a NZLCPEGHG apartment unit (154 m^2, 4 occupants) in a four-storey building, over 50 years. Battery storage is the most critical parameter regarding life cycle cost, swinging the net present value of the building from -46 to +47 USD2020/(m^2-of-gross-floor-area) over 50 years, with and without batteries, respectively. The greenhouse gas emissions factor of the electricity grid is the most critical parameter that affects achieving a NZLCPEGHG building, with cleaner grids making it harder to displace embodied greenhouse gas emissions. In light of these results and the sensitivity analysis, we provide a range of research, technical and policy-related recommendations to improve the life cycle environmental performance of buildings and help mitigate catastrophic climate change.

Keywords: Life cycle greenhouse gas emissions analysis; Life cycle cost analysis; Energy efficiency; Photovoltaic; Zero carbon; Residential buildings; Lebanon

1 Introduction

Greenhouse gas emissions from human activity is destabilising the climate of the Earth by intensifying the greenhouse effect and disturbing the water cycle [1, 2]. The operation of buildings alone is responsible for a third of final energy use [3] and associated greenhouse gas emissions, globally. This has been a driver for improving the operational energy efficiency of buildings (e.g. Energy Performance of Buildings Directive [4] or Passive House [5]), down to net zero energy buildings and positive energy buildings, which produce more energy than what they use for their operation [6]. However, improving the operational energy efficiency of buildings typically requires additional materials and insulation (depending on the climate) and thus, additional energy and greenhouse gas emissions to produce these materials, i.e. embodied energy and greenhouse gas emissions [7-11]. To date, very few studies have evaluated the feasibility of achieving net zero life cycle primary energy [12] and greenhouse gas emissions buildings, while quantifying the associated life cycle cost premium. If we are to effectively improve the environmental performance of buildings, we need to reduce their net life cycle greenhouse gas emissions to zero, and even further. With the continuing population growth [13] and the need for more compact housing [14, 15], achieving net zero life cycle energy and greenhouse gas emissions apartment buildings is critical. It is equally challenging, given the smaller useful area per inhabitant to install local renewable energy generation compared to other housing typologies.

1.1 Aim and scope

The aim of this study is to evaluate the feasibility of achieving net zero life cycle energy and greenhouse gas emissions apartment buildings in a Mediterranean climate and quantify the associated life cycle cost. This is complemented by a thorough sensitivity analysis that varies the main environmental and financial parameters to test the robustness of the findings.

This study is a further addition to the previous work of the authors [16, 17] on a representative case study apartment building located in Sehaileh, Lebanon (see Section 3.2). Previous studies had established a benchmark life cycle energy use, including embodied, operational and user-transport requirements, as well as evaluated different measures to reduce these. The scope of this study is presented in Figure 1 below, in light of the existing studies. It includes quantifying the life cycle embodied and operational energy and greenhouse gas emissions of a representative case study building as well as its net zero life cycle energy and greenhouse gas emissions counterpart. Energy use (and associated greenhouse gas emissions) for the mobility of occupants (user-transport) and for the construction of nearby roads and infrastructure is not considered in this paper. The life cycle stages A1-A5 and B1, B5 and B6, according to the European Standard 15978 [18] are included in the scope of this paper. This goes beyond the ‘Net Zero Carbon Buildings’ definition proposed by the UKGBC [19], which does not include the replacement and maintenance of construction materials. The embodied and operational energy and greenhouse gas emissions are first reduced through a series of measures. The remaining embodied and operational energy use and greenhouse gas emissions are covered and displaced, respectively, by generating photovoltaic energy and selling it on the grid.

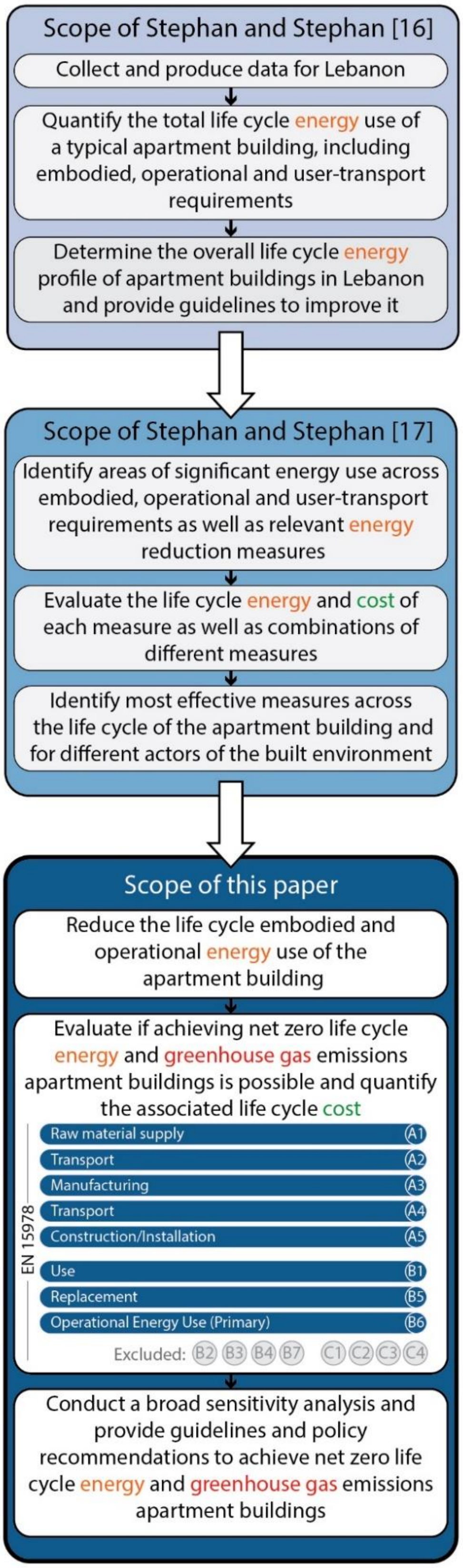

Figure 1: Scope of this study

2 Existing studies evaluating the feasibility of achieving net zero life cycle energy and greenhouse gas emissions buildings

The dominant majority of existing studies focuses on net zero operational energy and/or greenhouse gas emissions (e.g. [6, 20-25]). Very few studies have attempted to achieve net zero life cycle primary energy (as defined by Hernandez and Kenny [12]) and/or greenhouse gas emissions buildings). Crawford [26] modelled a net zero life cycle primary energy detached house (270.8 m^2 residence + 36.9m^2 garage) in Melbourne, Australia. He found that to achieve a net zero life cycle embodied and operational energy house, a solar photovoltaic array of 14.9 kW_p was needed, which would result in 125 m^2 of panels in 2010 (~12% efficiency) and in 74.5 m^2 of panels assuming a 20% efficiency in 2020. Crawford [26] used a hybrid life cycle inventory in evaluating embodied energy, which provides more comprehensive system boundaries compared to process analysis (see Section 3.4 for more details). This Australian study demonstrates the challenge of achieving this target even when using a detached house typology, which provides the largest roof area per capita in order to achieve net zero life cycle energy use. The study did not consider the financial cost.

More recently, and in one of the advanced studies of this type, Birge and Berger [27] quantified the life cycle greenhouse gas emissions associated with villas in the United Arab Emirates, including embodied, operational and mobility requirements, as advocated for by [28]. Birge and Berger [27] found that it was possible to achieve net zero life cycle greenhouse gas emissions villas in Abu Dhabi. Their most effective scenario relied on reducing the house size (see [14, 15] for additional research on this topic), adding insulation, electrifying the operational energy demand and using efficient appliances, using water sources with a reduced energy intensity, using electric cars and planting 3-10 trees per villa to sequestrate remaining greenhouse gas emissions over the life of the trees (note that the baseline business as usual scenario required to plant 1 747- 6 116 trees to offset life cycle greenhouse gas emissions). However, as in Crawford [26], their study relied on the detached house typology and did not attempt to consider more challenging typologies such as apartment buildings. Furthermore, the life cycle inventory technique that they used is process analysis, which is known to underestimate embodied energy and greenhouse gas emissions, as compared to hybrid analysis (see Section 3.4 for more details). Moreover, their study did not consider the cost implications of achieving this level of performance.

In their recent paper, Satola *et al.* [29] evaluate the potential to achieve zero life cycle energy and greenhouse gas emissions for detached houses in Sydney, Atlanta, Shanghai and New Delhi. Their results find that this is possible for the house in Sydney, using a 6 kW_p system, but not in the other cities where they achieved either a net zero operational energy and greenhouse gas emissions house (Atlanta), or just a low energy house (New Delhi and Shanghai). However, their study also relies on process data which underestimates embodied energy and greenhouse gas emissions (the house in Sydney has an annualised life cycle embodied greenhouse gas emissions intensity per unit of gross floor area of ~19 $kgCO_2e/(m^2 \cdot a)$ compared to ~27 $kgCO_2e/(m^2 \cdot a)$ in this study which uses Australian data, see Section 4). As in the studies mentioned above, they also use a detached house as a case study, with plenty of roof area to cover energy use and displace greenhouse gas emissions. Other studies, such as Goggins *et al.* [9], Cellura *et al.* [10] study investigate the embodied energy of zero operational energy houses, but do not attempt to cover the embodied energy nor displace or offset embodied greenhouse gas emissions.

This brief review of the literature, which is by no means exhaustive, demonstrates the need to better understand the feasibility of achieving zero life cycle primary energy and greenhouse gas emissions apartment buildings and quantifying the associated life cycle cost. The method used to address this gap is presented below.

3 Method

The section describes the research method, the case study building, the measures used to reach a net zero life cycle energy and greenhouse gas emissions performance and the quantification algorithms used for energy, greenhouse gas emissions and cost.

3.1 Overall research strategy

Figure 2 depicts the overall research strategy. The research relies on a case study approach, using the same case study building as previously (see Section 3.2 for a justification of the approach and details on the case study building). The bill of material quantities and the operational life cycle energy demand are taken from the previous research conducted by the authors in [16] and [17]. These are used to quantify the life cycle embodied energy and greenhouse gas (GHG) emissions of the base case apartment building and its life cycle operational energy use and GHG emissions, respectively. Combining the two provides the life cycle energy and GHG emissions profile of the base case apartment building, as a benchmark to compare against. A range of life cycle energy and GHG emissions reduction measures, adapted from [17] are applied to the base case to improve its life cycle energy and GHG emissions profile. Photovoltaic panels are then installed on the building to cover the remaining life cycle energy use and displace GHG emissions. The difference in life cycle cost between the base case apartment building and the resulting net zero life cycle primary energy and GHG emissions apartment building is then calculated. A broad sensitivity analysis, including environmental, built environment and financial parameters, is conducted to broaden the applicability of the results and identify critical parameters.

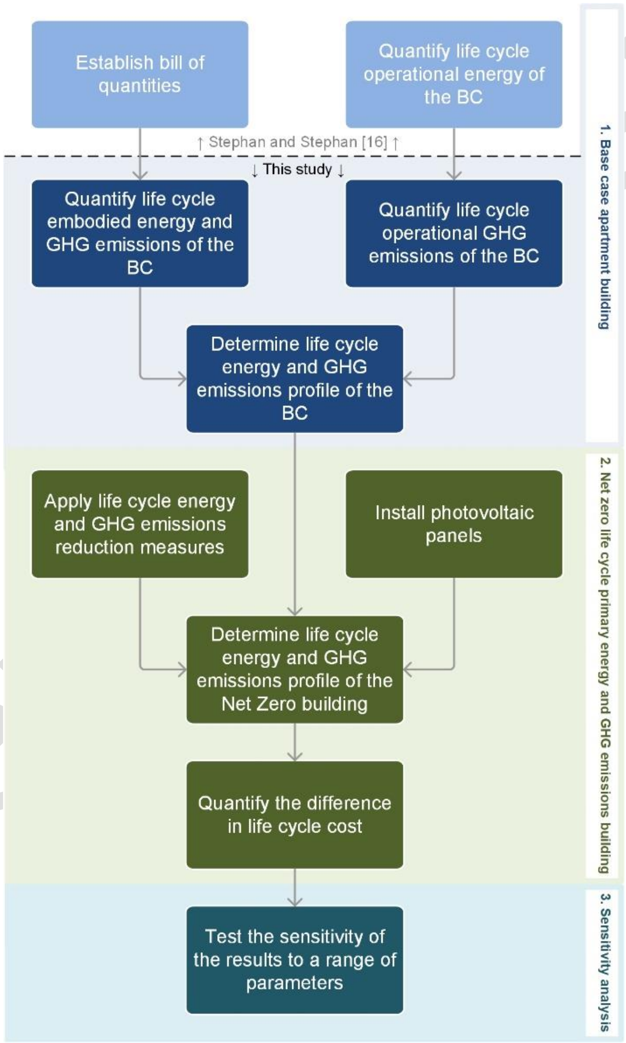

Figure 2: Overall research strategy. Note: BC = Base Case, GHG = Greenhouse gas.

3.2 Case study apartment building

This paper uses a single case study approach as its main research method. The system that is studied (the life cycle cost, energy use and greenhouse gas emissions of an apartment building in a

Mediterranean climate) is common but data is lacking in a Lebanese context, making the case study critical and exploratory, as described by Yin [30]. In addition, the focus of the study is novel and there are no existing datasets with consistent and structured information on a large sample of the population (i.e. zero life cycle primary energy and greenhouse gas emissions buildings) that can be used. The single case study needs to be representative of the population to maximise the external validity (extrapolation) of the results [30, 31]. The case study building is highly representative of recent Lebanese apartment buildings, as demonstrated in Stephan and Stephan [16]. We also use the same building as in the [16, 17] for consistency.

The case study is a four-storey apartment building built in 2008, and located in Sehaileh, Lebanon in the Mount-Lebanon ranges, 25 km North of the capital Beirut, at 515 m above sea level. The building has a South orientation and two apartments per storey (eight in total), of 154 m^2 gross floor area and 113 m^2 of usable floor area (see Figure 2) each. It accommodates 32 occupants in total (four in each apartment). The roof has central flat area and two slopes to the East and West. Sloped areas represent 190 m^2 while the central flat area covers 76 m^2. The building has a reinforced concrete structure with cast *in situ* reinforced concrete slabs that use hollow core concrete blocks. Outer walls are made of concrete blocks (2×100 mm) with an air blade (100 mm) and are clad with natural stone as per local regulation. Double-glazed windows with aluminium frames and external aluminium roller sunshades are installed. Ceramic floor tiling is used in all rooms. Each unit is heated through a central gas heating system (efficiency of 95%) and cooled with air conditioning units (COP of 2.5). More detailed information about the case study building, including façade details, bill of material quantities, energy modelling and others can be found in Stephan and Stephan [16]. We sourced all the information on the building directly from the construction company [32], resulting in reliable data for many significant variables such as the bill of material quantities, building systems installed and their efficiency. Table 1 summarises the main characteristics of the base case study building.

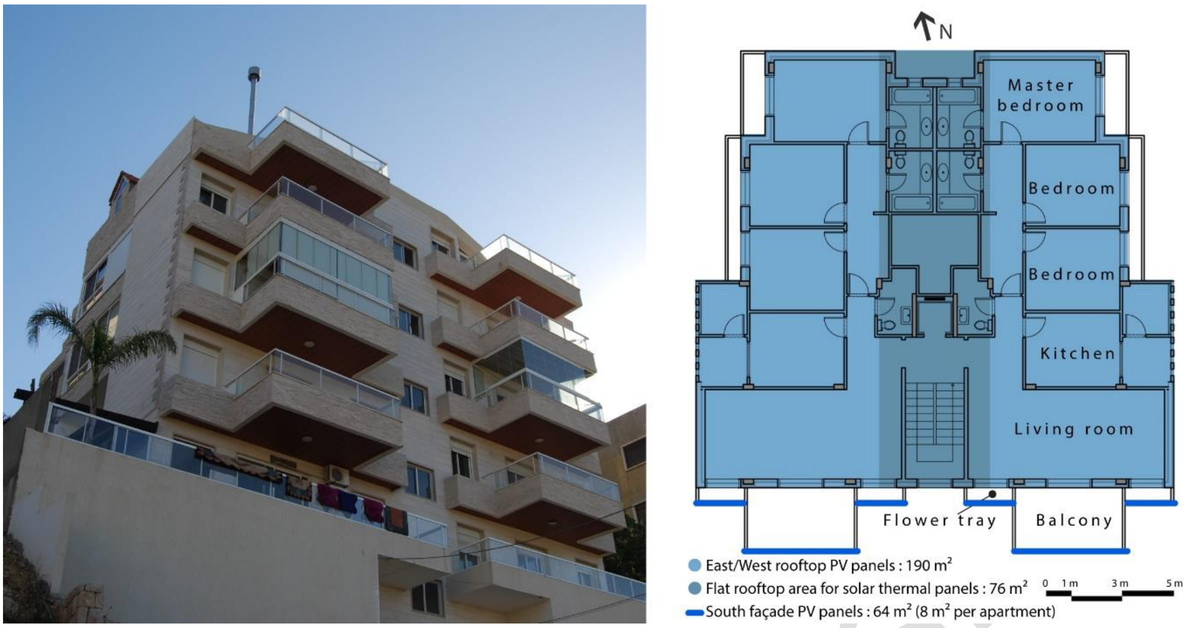

Figure 3: South elevation and floor plan of case study apartment building in Sehaileh, Lebanon. Note: PV = photovoltaic. Areas and floor plan based on Technical Enterprises Co. [32].

Table 1: Main characteristics of the case study apartment building in Sehaileh, Lebanon.

Characteristic	Value
Building useful life	50 years
Gross floor area per apartment	154 m²
Useful floor area per apartment	113 m²
Useful flat roof area for solar hot water panels	76 m² (tilt=30°, azimuth=0°)
Useful roof area for photovoltaic panels	95 m² East-facing (tilt=18°, azimuth=90°) 95 m² West-facing (tilt=18°, azimuth=-90°)
Useful south façade area for photovoltaic panels	64 m² (tilt=90°, azimuth=0°)
Number of apartments	8
Number of occupants per apartment	4
Structure type	Reinforced concrete
Façade	Double concrete block wall, 100 mm air blade, Double glazed aluminium framed windows
Slabs	Hollow concrete blocks with cast in-situ reinforced concrete slab
Roof	Hollow concrete blocks with cast in-situ reinforced concrete slab, Terracotta tiles

Characteristic	Value
Finishes	Medium standard: Ceramic tiles and skirting – Floor to ceiling wall tiling in WC and kitchen – Water-based paint
Operational energy sources	Gas heating (efficiency = 95%) and cooking (efficiency = 90%); Electrical cooling with a heat pump (COP[a] = 2.5); Electric domestic hot water system (efficiency = 100%)
Primary energy conversion factors ($GJ^{PRIMARY}/GJ^{DELIVERED}$)b	Electricity: 3.8, Gas: 1.1
Greenhouse gas emissions factors ($kgCO_2e/GJ^{PRIMARY}$)c	Electricity (Heavy Fuel Oil 75%; Diesel 25%): 72.2225, Gas: 60.2 $kgCO_2e/GJ^{PRIMARY}$

Note: See Stephan and Stephan [16] for details on all the values in the table, except emissions factors

[a]COP = Coefficient of performance

[b]Based on calculations in [16], Appendix B.

[c]Based on emissions factors from [33], the emissions factor for electricity is based on a 75% and 25% generation from the state-owned heavy fuel oil power plants and the privately owned diesel generators, respectively. See Appendix A for details.

The overall life cycle energy demand of the case study building was evaluated in Stephan and Stephan [16] and [17] but the numbers for embodied energy are revised in this study and complemented with life cycle greenhouse gas emissions figures, using the most recent embodied energy and greenhouse gas emissions material coefficients from the EPiC database [34] (see Section 3.4).

3.3 Achieving zero life cycle primary energy and greenhouse gas emissions

The top contributors to the life cycle embodied and operational primary energy demand of the base case are electrical operational end-uses (notably domestic hot water), heating and concrete and steel that represent most of the embodied energy demand. In this study, we do not try to radically modify the floor plan of the apartment building, nor its construction materials. This enables us to maintain the same functional unit and maximise comparability, yet it prevents us from exploring more innovative measures, such as using structural timber, which is further discussed in Section 5.7. This implies that the main energy and GHG emissions reduction measures target operational energy use.

The measures to reduce operational energy and GHG emissions include adding expanded polystyrene insulation (100mm) in the outer walls and roof, installing a 5m² solar thermal collector (vacuum tube) for each apartment, replacing all lighting with light emitting diodes (LED), replacing all electrical appliances with energy efficient versions (European class A+++), replacing air conditioning split systems with a more energy efficient version (CoP of 5.9 instead of 2.5), removing the radiative heating system to use the air conditioning for heating instead. The measures to reduce embodied energy and GHG emissions include removing the internal partition wall between the kitchen and the living room (19.43m²) and replacing all ceramic tiles with stamped concrete. In addition, the central shaft of the building is slightly enlarged and replaced by an atrium to improve natural lighting. The remaining life cycle energy use and GHG emissions are displaced through the installation of photovoltaic panels on the roof and the South façade, totalling ~6.5 kW_p for each apartment.

This paper focuses on the overall energy and GHG emissions performance resulting from the combination of all these measures. The measures are not studied individually.

Table A.1, Appendix B details all measures, including assumptions and data pertaining to life cycle energy, greenhouse gas emissions and cost calculations, as well as their net (individual) effect on the life cycle energy, GHG emissions and cost balance of each apartment. Data from [16, 35, 36] are used in designing the measures.

3.4 Quantifying life cycle embodied primary energy and greenhouse gas emissions

There are three main approaches that can be used to quantify the embodied environmental flows, including energy and greenhouse gas emissions, of products and services, including construction materials. These three approaches are process analysis, input-output analysis and hybrid analysis. Process analysis is the most widely used approach when it comes to construction materials. It is a bottom-up approach that consists of collecting industrial data on the processes involved across the supply chain of a construction material [37]. For each process, inputs and outputs are quantified, such as energy and greenhouse gas emissions. As such, process analysis is very time-consuming but usually relies on the most specific and accurate data. The downside is known as the truncation error [38, 39], as it is practically impossible to collect data on every single process in a supply chain. The excluded processes are assumed not to contribute in any way which can underestimate the embodied energy and/or greenhouse gas emissions of a building by factors of 2.5-4 [40, 41]. The recently published EPiC database [34] shows an average truncation error of ~60% across 131 different building materials. In other words, more than 60% of the environmental effects are not accounted for in the process data, which includes almost 5 000 processes.

Input-output analysis is a macroeconomic top-down approach that accounts for financial transactions across different sectors of the economy [42]. By combining such data with environmental accounts, environmentally-extended input-output analysis [43] enables quantifying the total embodied environmental flows, e.g. energy and greenhouse gas emissions, of any service or product in the economy, across its supply chain. However, this comprehensiveness comes at the price of accuracy, as dozens, at best a few hundreds, of sectors are used to model an entire economy. Input-output analysis is comprehensive but unreliable for specific products [44].

Hybrid analysis combines both process and input-output analysis to try and mitigate their negative effects [45]. It uses the more accurate process data where available, and the more aggregated input-output data to fill gaps in the supply chain. The result is a more comprehensive system boundary that relies on the most accurate data available [46].

In light of the above, we use an input-output based hybrid analysis (see [45] for a detailed description of hybrid life cycle inventory techniques) to quantify embodied energy and greenhouse gas emissions. More specifically, we use the Australian EPiC database of embodied environmental flows [34] and complement that with Australian input-output data to cover remaining supply chain gaps. We decided to use the EPiC database because it is the only readily available database of hybrid embodied environmental flows coefficients, globally. Moreover, and as demonstrated in Stephan and Stephan [16], more than 35% of the embodied energy of the case study apartment building is due to materials produced outside Lebanon, and in multiple geographic regions. This means that in the absence of a global multi-regional hybrid embodied environmental flows database, it is very hard to accurately estimate the embodied energy and greenhouse emissions of Lebanese apartment buildings. We adopt a safe approach, using the database with the broadest system boundaries, and ensuring that the embodied energy and greenhouse gas emissions are not underestimated as in most existing studies. This makes it harder to achieve a net zero life cycle primary energy and greenhouse gas emissions building.

The EPiC database combines bottom-up process data with top-down macroeconomic environmentally extended input-output data to fill supply chain gaps. It is based on the path-exchange method for hybrid analysis [47] and uses an automated approach to streamline the path exchange [48]. The database is consistent and transparent: the background data for all materials are available on Figshare. The recurrent embodied energy and GHG emissions associated with the replacement of building materials over the period of analysis of 50 years is also taken into account. Average material service lives are sourced from Ding [49] and NAHB [50].

Eq. 1 below is used to quantify the life cycle embodied energy and GHG emissions of the building. We used the model developed by Stephan [51] and updated with the EPiC database. This model uses embodied environmental flows coefficients at the material level (e.g. glass), combines them into construction assemblies (e.g. double-glazed windows) and multiplies these intensities by the quantities of assemblies in the building. The sum of embodied energy and GHG emissions of all assemblies is complemented by a so-called 'input-output remainder' that covers remaining gaps in the supply chain.

$$\mathrm{LCEF_b} = \overbrace{\sum_{a=1}^{A}\sum_{m=1}^{M}\left(Q_{m,a,b} \times FC_m\right) + \left(TFRBS - \sum_{m=1}^{M} TER_m\right) \times C_b}^{Initial\ embodied\ flow}$$
$$+ \underbrace{\sum_{a=1}^{A}\sum_{m=1}^{M}\left[\left[\frac{POA}{SL_{m,a}} - 1\right] \times \left(Q_{m,a,b} \times FC_m\right) + \left(TFRBS - TFR_m - NATFR_m\right) \times C_{m,a,b}\right]}_{Recurrent\ embodied\ flow}$$

Eq.1

Where: $LCEF_b$ is the life cycle embodied flow of the building in flow unit (e.g. GJ for energy); *A* is the total number of assemblies in the building; *M* is the total number of materials in the element *e* or the assembly *a*; $Q_{m,a,b}$ is the quantity of material *m* in the assembly *a* in the building *b* (e.g. kilogrammes of steel); FC_m is the hybrid embodied environmental flow coefficient of material *m* in flow unit per functional unit of material (e.g. GJ/kg); *TFRBS* is the total flow requirement of the input-output sector associated with the residential building sector, in flow unit/current unit; TFR_m is the total flow requirement of the input-output pathway representing material *m*, in flow unit/currency unit; C_b is the cost of the building *b* in currency unit; *POA* is the period of analysis in years, e.g. 50 years; $SL_{m,a}$ is the service life of the material *m* as used in assembly *a,* in years; $NATFR_m$ is the total flow requirement of all input-output pathways not associated with the installation or production process of material *m* being replaced, in flow unit/currency unit, e.g. pathways representing concrete production when replacing aluminium window frames; and $C_{m,a,b}$ is the cost of the material *m* used in assembly *a*, in building *b,* in currency unit.

3.5 Quantifying life cycle operational primary energy and greenhouse gas emissions

Operational energy is quantified using a dynamic thermal simulation for heating and cooling and static equations for non-thermal operational energy demands, as in Stephan and Stephan [16]. Heating and cooling are quantified using DEROB-LTH, a dynamic energy simulation software that includes a detailed solar radiation model [52]. DEROB-LTH relies on an hourly timestep and considers thermal mass and building occupancy (see Appendix A in Stephan and Stephan [16] for details on the thermal energy model). Non-thermal operational energy demands are calculated by multiplying the power rating of the system/appliance by its operating hours over the period of analysis. Final energy demands are converted to delivered energy by considering the energy efficiency of the appliance (e.g. dividing the cooling demand calculated with DEROB-LTH by the coefficient of performance of the air conditioning unit). Delivered energy is converted to primary energy terms using the primary energy conversion factors for gas (1.1) and electricity (3.8), established in Stephan and Stephan [16].

Once primary operational energy figures are calculated, these are converted to GHG emissions using the emissions factors provided in Table 1, based on [16] and [33], and as per Eq. 2. These emissions factors account for the three main greenhouse gases, namely carbon dioxide, methane and nitrogen oxide and are expressed in $kgCO_2e$. The full details on the calculation of the emissions factor, and their comparison to official figures from 2011 from the Lebanese government [53] are provided in Appendix A.

$$LCOPGHG_b = \sum_{s=1}^{S} POPE_{s,b} \times EF_s \qquad Eq.2$$

Where: $LCOPGHG_b$ is the life cycle operational greenhouse gas emissions of the building b in $kgCO_2e$; S is the total number of fossil energy sources used in the building; $POPE_{s,b}$ is the primary operational energy demand associated with source *s*, used in building *b*, in $GJ^{PRIMARY}$; and EF_s is the greenhouse gas emissions factor of source *s* in $kgCO_2e/GJ^{PRIMARY}$.

3.6 Displacing life cycle energy use and greenhouse gas emissions through the installation of photovoltaic panels

Solar photovoltaic panels are used to displace the life cycle primary energy use and greenhouse gas emissions of the building, over 50 years. We chose solar photovoltaic panels because of the Lebanese Mediterranean climate and its high solar radiation values, combined with relatively mild temperatures (an average of ~20°C in Beirut) [54]. We also chose solar photovoltaic panels because of the sustained drop in their cost of installation, which had been the main barrier to their widespread installation until recently [36].

The case study building enables the installation of PV panels on the sloped portions of the roof. We dedicated the flat roof area to the installation of solar thermal collector. Portions of the South façade were also clad with panels, where relevant, and as depicted in Figure 3. That enabled us to install 190 m² of photovoltaic panels on the roof and 64 m² on the south façade. With a panel size of 2m² and a power rating of 415 W_p, the installed capacity per apartment unit is 6.588 kW_p or a total of 52.705 kW_p. When installing photovoltaic panels on the south façade, we assumed that the underlying natural stone would be removed, saving on embodied energy, greenhouse gas emissions and capital cost.

In order to quantify the net amount of energy produced and greenhouse gas emissions displaced by a photovoltaic array, we first calculated the additional embodied energy and greenhouse gas emissions associated with the production and installation of the entire system (panels, inverter, tubular gel batteries) as well as their replacement over time (see Table B.1, Appendix B for details). For each orientation, we computed the amount of solar radiation using data from Meteonorm [55]. We used this annual radiation to compute the electrical output of the solar photovoltaic arrays, taking into account environmental losses (20%) and the decrease of their efficiency over time. Eq. 3 describes how the amount of displaced greenhouse gas emissions was calculated.

$$DLCGHG_b = \overbrace{\left[\left(\sum_{ar=1}^{AR} PR_{ar} \times SR_{ar} \times \Phi^E \times \Phi_{ar}\right) \times POA \times PEF^{EL} \times EF^{EL}\right]}^{Displaced\ greenhouse\ gas\ emissions\ from\ the\ electricity\ grid} -$$

$$\overbrace{\sum_{c=1}^{C} \left[\left\lceil \frac{POA}{SL_c} \right\rceil \times \left(Q_{c,b} \times GHGC_c\right) + (TGHGRBS\text{-}TGHGR_c\text{-}NATGHGR_c) \times C_{c,b}\right]}^{Additional\ embodied\ greenhouse\ gas\ emissions\ of\ the\ PV\ system} +$$

$$\underbrace{\sum_{m=1}^{M}\left[\left\lceil\frac{POA}{SL_m}\right\rceil \times \left(Q_{m,b} \times GHGC_m\right) + \left(TGHGRBS - TGHGR_m - NATGHGR_m\right) \times C_{m,b}\right]}_{Avoided\ embodied\ greenhouse\ gas\ emissions\ due\ to\ the\ use\ of\ PV\ panels}$$

Eq. 3

Where: $DLCGHG_b$ is the displaced life cycle greenhouse gas emissions of building *b; ar* is a solar photovoltaic (PV) array with a certain orientation; PR_{ar} is the power rating of the solar PV array *ar* in kWp; SR_{ar} is the average annual solar radiation hitting the solar PV array *ar* in kWh/m²; Φ^{E} (=0.8) is a scalar representing environmental losses due to shading, dust, etc.; Φ_{ar} (=0.9) is a scalar representing the decrease in panel output over time, based on an 80% efficiency at the end of life of 25 years; POA is the period of analysis, in years; PEF^{EL} is the primary energy conversation factor for electricity in $GJ^{PRIMARY}/GJ^{DELIVERED}$; EF^{EL} is the greenhouse gas emissions factor for electricity, in $kgCO_2e/GJ^{PRIMARY}$; c is a component of the solar PV array; SL_c is the service life of component *c* in years; $Q_{c,b}$ is the amount of component *c* in the building, in functional unit of component (e.g. 1 inverter); $GHGC_c$ is the embodied greenhouse gas emissions coefficient of component *c* in $kgCO_2e$/functional unit; TGHGRBS is the total greenhouse gas emissions requirement of the input-output sector associated with the residential building sector, in $kgCO_2e$/current unit; $TGHGR_c$ is the total greenhouse gas emissions requirement of the input-output pathway representing component *c*, in $kgCO_2e$ /currency unit; $NATGHGR_c$ is the total flow requirement of all input-output pathways not associated with the installation or production process of component *c* being replaced, in $kgCO_2e$/currency unit, e.g. pathways representing concrete production when replacing solar photovoltaic panels; $C_{c,b}$ is the cost of component *c* in building *b* in currency unit; *m* is a material that is not installed anymore in the building because of the installation of the PV array; SL_m, $Q_{m,b}$, $TGHGR_m$, $NATGHGR_m$, *and* $C_{m,b}$ represent the same variables as those for component *c* but for material *m.*

Eq.3 clearly demonstrates the direct relationship between the amount of displaced greenhouse gas emissions and both the primary energy conversion factor for grid electricity as well as the greenhouse gas emissions factor of grid electricity. This will be further investigated in the sensitivity analysis, described in Section 3.8.

3.7 Quantifying life cycle cost

The life cycle cost of the net zero life cycle primary energy and greenhouse gas emissions building is calculated in net present value (NPV) terms. We calculate the NPV for each energy reduction measure and for the combination of all measures, over 50 years, as per Eq.4 below. The NPV of each measure is calculated as the net difference with the base case building. A positive NPV means that the measure is economically worth pursuing.

$$NPV_{NZ} = \sum_{y=0}^{POA} \frac{\left(\Delta Capex_y + ES_y + GS_y\right) \times (1 + CPI)^y}{(1 + r)^y}$$

Eq. 4

Where:

NPV_{NZ} is the net present value of the net zero life cycle primary energy and greenhouse gas emissions building *NZ* compared to the base case BC over the period of analysis, in USD; *y* is a specific year; *POA* is the period of analysis, in years; $\Delta Capex_y$ is the capital expenditure in year *y,* which is the difference between the investment for *NZ* minus the investment for the base case *BC* on that specific year *y*, in USD; ES_y is the delivered electricity savings in year *y,* which are the difference between the electricity spending for *NZ* minus the electricity spending for the base case on that specific year *y*, in USD; GS_y is the delivered gas savings in year *y*, which are the difference between the gas spending for *NZ* (in this case zero for all measures), minus the gas spending of the base case on that specific year *y*; CPI = the considered inflation rate (3.9%), which is computed as the average of the consumer price index (CPI) over the last 20 years, after the end of the Lebanese civil war and return to normality, based on data from IMF and the Central Administration of Statistics; and r = the discount rate (12.2%), calculated as described in Stephan and Stephan [17].

We assumed that the residual value of all the construction materials, appliances and photovoltaic systems is nil at the end of the period of analysis. In other terms, we assume that there is no resell value. The last replacement of any item is performed so that the end of its service life coincides with the end of the period of analysis.

Prices of construction materials, systems, appliances, and other components are based from a market study conducted in September 2019 in Lebanon and are based on average retail prices from major suppliers. Note that we did not consider the financial situation in Lebanon as of October 2019 to date due to public unrest in the country and its economic collapse which would significantly distort any life cycle costing attempts. Electricity tariffs for the state owned Electricité du Liban (EdL) are based on current official figures and are presented in Table 2. The average neighbourhood electricity generator fee for a standard connection is based on figures from 2014 to 2019 in the Zouk-Mosbeh area, Mount-Lebanon and are presented in Table 3. Generators are assumed to cover 25% of the electricity demand as in Stephan and Stephan [16], based on figures from the Lebanese Ministry of Energy and Water [56].

All prices include tax and are corrected for inflation over the period of analysis of 50 years. The price of materials and components replaced over the period of analysis is also indexed based on the year of replacement. For instance, the life cycle cost of a LED light replaced every 10 years is the sum of its current price, its price in 2030, 2040, 2050 and 2060 as well as the associated electricity use.

Table 2: Average monthly electricity prices in Lebanon as of 2020, in USD/kWh.

Electricity demand (kWh/month)	Cost (USD/kWh)
0-100	0.0255
100-300	0.0401
300-400	0.0584
400-500	0.0876
>500	0.146

Table 3: Average generator monthly tariff for a 5 Amperes connection in Zouk-Mosbeh, Lebanon for 2014-2019, in USD

Average price for a 5 A connection (USD)	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	Average
2014	66	67	67	47	47	84	93	97	90	90	66	57	72.6
2015	62	62	45	45	50	50	73	70	79	54	40	46	56.3
2016	53	37	33	30	30	44	54	63	43	40	40	57	43.7
2017	46	42	16	17	25	20	28	30	20	23	40	40	28.9
2018	70	33	27	30	63	61	64	50	30	25	22	25	41.7
2019	25	46	27	24	47	50	47	53	26	22	30	53	37.5
Average	46.78 USD												
Specific price[a]	0.177 USD/kWh												

Note: [a]The specific price is based on the assumption of full capacity use (5 A ↔ 1.1 kW) for the entire time a generator is on over 30 days (8 h/day as in Stephan and Stephan (2014)). This gives: 1.1 × 8 ×

30 = 264 kWh of generator energy per month. The price is therefore: 46.78/264 = 0.177 USD/kWh, which is 18.8% lower than what was used in Stephan and Stephan [57] based only on 2014-2016 data, revealing an overall decrease in private generator tariffs over the course of 2017-2019, which is correlated with a decrease in global oil prices.

3.8 Sensitivity analysis scenarios

Life cycle assessment studies can suffer from significant uncertainty as they involve a large number of independent variables over a long period of time. As such, it is critical to conduct a sensitivity analysis in order to evaluate how the core findings are affected for changes in key variables [58]. This also enables us to broaden the applicability of results to other countries and contexts by modifying the values of parameters to encompass those of other countries or contexts (e.g. the primary energy conversion factor for electricity). In order to do so, we rely on so-called 'what-if scenarios' [59] and specify different values for key variables that affect the life cycle energy, greenhouse gas emissions and/or cost of the building. This is in line with the systematic sensitivity analyses that we have conducted in our previous life cycle assessments of the case building [17, 57].

Table 4 summarises all the key parameters that are varied in the sensitivity analysis, the values investigated, a justification of the parameter and the values chosen. We investigated the sensitivity of the results to different parameters, separately.

Table 4: Details of the sensitivity analysis parameters, values, and justification

Parameter(s)	Investigated values	Justification
Inflation (CPI), and discount rates (r)	• CPI=2%; r=3% • CPI=4.4%; r=15%	Any life cycle costing exercise needs to account for the very uncertainty in the average inflation and discount rate over long periods of time [60]. We decided to investigate two scenarios, namely one with a low inflation and discount rate, aligned with values that are typically used in more stable economies (e.g. [61]) and a worst case scenario, where the discount rate is even higher than the 12.2% used. These values are in line with those used in the sensitivity analysis in [17]..
Greenhouse gas emissions factor	• EF^{EL}=0 $kgCO_2e/GJ^{PRIMARY}$ • EF^{EL}=10 $kgCO_2e/GJ^{PRIMARY}$ • EF^{EL}=20 $kgCO_2e/GJ^{PRIMARY}$	In order to broaden the applicability of the results and measure the effects of decreasing the greenhouse gas intensity of the electricity grid, it is essential to consider a broad range of decarbonisation scenarios, translated into different greenhouse gas emissions

for electricity generation	• EF^{EL}=30 $kgCO_2e/GJ^{PRIMARY}$ • EF^{EL}=40 $kgCO_2e/GJ^{PRIMARY}$ • EF^{EL}=50 $kgCO_2e/GJ^{PRIMARY}$ • EF^{EL}=60 $kgCO_2e/GJ^{PRIMARY}$	factors for the electricity grid. This is advocated for by Asdrubali *et al.* [62] who recently studied the influence of the greenhouse gas emissions intensity of the electricity grid on the life cycle assessment of zero energy buildings. We consider that the current Lebanese grid is very emissions intensive and thus investigate increasingly less emissions-intensive grids, including a theoretical zero greenhouse gas emissions grid.
Number of storeys of the building	• 5 storeys • 10 storeys	As flagged in Section 2 and Section 3.2, we decided purposely to use an apartment building to consider the challenge of a reduced roof area available for renewable energy systems. As such, we also consider the sensitivity of the results to increasing the number of storeys to 5 and 10, from the original 4. This implies a modification to the cost of the photovoltaic arrays as shipping becomes more effective (2.04 USD/W_p for the 5 storeys scenario and 2.06 USD/W_p for the 10 storeys scenario). Also, for the 10 storeys scenario, we can install only half of the solar thermal collectors (2.5 m²/apartment), increasing the operational energy demand and associated greenhouse gas emissions for domestic hot water (+564 GJ/apartment and +40 744 $kgCO_2e$/apartment compared to the four-storeys net zero life cycle primary energy and GHG emissions building, over 50 years)
Embodied energy and greenhouse gas emissions	• +40% • -40%	Embodied energy and greenhouse gas emissions suffer from significant uncertainty in their values, due to a range of factors [44]. Hybrid life cycle inventories, such as the EPiC database, can suffer from uncertainty of ±40% in the total value of embodied energy and greenhouse gas emissions [63].
Operational energy and greenhouse gas emissions	• +20% • -20%	Operational energy and greenhouse gas emissions are also subject to uncertainty in their modelling and significant variability in the lifestyle patterns of building occupants [64]. We use a margin of ±20% to account for that.
Primary energy conversion factor for electricity	• PEF^{EL}=2.6	The primary energy conversion factor in Lebanon (3.8 [16]) is very high compared to many other countries due to its ailing electricity infrastructure. In order to simulate more efficient electricity grids, we test the sensitivity of the results to using a primary energy conversion factor of 2.6, a value that is specified by energy efficiency standards in some European countries [65], including

	France and Spain, which include regions with a Mediterranean climate, like in Lebanon. From a life cycle greenhouse gas emissions perspective, reducing the primary energy conversion factor for electricity is directly equivalent to reducing the greenhouse gas emissions factor for electricity production to 50 $kgCO_2e/GJ^{PRIMARY}$. As such, we do not discuss this particular case on its own as it is directly included in the greenhouse gas emissions factor for electricity production. Similarly, we do not combine the reduction of the primary energy conversion factor with a reduction of the emissions factor as this is captured by one of the more significant reductions of the emissions factor.

3.9 Data availability

The data used in this study are made available open-access to ensure transparency and the replicability of results, in line with best practice guidance in industrial ecology [66]. The data are accessible on Figshare [67] at: https://doi.org/10.6084/m9.figshare.12452615. These data namely include:

- The detailed bill of material quantities of the base case;
- The detailed bill of assemblies quantities of the base case;
- The detailed life cycle cost calculations for each measure and the net zero life cycle primary energy and greenhouse gas emissions building;
- The detailed calculations related to the sensitivity analysis; and
- Other relevant data and information.

The EPiC database [34] used to quantify embodied energy and greenhouse gas emissions is available in open-access at: https://www.doi.org/10.26188/5dc228ef98c5a. Details on the calculations of each measure are provided directly in Appendix A below.

4 Results

Results show that achieving a net zero life cycle primary energy and greenhouse gas emissions apartment building in a Mediterranean climate is technically feasible, by using a moderate level of thermal energy efficiency, solar thermal panels for domestic hot water, electricity for all operational energy end-uses, installing a 6.5 kW_p solar photovoltaic array and most importantly avoiding emissions from inefficient and emissions-intensive Lebanese electricity grid. By deploying the measures mentioned above and detailed in Section 3.3, the net zero life cycle primary energy and greenhouse gas emissions building achieves a net life cycle primary energy balance of -888 GJ (-0.7 GJ/m² of gross floor area),and a net life cycle greenhouse gas emissions balance of -20 258 kgCO₂e (-17 kgCO₂e/m² of gross floor area), over 50 years. This comes at an additional initial capital cost of 92 000 USD2020 (75/m² of gross floor area) and a total life cycle cost of 57 283 USD2020 (47/m² of gross floor area) over 50 years, after taking into account the electricity and gas savings over that same period.

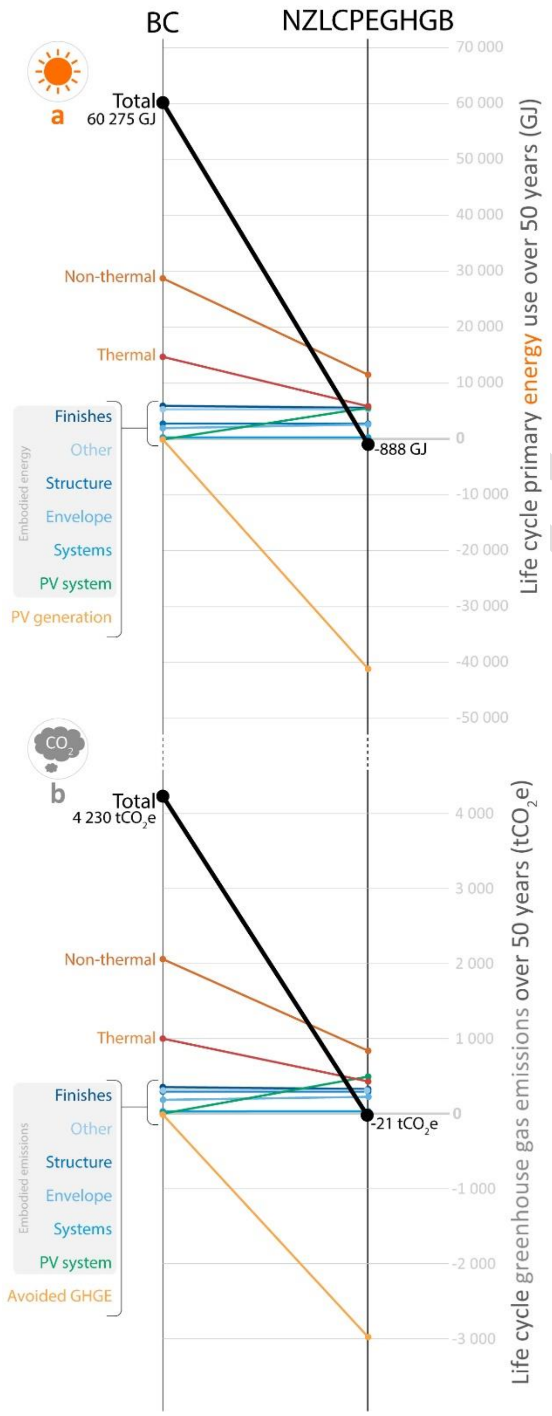

Figure 4 depicts the breakdown and change in the life cycle primary energy use and greenhouse gas emissions, by category, for the base case and the net zero life cycle primary energy and greenhouse gas emissions building. We can observe that operational energy and greenhouse gas emissions reductions outweigh the additional investment in embodied energy and greenhouse gas emissions. This is very visible for the solar photovoltaic panels, where an additional embodied energy of 61 630 GJ avoids the generation of 370 514 GJ of primary energy on the Lebanese grid. The largest net reduction in life cycle energy and greenhouse gas emissions comes from using very energy efficient appliances with a 59% reduction in non-thermal operational energy and emissions compared to assumed negligible change in embodied energy and emissions. It is important to note that removing the partition wall between the kitchen and the dining room and the other modifications to the finishes save 54% and 67% of the additional embodied energy and greenhouse gas emissions needed to insulate the building with 10 cm of EPS insulation and to install a new double-glazed window on the atrium per apartment. Small design changes involving embodied energy and greenhouse gas emissions intensive materials such as concrete and mortar (initial embodied flows) and paint (recurrent embodied flows) can provide an embodied environmental flows margin for significant life cycle energy efficiency upgrades.

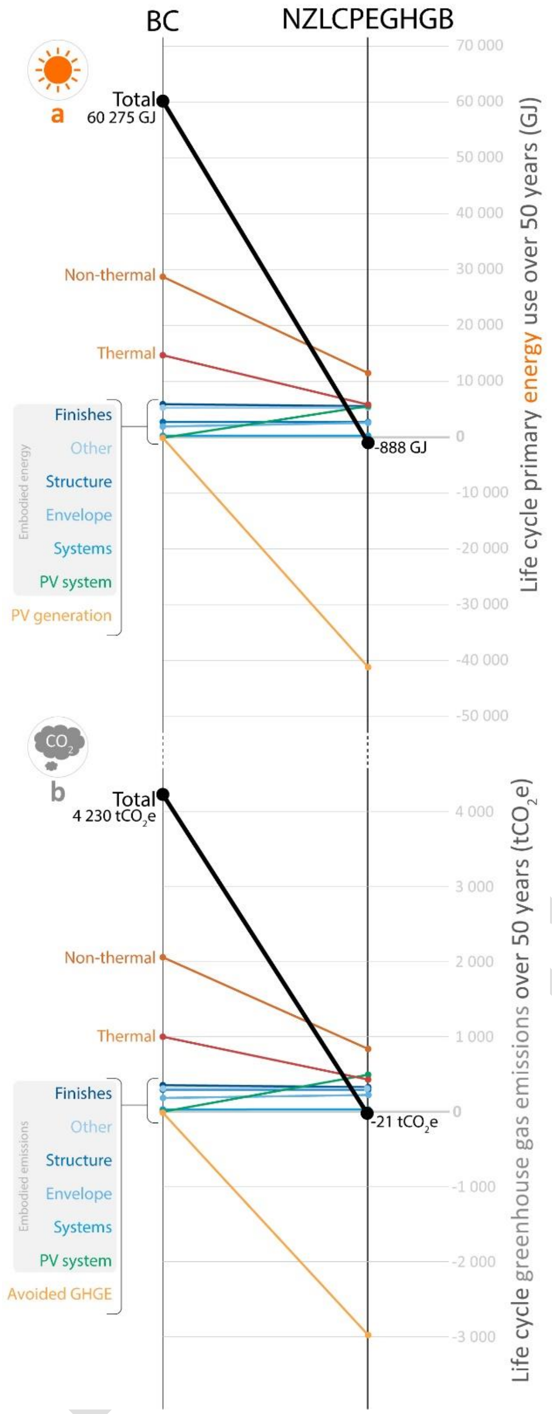

Figure 4: Parallel coordinates plot of the life cycle primary energy use (a) and life cycle greenhouse gas emissions (b) of the base case (BC) and net zero life cycle primary energy and greenhouse gas emissions apartment (NZLCPEGHG) buildings

Assuming that characteristics of electricity generation in Lebanon are constant over the coming 50 years, the solar photovoltaic array would take 7 years to payback its own embodied energy and 27.5 years to payback the embodied energy of the building and its own embodied energy. The life cycle primary energy payback occurs only in year 48. Payback times are 8 years for embodied greenhouse gas emissions for the solar array alone, 28 years for embodied greenhouse gas emissions for the building and the solar array and 49 years for life cycle greenhouse gas emissions. The very similar payback times show that embodied and operational energy and greenhouse gas emissions are very closely aligned in terms of their relative contributions, in this case. The very long payback times for life cycle energy and greenhouse gas emissions clearly showcase the sensitivity of the results to the primary energy conversion factor for electricity and the greenhouse gas emissions factor. The latter is explored in detail in Section 4.1.

Another important information to relay is the initial, recurrent and total life cycle embodied energy and greenhouse gas emissions intensity of the base case apartment building and the net zero life cycle primary energy and greenhouse gas emissions building. These are summarised in Table 5. We can see that the total life cycle embodied energy and greenhouse gas emissions increase by 35.9% and 43.4%, respectively. Recurrent embodied environmental flows increase more than initial embodied environmental flows (e.g. +130.9% compared to +21.1% for recurrent and initial embodied greenhouse gas emissions, respectively). The increase in initial embodied environmental flows is the most certain figure in this study as it does not depend on the future evolution of the local electricity grid nor on the emissions intensity of global supply chains for material production. These ‘locked-in’ emissions may never be paid back in contexts with a low-emissions grid, as discussed in Sections 4.1 and 5.

Table 5: Comparison of the embodied energy and greenhouse gas emissions intensities between the base case apartment building and the net zero life cycle primary energy and greenhouse gas emissions building

Embodied environmental flow	Unit	BC building	NZLCPEGHGE building	Relative difference (%)
Initial embodied energy	GJ/(m² of GFA)	9.8	11.8	+20.3%
Recurrent embodied energy over 50 years	GJ/(m² of GFA)	3.7	6.6	+77.4%
Life cycle embodied energy over 50 years	GJ/(m² of GFA)	13.5	18.4	+35.9%
Initial embodied greenhouse gas emissions	$kgCO_2e$/(m² of GFA)	755	914	+21.1%
Recurrent embodied greenhouse gas emissions over 50 years	$kgCO_2e$/(m² of GFA)	193	445	+130.9%
Life cycle embodied greenhouse gas emissions 50 years	$kgCO_2e$/(m² of GFA)	947	1 359	+43.4%

Note: GFA = Gross floor area; BC = Base case; NZLCPEGHGE = net zero life cycle primary energy and greenhouse gas emissions

Figure 5 depicts the annual cash flow of the apartment building, in net present value terms (USD2020) for the 50 years of period of analysis. Positive bars represent cost savings from electricity while negative bars associated with the initial (year 0) and replacement (subsequent years) costs of the different measures implemented (e.g. installing solar photovoltaic arrays). The bottom line represents the accumulated net present value of all the measures implemented in the apartment building (i.e. the sum of all bars up to a given year).

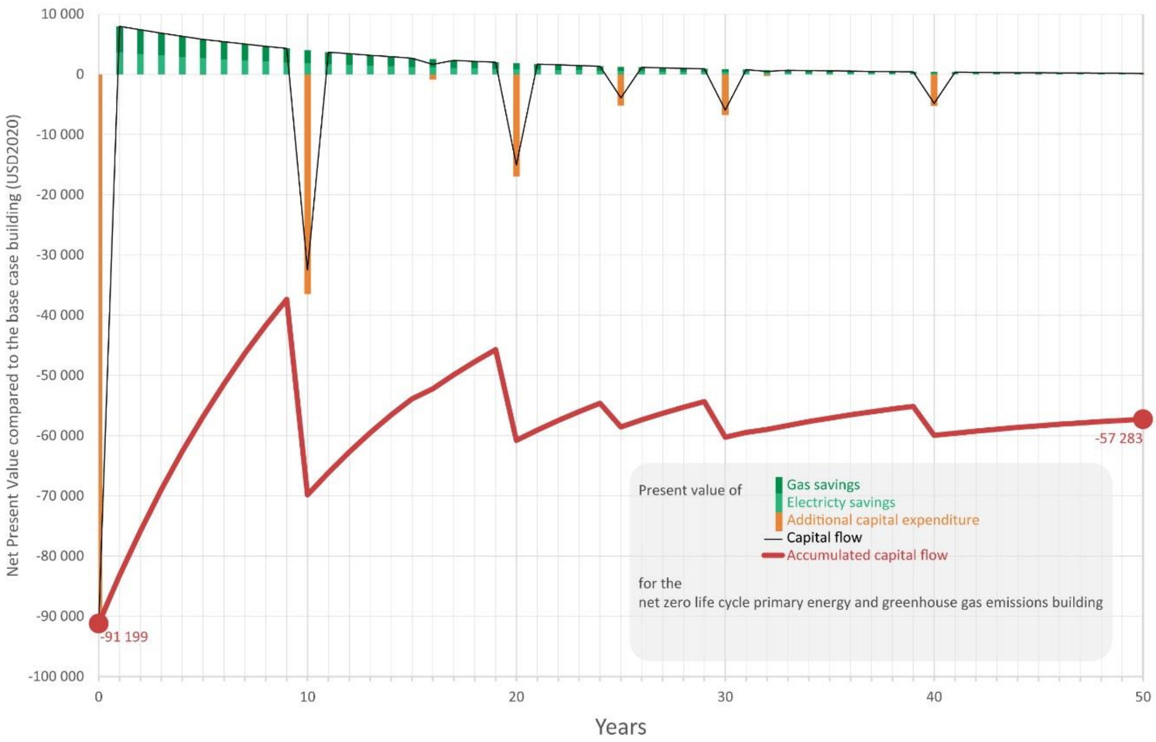

Figure 5: Life cycle cost of the net zero life cycle primary energy and greenhouse gas emissions apartment building, as compared to the base apartment building, over 50 years

Two main observations can be drawn from the results. Firstly, the additional capital cost of the net zero life cycle primary energy and greenhouse gas emissions apartment building is 92 000 USD2020 or 75 USD/m² of gross floor area including new appliances. When considering only the extra cost of fixed components, this capital cost falls to 89 000 USD2020 or 72.2 USD/(m² of gross floor area)which represents an 11% increase in the cost per m² of the base case apartment building (650 USD2020/(m² of gross floor area)). This percentage increase in initial capital cost is in line with similar studies on zero operational energy buildings, as discussed in Section 5. Secondly, the need for storage batteries due to the intermittent nature of state-owned electricity in Lebanon significantly increases the cost of the solar array, representing alone, 57% of the cost (1.21 of the 2.13 USD2020/kW$_p$). In addition, the discount rate of the Lebanese economy significantly reduces future cash flows, notably energy savings over time. This is very visible on the graph, with the first few years paying back a large amount of the cost, but the discount rate significantly reducing these savings over time. Furthermore, the fact that all the excess electricity from the solar array is given freely on the grid, without any buy-back rate further penalises the reliance on solar photovoltaic panels in Lebanon.

4.1 Results of the sensitivity analysis

Figure 6 depicts the results of the sensitivity analysis of the results to a range of factors. It shows the life cycle greenhouse gas emissions on the horizontal axis and the net present value compared to the base case on the vertical axis. A few general observations can be made from this graph. Firstly, most scenarios result in an apartment that is not able to reach a net zero life cycle energy and greenhouse gas emissions performance. Secondly, the identified scenarios result in a significant amount of variability in the results, namely from -769 kgCO_2e/m² gross floor area to +1 359 kgCO_2e/m² gross floor area for life cycle greenhouse gas emissions and from -47 USD2020/m² gross floor area to +76 USD2020/m² for the net present value over 50 years. These values vary widely compared to the original figures for the net zero life cycle primary energy and greenhouse gas emissions building, i.e. -20 kgCO_2e/m² gross floor area and -46 USD2020/m² gross floor area. Thirdly, almost all scenarios (27 out of 31 or 87%) result in a negative net present value over 50 years, demonstrating the need for financial incentives or support in most cases. Each set of parameters is discussed below.

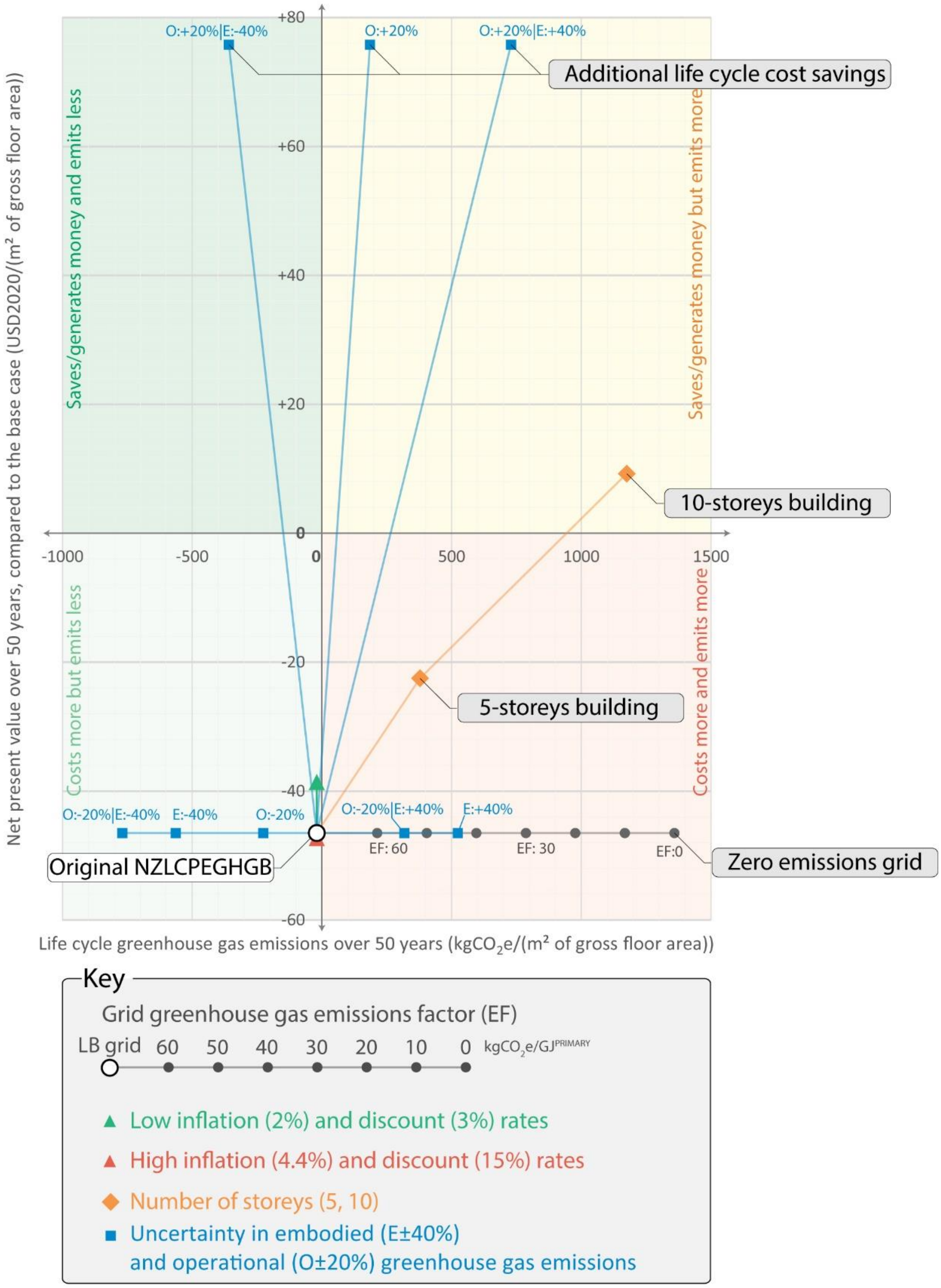

Figure 6: Sensitivity analysis of the life cycle greenhouse gas emissions and the life cycle cost of the apartment building, to variations in financial parameters, greenhouse gas emissions factors for electricity, number of storeys and uncertainty in embodied and operational energy calculations. Note:

NZLCPEGHGB = Net zero life cycle primary energy and greenhouse gas emissions building; LB = Lebanon

Variability in the discount rate and inflation rate did not affect much the overall net present value, which remains negative. The even higher discount (15%) and inflation (4.4%) rates have negligible effects on the net present value (further decreasing it by 1.7%). Since the BC is already based on high discount rate and inflation, further increasing them has very limited impact on the final NPV. A standard discount rate of 3% and an inflation rate of 2%, similar to most existing life cycle costing studies of buildings and building systems, increases the net present value to -47 545 USD2020 (-38.6 USD2020/(m^2 of gross floor area)), or an increase of 17%.

Reducing the emissions factor of the electricity grid has the most significant effect on the overall life cycle greenhouse gas emissions balance, moving it from an original -20 $kgCO_2e$/(m^2 of gross floor area) up to 1 359 $kgCO_2e$/(m^2 of gross floor area) for a theoretical, fully decarbonised grid. For a fully 'decarbonised' electricity grid, embodied greenhouse gas emissions are no longer displaced, and the result net life cycle greenhouse gas emissions balance of 1 359 $kgCO_2e$/(m^2 of gross floor area) becomes equal to the life cycle embodied greenhouse gas emissions. Assuming an average emissions factor of 50 (equivalent to primary energy conversion factor of 2.6 for electricity, see Table 1) or 30 $kgCO_2e/GJ^{PRIMARY}$ (similar to Italy) over 50 years to account for a greenhouse gas emissions free electricity grid by 2070 (which would still be too late according to one of the latest IPCC reports), the net greenhouse gas emissions balance would stand at 404 and 786 $kgCO_2e$/(m^2 of gross floor area)), respectively. This is still much lower than the life cycle greenhouse gas emissions intensity of the base case (3 429 $kgCO_2e$/(m^2 of gross floor area)) but far from a net zero outcome. This demonstrates the great challenge in trying to achieve net zero life cycle greenhouse gas emissions buildings. Simply improving operational energy efficiency and avoiding greenhouse gas emissions on the grid (e.g. photovoltaic panels) is not enough. Additional strategies, such as choosing materials that lock-in greenhouse gas emissions for decades to come (e.g. structural timber), are needed.

Uncertainty in embodied and operational energy figures have very significant effects on the life cycle greenhouse gas emissions and the life cycle cost, respectively. Overall, overestimating embodied and/or operational energy and associated emissions (E-40% and O-20% cases) has a logical beneficial effect on the actual life cycle greenhouse gas emissions which tend to be lower than expected. However, underestimating operational energy (O+20% case), which would actually be higher than modelled, has positive effects on the life cycle cost, turning the net present value over 50 years positive in three cases out of four, up to +76 USD2020/(m² of gross floor area). This is because a larger proportion of the energy produced from the solar photovoltaic array is saving costly electricity from the grid.

Finally, the number of stories of the apartment building has a significant effect on both the life cycle greenhouse gas emissions and the life cycle cost. Increasing the number of storeys to 5 from 4 (+25%) increases the life cycle greenhouse gas emissions to 378 kgCO_2e/(m² of gross floor area) but decreases the life cycle cost by 51%. Moving to 10 storeys results in a higher life cycle greenhouse gas emissions intensity of 1 175 kgCO_2e/(m² of gross floor area) but turns the net present value positive to +9 USD2020/(m² of gross floor area). All results and the sensitivity analysis are discussed in the following section.

5 Discussion

5.1 Contribution

This study has quantified the life cycle primary energy, greenhouse gas emissions and cost of achieving a net zero life cycle primary energy and greenhouse gas emissions apartment building in a Mediterranean climate. It has evaluated the feasibility of achieving this level of performance, both from the energy and emissions perspective as well as from a financial cost perspective. The study goes beyond recent research on net zero energy buildings (*inter alia* [9, 10, 20, 21, 24, 25]) by including embodied energy and greenhouse gas emissions (initial and recurrent), achieving a net zero life cycle energy and greenhouse gas emissions balance, and conducting a broad sensitivity analysis of the results, notably to the greenhouse gas emissions factor of the electricity grid.

Results show that while achieving a net zero life cycle primary energy and greenhouse gas emissions apartment building is possible in the current context and by relying on solar photovoltaic energy generation on site, this depends significantly on the greenhouse gas emissions intensity of the electricity grid. The higher the greenhouse gas emissions intensity of the grid, the easier is it to achieve this level of performance by installing photovoltaic panels, as demonstrated by Martinopoulos [68]. The results of the study have broad implications for future research, as well as policy, which are discussed below.

5.2 Revisiting the definition of net zero energy (and greenhouse gas emissions) buildings

Based on the findings of this research, it is critical to review existing definitions of net zero energy and greenhouse gas emissions buildings by including both initial and recurrent embodied energy (as in [11, 12]) and greenhouse gas emissions (as in Asdrubali *et al.* [62]), attempting to offset them, and including future reductions in the greenhouse gas emissions of the local electricity grid in the definition, as scenarios. Only then will we be able to realistically measure the overall life cycle energy and greenhouse gas emissions performance of a building. This is corroborated by the recent findings of Parkin *et al.* [69] that also call for a broader life cycle definition that includes both energy and greenhouse gas emission metrics as well as the greenhouse gas emissions intensity of the grid. We suggest that primary energy will still be relevant as an indicator in the coming decades, despite electricity grids with lower greenhouse gas emissions intensities, because primary energy is also highly correlated with other environmental impact categories, as demonstrated by Oregi *et al.* [70].

New policies focusing on improving the environmental performance of buildings need to adopt both a life cycle perspective, including both initial [71] and recurrent embodied environmental flows, as well as a systems approach, in order to yield net overall benefits. Otherwise, there is a high risk of simply displacing energy use or greenhouse gas emissions from one life cycle stage or location to another, without an overall reduction.

5.3 Reducing embodied energy and greenhouse gas emissions

In light of the results, the initial embodied energy and greenhouse gas emissions are the most significant metrics to consider as electricity grids in most countries seem to be set to decarbonise over time, which will reduce the life cycle contribution of operational emissions [62], and to some extent recurrent embodied greenhouse gas emissions (for electricity-operated processes). The significance of initial embodied energy and greenhouse gas emissions is further compounded by the increased material intensity of a zero life cycle primary energy and greenhouse gas emissions building (+20% on average for both indicators, see Table 5). This means that producing renewable energy onsite might never avoid the entirety of the initial embodied greenhouse gas emissions, dubbed the 'carbon spike' by Säynäjoki *et al.* [72].

To date, it seems to be very hard to significantly reduce the initial embodied energy and greenhouse gas emissions of buildings as demonstrated by previous research. For instance, Myers *et al.* [73] studied the potential of reducing the embodied energy of residential building by relying on renewable materials. Their results show a potential reduction of 31% but highlight the lack of ability to do this at scale and for different building typologies.

One way to reduce life cycle embodied greenhouse gas emissions would be to store carbon dioxide as carbon in building materials, using them as carbon sinks, notably through the use of timber products. In their recent study, Head *et al.* [74] develop a dynamic life cycle inventory database to account for the life cycle greenhouse gas emissions of timber products in Canada, from a gate-to-gate perspective. Their results, investigating a fraction of all possible scenarios that can be modelled, found that most wood products act as net carbon sinks over their life cycle avoiding the emissions of 500 – 1 500 $kgCO_2e/m^3$ of timber, over time horizons of 100-500 years. However, this study does not consider using timber at scale and associated supply chain repercussions which would change these carbon storage estimations. At the current rate of construction and population growth, it is very hard to imagine the use of timber products across the world, in a manner that ensures the protection of ecosystem, stock regeneration, and avoids deforestation.

Additional design approaches, beyond mere material substitution need to be investigated and deployed at scale. For instance, designing buildings with a smaller floor area per capita can yield immediate and significant reductions in material use, embodied and operational energy use, as well as associated greenhouse gas emissions [14, 15, 75]. As shown in this paper, small changes to the design (e.g. removing a partition wall) can reduce embodied energy and greenhouse gas emissions enough to compensate for the addition of more useful materials that reduce life cycle operational energy use. Design approaches for a low embodied energy and greenhouse gas emissions need to be tested, shared and taught to built environment professionals to support their uptake.

5.4 The challenge of mid-rise and high-rise buildings

Achieving a net zero life cycle primary energy and greenhouse gas emissions performance is significantly affected by the number of stories of a building (see Figure 6), as the on-site generation capacity per m^2 drops significantly with increasing building height. In this study, this level of performance could just be achieved for a building of up to five storeys, and by installing solar photovoltaic panels on the roof and the South façade, which could be shaded in many other situations. The challenge of achieving net zero life cycle primary energy and greenhouse gas emissions for high-rise buildings is further compounded by their premium-for-height, with significant additional structural materials and associated embodied energy and greenhouse gas emissions as height increases [76-78]. For high-rise buildings, horizontal or vertical axis wind turbines could be further explored for on-site renewable energy generation, which capitalises on increased wind speeds at height [79], but more life cycle assessment studies need to be conducted on that possibility. Another approach would be to rely on engineered timber for high-rise buildings [80] as a means to reduce embodied greenhouse gas emissions (see Section 5.3 and Head *et al.* [74]). This still needs further research on structural strengths, achievable building heights and life cycle assessment.

This raises other questions regarding decisions about having three low-rise buildings compared to one high-rise building, and planting the remaining land with trees to sequestrate carbon and offset some of the greenhouse gas emissions of the building. Similarly, questions of population density, viability of public transport and other parameters that affect the overall life cycle energy use and greenhouse gas emissions need to be considered [81]. We want to flag that the interplay between building height, availability of on-site renewable energy, climate and the ability to achieve a net zero life cycle primary energy and greenhouse gas emissions level of performance has multiple implications for urban planning and policy.

5.5 Improving the life cycle environmental performance of buildings through policy

Policy has a lot of power in supporting the improvement of the life cycle environmental performance of buildings, towards reaching net zero life cycle primary energy and greenhouse gas emissions. In light of our results, we advocate for three main policy actions.

Firstly, it is critical to integrate life cycle embodied environmental flows into any building environmental performance regulation or certification, as advocated for by multiple scientists for a long time [7, 63, 82-86], more recently by the World Green Building Council [71] and already implemented in some countries such as The Netherlands [87]. This is because the embodied energy and greenhouse gas emissions premium is significant (+36% and +43% in this study), notably when using the comprehensive system boundaries of hybrid analysis for the compilation of the life cycle inventory. More importantly, in the context of net zero energy and greenhouse gas emissions buildings (operational only or life cycle) the decreasing greenhouse gas emissions intensity of electricity grids can result in the initial embodied greenhouse gas emissions never being avoided through on-site electricity generation.

In order to decrease embodied environmental flows in buildings and the built environment, we need to first define a systematic and more transparent manner of conducting comprehensive life cycle assessments. Environmental Product Declarations are a good step in that direction, but they need to be much more robust and rely on hybrid analysis to correctly measure a 'net' gain or loss in environmental performance, when comparing to operational flows. Based on this more transparent information, subsidies could be introduced either for low embodied environmental flows materials or for certain levels of performance of embodied environmental flows (e.g. less than 400 kgCO_2e/m² for a particular gross floor area band of residential houses).

Secondly, the financial viability of achieving a net zero life cycle energy and greenhouse gas emissions performance is currently directly linked to the installation of batteries. Indeed, the additional capital cost is 74 or 22 USD2020/(m² of gross floor area) and the net present value is -57 283 USD2020 (-46 USD2020/(m² of gross floor area)) or 58 448 USD (+47 USD2020/(m² of gross floor area)) at 50 years, if we include batteries for the solar array or not, respectively. Batteries alone represent 50% of the total cost of the photovoltaic solar array. When no batteries are needed, the additional capital cost of the solar photovoltaic array that avoids life cycle greenhouse gas emissions is paid back within four years only with an inflation rate of 3.9% and a discount rate of 12.2%. Achieving net zero life cycle primary energy and greenhouse gas emissions buildings could therefore be financially viable in many locations, with current electricity tariffs. To further support the adoption of this level of performance, the additional capital cost could be subsidised, while simultaneously requiring the additional initial embodied greenhouse gas emissions to meet regulatory benchmarks. There are precedents in terms of schemes providing a financial subsidy per square metre to help support the uptake of more energy efficient buildings. For instance, the additional capital cost per square metre in this study (74 or 22 USD2020/(m² of gross floor area)) is very similar to the level of subsidy provided by the Brussels Capital Region back in 2010 to achieve a Passive House Standard (50 EUR/m² for new buildings over 150 m² of gross floor area) [88]. Providing a smart grid infrastructure that enables selling back electricity without the need for onsite batteries can significantly reduce the capital and ongoing costs of a solar photovoltaic array that is large enough to cover life cycle energy use and avoid life cycle greenhouse gas emissions. It is important to flag that this solution is not applicable to all buildings, as some form of storage would be needed at the grid level due to the intermittent nature of solar radiation. Should batteries be indispensable, subsidising buildings that strive to achieve a positive life cycle environmental performance would support their uptake, reduce costs through scale and increase awareness.

Thirdly, urban planning policy needs to rely more on science and evidence to guide planning decisions [89] in order to embrace the complexity of life cycle environmental performance, as advocated for in the field of health and transport [90] or nature-based solutions [91]. This field is still in its infancy, with very few studies integrating embodied environmental flows at the city level [92] (e.g. Stephan and Athanassiadis [93]), but it can yield significant potential. Based on the findings of this paper, there seems to be a complex relationship between the greenhouse gas emissions intensity of the electricity grid, the building typology in terms of number of storeys and potential for on-site renewable energy generation, and the ability to achieve net zero life cycle primary energy and greenhouse gas emissions building. We can imagine how future neighbourhoods could be planned and policy designed to try and factor in such relationships, among others.

5.6 Applicability of the results in other countries

Despite the fact that this study occurs in a Lebanese context and is therefore relevant to its climate, particular (currently dire) economic situation, energy mix, and building typology, a number of findings are relevant to other countries and contexts. Firstly, the main finding of this paper, i.e. achieving net zero life cycle primary energy and greenhouse gas emissions buildings is currently possible, is valid for locations with a Mediterranean climate and a similar greenhouse gas emissions intensity of the electricity grid (as well as a similar primary energy conversion factor), such as Greece. Using the sensitivity analysis to reduce the emissions factor of electricity, the adjusted results are applicable to other locations, *inter alia,* Israel, Italy, Spain, Tunisia and Turkey, parts of South Australia and California. Secondly, the life cycle cost results, broadened by the sensitivity analysis are relevant to multiple economic contexts (discount rate varying between 4-15% and inflation between 2-4.4%). The net present value of achieving a net zero life cycle primary energy and greenhouse gas emissions building is negative and needs subsidies. However, when removing batteries from the solar photovoltaic system (assuming storage on the grid, which is not possible in Lebanon due to the intermittent nature of electricity), the NPV changes to 47 USD2020/(m² of gross floor area), 174 USD2020/(m² of gross floor area), and 35 USD2020/(m² of gross floor area) for inflation and discount rates of 4% and 12%, 2% and

4% and 4.4% and 15%, respectively. This makes it economical to achieve a net zero life cycle primary energy and greenhouse gas emissions in countries outside of Lebanon, where batteries are not needed.

5.7 Limitations and future research

As any scientific endeavour, this paper has limitations. Firstly, it relies on a single case study, which means that the results are valid for this case study only, even if great care was taken in selecting it as representative of the building stock it is representing. Secondly, all calculations of energy, greenhouse gas emissions and costs, forecasted decades into the future, suffer from significant uncertainty. While a sensitivity analysis was undertaken to mitigate that uncertainty, it can still significantly affect the results. Thirdly, this study uses the Australian EPiC database to quantify embodied energy and greenhouse gas emissions. This might result in errors in embodied energy and greenhouse gas emissions calculations. While the use of Australian data and its potential effects on the results is discussed thoroughly in Stephan and Stephan [16], we do adopt a conservative approach by using hybrid data, which provides higher embodied energy and greenhouse gas emissions figures than process data, making achieving net zero life cycle primary energy and greenhouse gas emissions apartment buildings harder. In the absence of a global equivalent to the EPiC database, relying on multi-regional input-output data and process data, we use the most comprehensive database available. Fourthly, the study does not consider the depletion of rare materials needed to achieve a net zero life cycle energy and greenhouse gas emissions apartment buildings. Given that large monocrystalline photovoltaic arrays are installed to reach that level of performance, a significant amount of silver, rare earth and other depleting materials [94] are needed. Future research is needed to better understand the effects of upscaling these solutions on material criticality [95]. Despite these limitations, this work provides new data and knowledge on achieving net zero life cycle energy and greenhouse gas emissions apartment buildings in a Mediterranean climate.

6 Conclusion

This study has quantified the life cycle energy, greenhouse gas emissions and cost of achieving a net zero life cycle primary energy and greenhouse gas emissions apartment building in Lebanon, in a Mediterranean climate. While it is currently possible to achieve that level of performance through the installation of a large solar photovoltaic array, this is only possible in locations with a very greenhouse gas emissions intensive electricity grid. A broad sensitivity analysis reveals that it is very hard to maintain that level of performance when electricity grids are decarbonised as embodied greenhouse gas emissions may never be avoided by on-site renewable energy generation. Furthermore, the life cycle cost of achieving that level of performance are still prohibitive without subsidies if onsite battery storage is required, regardless of the discount and inflation rates adopted. The paper provides various recommendations to support the uptake of net zero life cycle primary energy and greenhouse gas emissions buildings, namely a consistent and better definition, including embodied environmental flows, subsidising the capital cost and exploring new urban environmental policy and planning pathways and relationships. This will ultimate contribute to improving the environmental performance of buildings and help mitigate the current climate emergency.

Authors contributions

AS and LS designed the study. LS and AS sized and calculated the Photovoltaic system arrays. AS conducted the life cycle energy and greenhouse gas emissions analysis. LS collected the financial data and conducted the life cycle cost analysis. AS wrote the paper and made the figures. LS and AS reviewed the paper.

Appendix A Calculation of emissions factors for purchasing electricity in Lebanon

As there is no electricity emissions factor for Lebanon readily available to use, we had to calculate it. We used the data on average greenhouse gas emissions from fuel combustion for the two main fuels used to produce electricity in Lebanon, namely heavy fuel oils for the state-owned power plants and diesel for the privately owned generators. The emission factor is a weighted average of the two and its calculation is summarised in Table A.1.

Table A.1: Calculation of the greenhouse gas emissions factor of the Lebanese electricity grid

Parameter	Value	Source
Emissions factor for the combustion of heavy fuel oil for the state owned power plants	73.13 $kgCO_2e/GJ$	Department of Climate Change and Energy Efficiency [33]
Share of electricity delivered from state owned power plants	75%	Based on MEW [56] and consistent with Stephan and Stephan [16]
Emissions factor for the combustion of diesel for privately-owned generators	69.5 $kgCO_2e/GJ$	Department of Climate Change and Energy Efficiency [33]
Share of electricity delivered from privately-owned generators	25%	Based on MEW [56] and consistent with Stephan and Stephan [16]
Average emissions factor for Lebanon	73.13×0.75+69.5×.025= **72.2225** $kgCO_2e/GJ^{PRIMARY}$ (equivalent to 0.997 $kgCO_2e/kWh^{DELIVERED}$)	

In order to confirm the validity of this figure, we used the average emissions factors for public (847 $kgCO_2e/MWh$) and private electricity generation (713 $kgCO_2e/MWh$) in Lebanon, reported in [53] It is important to note that these emissions factors do not take into account transmission losses and production losses and are therefore 'at plant' and unusable as such. To convert them to emissions per primary energy unit, we used the plant and generator efficiency from Stephan and Stephan [16] and obtained 65.8 $kgCO_2e/GJ^{PRIMARY}$ and 73.99 $kgCO_2e/GJ^{PRIMARY}$ for state-owned power plants and private generators, respectively. Using a 74% and 26% contribution of state-owned power plants and private generators to the energy mix, as specified in [53], we obtain an average emissions factor for Lebanese electricity of 67.77 $kgCO_2e/GJ^{PRIMARY}$, which is 6% less than what we used. Given that since 2011, the contribution of private generators has increased following the business as usual scenario in [53] (the gap between state-owned electricity generation and demand has increased since 2011), and that the power plants efficiency is continuing to decrease over time, we estimate that the emissions factor of 72.2225 $kgCO_2e/GJ^{PRIMARY}$ may not only be more realistic, but might also be conservative.

Appendix B Details of all investigated measures

Table B.1 provides a summary of all applied measures. For more details on the calculations, notably energy and greenhouse gas emissions figures, please refer to data files referred to in Section 3.9.

Table B.1: Summary of all investigated measures, including details on calculations

Measure	**DETAILS**	**NUMBER OF REPLACEMENTS OVER 50 YEARS**	**ADDITIONAL COMMENTS ON COST**
Install a solar thermal collector for each apartment	Collector size: 5 m^2 Collector type: Vacuum tube Covers: 80% of the domestic hot water demand, the rest are covered by an electric resistance	1	The installation cost of each solar thermal collector system is 2 300 USD based on three quotes from three different providers. Most of the cost is associated with the vacuum tubes (1 200 USD) and heat exchanger (700 USD). The remaining 400 USD cover insulated piping and labour cost. From this total cost, we deducted the cost of the electric hot water cylinder present in the base case since it is not needed anymore. This amounts to 250 USD which results in a final net cost for the solar collector system of 2 050 USD.
Replace all lighting from compact fluorescent lights to light emitting diodes	Average LED light power: 7W Quantity: 10 lights per apartment	4	The cost of each 7 W LED light is 8.5 USD compared to 2.5 USD for a 12 W CFL. LEDs are assumed to be replaced four times even if their average life is around 50 000 hours [56] (leading to a single replacement over 50 years). That is because of the variability in the voltage in provided electricity that tends to disrupt their electronic circuits and shorten their lifespan.

Replace all electric appliances with energy efficient ones (a+++)	Replaces the fridge, washing machine and television (TV) with high efficiency A+++ EU-labelled appliances. See details in [17].	Washing Machine: 2 Fridge: 2 TV: 4	The cost of new appliances is obtained from a major electronic devices retailer. We selected the most affordable models meeting the required energy efficiency level. The prices of the fridge, washing machine and TV are 1 239 USD, 529 USD and 350 USD, respectively.
Replace the air conditioning split systems with energy efficient ones	Quantity: 10 Old CoP[a]: 2.5 New CoP: 5.9	2	The price of the energy efficient air conditioning (AC) unit is 450 USD based on quotes from different suppliers. This compares with an average price of 350 USD for the AC units used in the BC. The installation cost and maintenance costs are not considered since they are assumed to be the same as in the BC.
Remove radiative heating system and use air conditioning instead	Quantity of radiators removed: 10 Quantity of boilers removed: 1	N/A	Removing the radiator units from each apartment saves 5 250 USD. This is calculated using a material cost of 90 USD per radiator, an accessories (e.g. valves) cost of 10 USD per radiator, a piping cost of 70 USD per radiator, and an installation cost of 70 USD per radiator. In addition, we use a gas boiler cost of 1200 USD, a boiler installation cost of 150 USD. An additional 1500 USD would be needed for the gas system, including the tank, pipes, valves and labour.
Replace central shaft by atrium	Convert surrounding walls to outer wall assemblies (painted, not covered with natural stone). Increases daylight indoors, reduces cooling demand in summer. Wall area: 22.388 m²	Paint: 4	Converting the central shaft into an atrium requires converting the shaft walls into outer walls and adding a single window of 1.5m². This costs an additional 702 USD per apartment. We use a wall area of 22.388 m²/apartment and a cost of 9.7 USD/m² for the additional 100 mm thick masonry wall, 4.5 USD/m² of plastering (on one side), 6 USD/m² of water-based paint, and a cost of 250 USD for the 1.5m² window. The cost of insulation is not included here, as it is already accounted for when insulating the building.
Remove internal partition wall between kitchen and living room	Wall area: 19.43m²	N/A	This measure saves 1 232 USD per apartment. This is due to removing 19.43m² of wall, costing 9.7 USD/m² for the wall, 4.5 USD/m² for plastering, and 5.5 USD/m² for water-based

			paint. We also save tiling the wall on the kitchen side, at a cost of 23.5 USD/m² and their skirting (55 USD). Finally, we also save the cost of a door, at 250 USD per unit.
Replace all ceramic tiles indoors with stamped concrete	Floors area: 114.5m² Same cost as ceramic tiles	0	The cost of stamped concrete is 25 USD/m² and the cost of ceramic tiles is 23.5 USD/m². As such, we adopt a conservative approach and assume no cost savings in this case.
Add insulation in all outer walls	Insulation type: Expanded Polystyrene Insulation thickness: 100 mm	0	The price of EPS is 66 USD/m³ based on quotes from different suppliers. The installation cost is 35 USD/m³ based on internal data from Technical Enterprises Co.
Add photovoltaic panels to roof	Panel type: monocrystalline Panel power rating: 415 W_p Panel size: 2 m² Orientation: East and West Slope: 15° Includes 24 batteries and an inverter	Panels: 1 Batteries and inverter: 4	The price for the considered system is based on a quote from an international suppliers. The total cost of the system is 2.13 USD/W_p, including shipping (1.95 USD/W_p without shipping). The solar panels with their mounting system cost 0.303 USD/W_p at the factory. Each tubular gel battery costs 240 USD at the factory. We assume shipping one container from China containing the panels, batteries and mounting system (a container can accommodate 360 panels and 420 batteries). The cost of the shipping totals 9558 USD (5% custom duties, 11% value-added tax, 140 USD stamp fee, 500 USD clearance fee, 1000 USD container shipment from China, 600 USD inland transport by truck). The price of the inverter is considered as an average 0.15 USD/W_p based on current market prices. Another 0.15 USD/W_p are added for design and installation costs. A final 0.1 USD/W_p is considered for electrical accessories.
Add photovoltaic panels to the south façade	Place panels on the face of balconies and flower pots only. Slope: 90°, azimuth: 0° Orientation: South Other parameters same as above	Panels: 1	We use the same cost per W_p as for the roof photovoltaic panels, and depending on the number of storeys (see Table 4). To that, we add savings resulting from not covering the surface of the panels with natural stone underneath, at a cost of 47 USD/m².

Combination of all the above + convert all operational end-uses to electricity	Panel area: 64 m² New annual delivered electricity demand: 3 202 kWh Total photovoltaic array size per apartment: 6.588 kW_p	See above	Combining all the measures above yields some compounding effects. The total additional capital cost per apartment is 11 400 USD and Net Present Value is -7 160 USD.

Note: ΔNPV= difference in net present value; ΔLCEE= difference in life cycle embodied energy; ΔLCEGHG= difference in life cycle embodied greenhouse gas emissions; ΔLCOPE= difference in life cycle operational energy; ΔLCOPGHG= difference in life cycle operational greenhouse gas emissions; ΔLCC= difference in life cycle cost.

References

[1] IPCC. Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA: Intergovernmental Panel on Climate Change; 2013.

[2] IPCC. Global warming of 1.5 °C an IPCC special report on the impacts of global warming of 1.5 °C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty. In: Allen M, Babiker M, Chen Y, Coninck Hd, Connors S, Diemen Rv, et al., editors. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA: Intergovernmental Panel on Climate Change; 2018. p.34.

[3] IEA. World energy outlook 2019. Paris: International Energy Agency; 2019. p.810.

[4] EC. Directive 2010/31/EU of the European Parliament and the Council of the European Union of the 19 May 2010 on the Energy Performance of Buildings. Official Journal of the European Communities. Brussels: European Parliament and the Council of the European Union; 2010. p.23.

[5] Feist W. What is a Passive House? Passivhaus Institute2007.

[6] Marszal AJ, Heiselberg P, Bourrelle JS, Musall E, Voss K, Sartori I, et al. Zero Energy Building – A review of definitions and calculation methodologies. Energ Buildings. 2011;43:971-9. doi:https://doi.org/10.1016/j.enbuild.2010.12.022

[7] Blengini GA, Di Carlo T. The changing role of life cycle phases, subsystems and materials in the LCA of low energy buildings. Energ Buildings. 2010;42:869-80. doi:https://www.doi.org/10.1016/j.enbuild.2009.12.009

[8] Stephan A, Crawford RH, de Myttenaere K. A comprehensive assessment of the life cycle energy demand of passive houses. Appl Energ. 2013;112:23-34. doi:http://dx.doi.org/10.1016/j.apenergy.2013.05.076

[9] Goggins J, Moran P, Armstrong A, Hajdukiewicz M. Lifecycle environmental and economic performance of nearly zero energy buildings (NZEB) in Ireland. Energ Buildings. 2016;116:622-37. doi:https://doi.org/10.1016/j.enbuild.2016.01.016

[10] Cellura M, Guarino F, Longo S, Mistretta M. Energy life-cycle approach in Net zero energy buildings balance: Operation and embodied energy of an Italian case study. Energ Buildings. 2014;72:371-81. doi:10.1016/j.enbuild.2013.12.046

[11] Chastas P, Theodosiou T, Bikas D. Embodied energy in residential buildings-towards the nearly zero energy building: A literature review. Building and Environment. 2016;105:267-82. doi:http://dx.doi.org/10.1016/j.buildenv.2016.05.040

[12] Hernandez P, Kenny P. From net energy to zero energy buildings: Defining life cycle zero energy buildings (LC-ZEB). Energ Buildings. 2010;42:815-21. doi:https://doi.org/10.1016/j.enbuild.2009.12.001

[13] United Nations DoEaSA, Population Division. World Population Prospects 2019: Press Release. New York 2019.

[14] Wilson A, Boehland J. Small is Beautiful U.S. House Size, Resource Use, and the Environment. J Ind Ecol. 2005;9:277-87. doi:https://www.doi.org/10.1162/1088198054084680

[15] Stephan A, Crawford RH. The relationship between house size and life cycle energy demand: Implications for energy efficiency regulations for buildings. Energy. 2016;116, Part 1:1158-71. doi:http://dx.doi.org/10.1016/j.energy.2016.10.038

[16] Stephan A, Stephan L. Reducing the total life cycle energy demand of recent residential buildings in Lebanon. Energy. 2014;74:618-37. doi:http://dx.doi.org/10.1016/j.energy.2014.07.028

[17] Stephan A, Stephan L. Life cycle energy and cost analysis of embodied, operational and user-transport energy reduction measures for residential buildings. Appl Energ. 2016;161:445-64. doi:http://dx.doi.org/10.1016/j.apenergy.2015.10.023

[18] European Standard 15978. Sustainability of construction works -Assessment of environmental performance of buildings - Calculation method. Brussels: European Committee for Standardization (CEN); 2011. p.66.

[19] UKGBC. Net Zero Carbon Buildings: A Framework Definition. London: United Kingdom Green Building Council; 2019. p.25.

[20] Attia S, Hamdy M, O'Brien W, Carlucci S. Assessing gaps and needs for integrating building performance optimization tools in net zero energy buildings design. Energ Buildings. 2013;60:110-24. doi:http://dx.doi.org/10.1016/j.enbuild.2013.01.016

[21] Leckner M, Zmeureanu R. Life cycle cost and energy analysis of a Net Zero Energy House with solar combisystem. Appl Energ. 2011;88:232-41. doi:http://dx.doi.org/10.1016/j.apenergy.2010.07.031

[22] Cao X, Dai X, Liu J. Building energy-consumption status worldwide and the state-of-the-art technologies for zero-energy buildings during the past decade. Energ Buildings. 2016;128:198-213. doi:https://doi.org/10.1016/j.enbuild.2016.06.089

[23] Hamdy M, Nguyen A-T, Hensen JLM. A performance comparison of multi-objective optimization algorithms for solving nearly-zero-energy-building design problems. Energ Buildings. 2016;121:57-71. doi:https://doi.org/10.1016/j.enbuild.2016.03.035

[24] D'Agostino D, Mazzarella L. What is a Nearly zero energy building? Overview, implementation and comparison of definitions. Journal of Building Engineering. 2019;21:200-12. doi:https://doi.org/10.1016/j.jobe.2018.10.019

[25] Kim D, Cho H, Koh J, Im P. Net-zero energy building design and life-cycle cost analysis with air-source variable refrigerant flow and distributed photovoltaic systems. Renew Sust Energ Rev. 2020;118:109508. doi:https://doi.org/10.1016/j.rser.2019.109508

[26] Crawford RH. Zero-emissions housing: the great impossible Australian dream? 44th Annual Conference of the Architectural Science Association, ANZAScA 2010. Auckland, New Zealand: Unitec Insitute of Technology; 2010.

[27] Birge D, Berger AM. Transitioning to low-carbon suburbs in hot-arid regions: A case-study of Emirati villas in Abu Dhabi. Building and Environment. 2019;147:77-96. doi:https://doi.org/10.1016/j.buildenv.2018.09.013

[28] Stephan A, Crawford RH. A multi-scale life-cycle energy and greenhouse-gas emissions analysis model for residential buildings. Archit Sci Rev. 2014;57:39-48. doi:http://dx.doi.org/10.1080/00038628.2013.837814

[29] Satola D, Wiberg AH, Gustavsen A. Towards Zero Emission Residential Buildings (ZEBs) in a Humid Subtropical Climate. Analysis Emissions from Energy Use and Embodied Emissions from Materials in Referential Locations According to Obligatory Residential Energy Codes and Using Generic LCA Data Sources. In: Wang Z, Zhu Y, Wang F, Wang P, Shen C, Liu J, editors. Proceedings of the 11th International Symposium on Heating, Ventilation and Air Conditioning (ISHVAC 2019). Singapore: Springer Singapore; 2020. p.979-89.

[30] Yin RK. Case study research and applications: design and methods. Sixth ed. Los Angeles: SAGE; 2018.

[31] Fellows R, Liu A. Research methods for construction. Fourth ed. The Atrium, Southern Gate, Chichester, West Sussex , United Kingdom: John Wiley & Sons, Ltd; 2015.

[32] Technical Enterprises Co. *Le Peuplier - New Sehaileh*, Available from www.tecentlb.com, 2013 (Accessed July 22nd 2013).

[33] Department of Climate Change and Energy Efficiency. National greenhouse accounts factors. Canberra: Commonwealth of Australia; 2011. p.77.

[34] Crawford RH, Stephan A, Prideaux F. Environmental Performance in Construction (EPiC) database. Melbourne: The University of Melbourne; 2019.

[35] Principi P, Fioretti R. A comparative life cycle assessment of luminaires for general lighting for the office – compact fluorescent (CFL) vs Light Emitting Diode (LED) – a case study. J Clean Prod. 2014;83:96-107. doi:http://dx.doi.org/10.1016/j.jclepro.2014.07.031

[36] Kinab E, Elkhoury M. Renewable energy use in Lebanon: Barriers and solutions. Renew Sust Energ Rev. 2012;16:4422-31. doi:http://dx.doi.org/10.1016/j.rser.2012.04.030

[37] Finnveden G, Hauschild MZ, Ekvall T, Guinée J, Heijungs R, Hellweg S, et al. Recent developments in life cycle assessment. J Environ Manage. 2009;91:1-21. doi:https://www.doi.org/10.1016/j.jenvman.2009.06.018

[38] Suh S, Lenzen M, Treloar GJ, Hondo H, Horvath A, Huppes G, et al. System boundary selection in life-cycle inventories using hybrid approaches. Environ Sci Technol. 2004;38:657-64.

[39] Majeau-Bettez G, Strømman AH, Hertwich EG. Evaluation of process- and input-output-based life cycle inventory data with regard to truncation and aggregation issues. Environ Sci Technol. 2011;45:10170-7. doi:https://www.doi.org/10.1021/es201308x

[40] Crawford RH, Stephan A. The significance of embodied energy in certified passive houses. ICCBM 2013: International Conference on Construction and Building Materials. Copenhagen: World Academy of Science, Engineering and Technology; 2013. p.473-9.

[41] Crawford RH, Stephan A, Prideaux F. A comprehensive database of environmental flow coefficients for construction materials: closing the loop in environmental design. In: Agrawal A, editor. Revisiting the Role of Architecture for 'Surviving' Development 53rd International Conference of the Architectural Science Association 2019. Roorkee, India: The Architectural Science Association; 2019.

[42] Leontief W. Environmental repercussions and the economic structure: an input-output approach. Rev Econ Statistics. 1970;52:262-71.

[43] Isard W, Romanoff E. Water Use and Water Pollution Coefficients: Preliminary Report. Technical paper No. 6. Cambridge, MA, USA: Regional Science Research Institute; 1967.

[44] Lenzen M. Errors in Conventional and Input-Output-based Life-Cycle Inventories. J Ind Ecol. 2000;4:127-48. doi:https://www.doi.org/10.1162/10881980052541981

[45] Crawford RH, Bontinck P-A, Stephan A, Wiedmann T, Yu M. Hybrid life cycle inventory methods – a review. J Clean Prod. 2018;172:1273-88. doi:https://doi.org/10.1016/j.jclepro.2017.10.176

[46] Pomponi F, Lenzen M. Hybrid life cycle assessment (LCA) will likely yield more accurate results than process-based LCA. J Clean Prod. 2018;176:210-5. doi:https://doi.org/10.1016/j.jclepro.2017.12.119

[47] Lenzen M, Crawford RH. The Path Exchange Method for Hybrid LCA. Environ Sci Technol. 2009;43:8251-6. doi:https://www.doi.org/10.1021/es902090z

[48] Stephan A, Crawford RH, Bontinck P-A. A model for streamlining and automating path exchange hybrid life cycle assessment. Int J Life Cycle Ass. 2018;24:237-52. doi:https://www.doi.org/10.1007/s11367-018-1521-1

[49] Ding G. The development of a multi-criteria approach for the measurement of sustainable performance for built projects and facilities [Ph.D. thesis]. Sydney: University of Technology; 2004.

[50] NAHB, Bank of America. Study of life expectancy of home materials. In: Jackson J, editor. Washington DC: National Association of Home Builders; 2007. p.19.

[51] Stephan A. Towards a comprehensive energy assessment of residential buildings. A multi-scale life cycle energy analysis framework [Ph.D. thesis]. Brussels: Université Libre de Bruxelles and The University of Melbourne; 2013.

[52] Bataineh KM, Fayez N. Analysis of thermal performance of building attached sunspace. Energ Buildings. 2011;43:1863-8. doi:http://dx.doi.org/10.1016/j.enbuild.2011.03.030

[53] MOE/UNDP/GEF. National Greenhouse Gas Inventory Report and Mitigation Analysis for the Energy Sector in Lebanon. Beirut: Ministry of Environment, United Nations Development Program and Global Environment Facility; 2015. p.76.

[54] UNDP/GEF/MPWT/DGU. Climatic Zoning for Buildings in Lebanon. United National Development Program, Global Environment Facility, Ministry of Public Works and Transport and Lebanese General Directorate of Urban Planning; 2005. p.43.

[55] MeteoTest. Meteonorm 7.1.3. Bern 2012.

[56] MEW. Policy Paper for the Electricity Sector - (COM#1-21/06/2010). Beirut: Ministry of Energy and Water; 2010.

[57] Stephan A, Stephan L. Life cycle water, energy and cost analysis of multiple water harvesting and management measures for apartment buildings in a Mediterranean climate. Sustainable Cities and Society. 2017;32:584-603. doi:https://doi.org/10.1016/j.scs.2017.05.004

[58] Tian W. A review of sensitivity analysis methods in building energy analysis. Renew Sust Energ Rev. 2013;20:411-9. doi:http://dx.doi.org/10.1016/j.rser.2012.12.014

[59] Pesonen H, Ekvall T, Fleischer G, Huppes G, Jahn C, Klos Z, et al. Framework for scenario development in LCA. Int J Life Cycle Ass. 2000;5:21-30. doi:10.1007/bf02978555

[60] Berk JB, DeMarzo PM. Corporate finance. 2nd edition ed. Boston: Pearson Education; 2010.

[61] Morrissey J, Horne RE. Life cycle cost implications of energy efficiency measures in new residential buildings. Energ Buildings. 2011;43:915-24. doi:https://www.doi.org/10.1016/j.enbuild.2010.12.013

[62] Asdrubali F, Baggio P, Prada A, Grazieschi G, Guattari C. Dynamic life cycle assessment modelling of a NZEB building. Energy. 2020;191:116489. doi:https://doi.org/10.1016/j.energy.2019.116489

[63] Crawford RH. Life cycle assessment in the built environment. London: Spon Press; 2011.

[64] Gram-Hanssen K. Residential heat comfort practices: understanding users. Build Res Inf. 2010;38:175-86. doi:https://www.doi.org/10.1080/09613210903541527

[65] Molenbroek E, Stricker E, Boermans T. Primary energy factors for electricity in buildings: Toward a flexible electricity supply. Utrecht: Ecofys; 2011.

[66] Hertwich E, Heeren N, Kuczenski B, Majeau‐Bettez G, Myers Rupert J, Pauliuk S, et al. Nullius in Verba: Advancing Data Transparency in Industrial Ecology. J Ind Ecol. 2018;22:6-17. doi:https://www.doi.org/10.1111/jiec.12738

[67] Stephan A, Stephan L. *Data used to quantify the life cycle cost, primary energy and greenhouse gas emissions of a net zero life cycle primary energy and greenhouse gas emissions apartment building in a Mediterranean climate*, Available from https://doi.org/10.6084/m9.figshare.12452615, 2020 (Accessed).

[68] Martinopoulos G. Are rooftop photovoltaic systems a sustainable solution for Europe? A life cycle impact assessment and cost analysis. Appl Energ. 2020;257. doi:https://www.doi.org/10.1016/j.apenergy.2019.114035

[69] Parkin A, Herrera M, Coley DA. Net-zero buildings: when carbon and energy metrics diverge. Buildings and Cities. 2020;1:86-99. doi:https://www.doi.org/10.5334/bc.27

[70] Oregi X, Hernandez P, Gazulla C, Isasa M. Integrating Simplified and Full Life Cycle Approaches in Decision Making for Building Energy Refurbishment: Benefits and Barriers. Buildings. 2015;5:354-80.

[71] WGBC. Bringing embodied carbon upfront. London: World Green Building Council,; 2019. p.35.

[72] Säynäjoki A, Heinonen J, Junnila S. A scenario analysis of the life cycle greenhouse gas emissions of a new residential area. Environ Res Lett. 2012;7:034037.

[73] Myers F, Fuller R, Crawford RH. The potential to reduce the embodied energy in construction through the use of renewable materials. In: Skates H, editor. ASA2012: The 46th Annual Conference of the Architectural Science Association - Building on Knowledge: Theory and Practice. Gold Coast 2012.

[74] Head M, Levasseur A, Beauregard R, Margni M. Dynamic greenhouse gas life cycle inventory and impact profiles of wood used in Canadian buildings. Building and Environment. 2020;173. doi:https://www.doi.org/10.1016/j.buildenv.2020.106751

[75] Clune S, Morrissey J, Moore T. Size matters: House size and thermal efficiency as policy strategies to reduce net emissions of new developments. Energy Policy. 2012;48:657-67. doi:http://dx.doi.org/10.1016/j.enpol.2012.05.072

[76] Helal J, Stephan A, Crawford RH. Beyond the “premium-for-height” framework for designing the structural systems of tall buildings. In: Rajagopalan P, editor. Engaging Architectural Science: Meeting the Challenges of Higher Density: 52nd International Conference of the Architectural Science Association 2018. Melbourne, Australia: The Architectural Science Association and RMIT University; 2018.

[77] Helal J, Stephan A, Crawford RH. Towards a design framework for the structural systems of tall buildings that considers embodied greenhouse gas emissions. In: Cruz PJS, editor. Structures and Architecture: Bridging the Gap and Crossing Borders. Lisbon, Portugal: CRC Press; 2019. p.881-8.

[78] Helal J, Stephan A, Crawford RH. The influence of structural design methods on the embodied greenhouse gas emissions of structural systems for tall buildings. Structures. 2020;24:650-65. doi:https://doi.org/10.1016/j.istruc.2020.01.026

[79] Abohela I, Hamza N, Dudek S. Effect of roof shape, wind direction, building height and urban configuration on the energy yield and positioning of roof mounted wind turbines. Renew Energ. 2013;50:1106-18. doi:https://doi.org/10.1016/j.renene.2012.08.068

[80] Foster Robert M, Reynolds Thomas PS, Ramage Michael H. Proposal for Defining a Tall Timber Building. Journal of Structural Engineering. 2016;142:02516001. doi:https://www.doi.org/10.1061/(ASCE)ST.1943-541X.0001615

[81] Steemers K. Energy and the city: density, buildings and transport. Energ Buildings. 2003;35:3-14. doi:Pii S0378-7788(02)00075-0

[82] Treloar GJ. A comprehensive embodied energy analysis framework [Ph.D. Thesis]. Geelong: Deakin University; 1998.

[83] García-Casals X. Analysis of building energy regulation and certification in Europe: their role, limitations and differences. Energ Buildings. 2006;38:381-92. doi:https://www.doi.org/10.1016/j.enbuild.2005.05.004

[84] Szalay AZ-Z. What is missing from the concept of the new European Building Directive? Building and Environment. 2007;42:1761-9. doi:https://www.doi.org/10.1016/j.buildenv.2005.12.003

[85] Stephan A, Crawford RH, de Myttenaere K. Towards a comprehensive life cycle energy analysis framework for residential buildings. Energ Buildings. 2012;55:592-600. doi:https://www.doi.org/10.1016/j.enbuild.2012.09.008

[86] Crawford RH, Bartak EL, Stephan A, Jensen CA. Evaluating the life cycle energy benefits of energy efficiency regulations for buildings. Renew Sust Energ Rev. 2016;63:435-51. doi:http://dx.doi.org/10.1016/j.rser.2016.05.061

[87] de Klijn-Chevalerias M, Javed S. The Dutch approach for assessing and reducing environmental impacts of building materials. Building and Environment. 2017;111:147-59. doi:http://dx.doi.org/10.1016/j.buildenv.2016.11.003

[88] IBGE. Primes Energie - 2010. Brussels: Brussels Institute for the Environment; 2010. p.3.

[89] Krizek K, Forysth A, Slotterback CS. Is There a Role for Evidence-Based Practice in Urban Planning and Policy? Planning Theory & Practice. 2009;10:459-78. doi:https://www.doi.org/10.1080/14649350903417241

[90] Sallis JF, Bull F, Burdett R, Frank LD, Griffiths P, Giles-Corti B, et al. Use of science to guide city planning policy and practice: how to achieve healthy and sustainable future cities. The Lancet. 2016;388:2936-47. doi:https://doi.org/10.1016/S0140-6736(16)30068-X

[91] Frantzeskaki N, McPhearson T, Collier MJ, Kendal D, Bulkeley H, Dumitru A, et al. Nature-Based Solutions for Urban Climate Change Adaptation: Linking Science, Policy, and Practice Communities for Evidence-Based Decision-Making. BioScience. 2019;69:455-66. doi:https://www.doi.org/10.1093/biosci/biz042

[92] Lotteau M, Loubet P, Pousse M, Dufrasnes E, Sonnemann G. Critical review of life cycle assessment (LCA) for the built environment at the neighborhood scale. Building and Environment. 2015;93, Part 2:165-78. doi:http://dx.doi.org/10.1016/j.buildenv.2015.06.029

[93] Stephan A, Athanassiadis A. Quantifying and mapping embodied environmental requirements of urban building stocks. Building and Environment. 2017;114:187-202. doi:http://dx.doi.org/10.1016/j.buildenv.2016.11.043

[94] Grandell L, Lehtilä A, Kivinen M, Koljonen T, Kihlman S, Lauri LS. Role of critical metals in the future markets of clean energy technologies. Renew Energ. 2016;95:53-62. doi:https://doi.org/10.1016/j.renene.2016.03.102

[95] Glöser S, Tercero Espinoza L, Gandenberger C, Faulstich M. Raw material criticality in the context of classical risk assessment. Resources Policy. 2015;44:35-46. doi:https://doi.org/10.1016/j.resourpol.2014.12.003