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Towards zero life cycle GHG emissions apartment buildings in Lebanon

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Abstract. Buildings are one of the main drivers of greenhouse gas (GHG) emissions and their life cycle emissions need to be significantly reduced in order to address the unprecedented climate emergency. While there are numerous studies on zero operational energy and GHG emissions buildings, very few studies exist on buildings that aim to reach zero life cycle GHG emissions buildings. The apartment building typology is particularly challenging due to the very small roof area per apartment and the limited capacity for renewable energy generation. This study investigates a four-storey apartment building in Sehaileh, Lebanon and modifies it to reach zero life cycle GHG emissions through a series of measures targeting embodied and/or operational GHG emissions. Both a life cycle GHG emissions analysis and a life cycle cost analysis are conducted on all measures their combination, including the installation of a 50kW$_p$ photovoltaic array for the building. Results demonstrate that it is possible to achieve zero life cycle GHG emissions for that building typology and number of storeys, in a Lebanese Mediterranean climate, but at a net life cycle cost of ~43 kUSD2020 over 50 years, compared to the base case guilding. Implications in terms of policy and further research are discussed.

1. Introduction

It is critical for humanity to rise to the challenge of the current climate emergency in order to mitigate the effects of climate change and adapt to them [1]. This cannot be done without drastically reducing greenhouse gas (GHG) emissions associated with buildings [2], including both emissions required for material production and replacement (i.e. embodied GHG emissions) and emissions occurring during the operation of the building (i.e. operational GHG emissions). While the reduction of operational emissions has been targeted for decades through the reduction of the operational energy of buildings and their improved energy efficiency [3], the reduction of embodied emissions is only becoming a priority now. This is demonstrated by the latest report of the world green building council [4] that calls for an immediate consideration of embodied GHG emissions.

Despite the scientific evidence about the significance of both embodied and operational GHG emissions, there is scarce literature that evaluates if zero life cycle greenhouse emissions buildings can be currently achieved and at what cost. In their review of zero energy buildings, Chastas, Theodosiou et al. [5] demonstrate the need to consider embodied energy and GHG emissions in order to avoid rebound effects. Similarly, Stephan, Crawford et al. [6] reveal that passive houses can use more energy than less efficient buildings when considering their life cycle energy use.

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One of the rare studies that considers life cycle GHG emissions is from Birge and Berger [7] which focus on villas in the United Arab Emirates and quantify their total GHG emissions including how many trees would need to be planted to offset them. However, they do not consider financial cost and use detached dwellings which provide enough roof area for the installation of large photovoltaic arrays. Crawford [8] quantified the size of the photovoltaic array required to achieve a net zero life cycle energy house in Melbourne, Australia. Similarly to Birge and Berger [7], Crawford [8] used a detached house typology and did not include the financial cost. While other studies aiming to evaluate the feasibility of achieving zero life cycle GHG emissions housing, none have focused on the typology of apartment buildings in a Mediterranean context, more specifically in Lebanon. Given the data-poor context of the Levantine region and it being marred by conflict, it is critical to develop the knowledge base to inform current and future housing forms that can help mitigate climate change and address the pressing challenge of our time.

1.1. Aim and Scope

The aim of this paper is to evaluate the feasibility of achieving zero life cycle GHG emissions for a typical apartment buildings in the Mediterranean climate of Lebanon, both from an emissions perspective and from a financial cost perspective.

The scope is limited to a typical case study apartment already investigated by the authors in existing studies [9-11] and to GHG emissions only, over 50 years. The life cycle stages A1-A5 and B4 and B6 (converted to GHG emissions) are taken into account, as per European Standard 15978 [12].

2. Evaluating the feasibility of achieving zero life cycle GHG emissions in apartment buildings

This section describes the overall method used, the case study building and presents the approaches used to quantify embodied and operational GHG emissions as well as offsets.

2.1. Overall research strategy

This paper uses a single representative case study research to explore the feasibility of achieving zero life cycle GHG emissions apartment buildings in Lebanon. The choice of a single case study approach is justified since the research is exploratory in nature, the case study is very representative of recent apartment buildings in Lebanon and data is scarce [13].

The research strategy is depicted in Figure 1 below and consists of calculating the life cycle GHG emissions of a base case apartment building as a benchmark and then modifying it to reduce life cycle GHG emissions as much as possible while offsetting the rest. The measures reduce embodied and/or operational emissions (see Table 1) and are based on standard best practice. The additional life cycle cost required to achieve zero life cycle GHG emissions is calculated to evaluate feasibility.

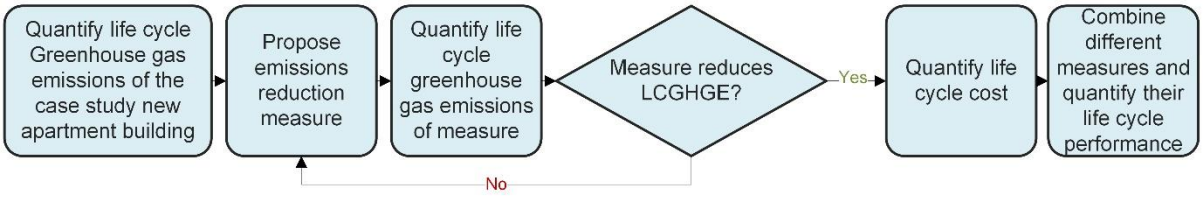

Figure 1: Overall research strategy. Note: LCGHGE = life cycle GHG emissions

2.2. Case study description

The case study building is a four-storey apartment building located in Sehaileh, Lebanon (Mediterranean climate, 515 m above sea level). It comprises two apartment units per storey, each totalling 154 m² in gross floor area (including common areas, such as the lift and stairways) and 113 m² of net floors area. The building is oriented to the south and uses a reinforced concrete structure, a double block cavity wall (2×100 mm concrete blocks with an air gap of 100 mm) and is stone-clad. Double-glazed windows with non-thermally broken aluminium frames are used in all apartment units. The building houses 32 occupants (4 in each of the 8 apartments). Each apartment has a central gas

heating system with radiators (95% efficiency) and air conditioning units (coefficient of performance of 2.5). The south façade and floor plan of the building are depicted in Figure 2. The building is studied over a period of 50 years.



Figure 2: South façade and floor plan of the case study building

This case study building is modified to reduce both its embodied GHG emissions and its operational GHG emissions, using a range of different measures. These measures are summarised in Table 1. Each measure is applied to one apartment and the results are scaled up to the whole building level.

Table 1: Details of adopted measures to reduces the life cycle GHG emissions of the case study building, for each apartment

Measure	**Details**	**Affects EGHGE**[a]	**Affects OPGHGE**[b]
Install a solar thermal collector for each apartment	Collector size: 5 m² Collector type: Vacuum tube Covers: 80% of the domestic hot water demand, the rest are covered by an electric resistance Capital cost: 2 050 USD Replaced: 1× over 50 years	×	×
Replace all lighting from compact fluorescent lights to light emitting diodes	Average LED light power: 7W Quantity: 10 lights per apartment Replace: 4× over 50 years Capital cost: 12.5 USD		×
Replace all electric appliances with energy efficient ones (A+++)	See [10]		×
Replace the air conditioning split systems with energy efficient ones	Quantity: 10 Additional cost: Old CoP[a]: 2.5 New CoP: 5.9		×
Remove radiative heating system and use air conditioning instead	Quantity of radiators removed: 10 Quantity of boilers removed: 1	×	×
Replace central shaft by atrium	Convert surrounding walls to outer wall assemblies (painted, not covered with natural stone).	×	×

Measure	Details	Affects EGHGE[a]	Affects OPGHGE[b]
	Increases daylight indoors, reduces cooling demand in summer.		
Remove internal partition wall between kitchen and living room	Wall area: 19.43m²	×	
Replace all ceramic tiles indoors with stamped concrete	Floors area: 114.5m² Same cost as ceramic tiles	×	
Add insulation in all outer walls	Insulation type: Expanded Polystyrene Insulation thickness: 100 mm	×	×
Add photovoltaic panels to roof	Panel type: monocrystalline Panel power rating: 415 W_p Panel size: 2 m² Orientation: East and West Slope: 15° Replaced: 1× over 50 years Includes 24 batteries and an inverter replaced 4 × times over 50 years	×	×
Add photovoltaic panels to the south façade	Place panels on the face of balconies and flower pots only. Slope: 90° Orientation: South Other parameters same as above	×	×
Combination of all the above + convert all operational end-uses to electricity	New annual delivered electricity demand: 3 200 kWh Total photovoltaic array size per apartment: 6.25 kW_p	×	×

Notes: [a]EGHGE = embodied greenhouse gas emissions, [b]OPGHGE = operational greenhouse gas emissions, [c]: CoP = Coefficient of Performance

2.3. Quantifying embodied greenhouse gas emissions

Embodied GHG emissions represent the sum of all greenhouse gases emitted across all supply chains supporting the production of building materials and the construction of the building and its maintenance (stage A1-A5 and B4 in [12]). These are calculated using a hybrid life cycle inventory technique that combines industrial process data and top-down macroeconomic data to fill gaps in the supply chain and ensure comprehensiveness [14]. The Australian EPiC database [15] is used due to the lack of data for Lebanon, and it being the only readily available hybrid life cycle inventory database for construction materials, globally. For a thorough discussion on the use of an Australian database in a Lebanese context, the reader is referred to the discussion section in [9]. Materials are replaced after a standard useful life from a range of sources. Equation 1 describes the quantification of life cycle GHG emissions. For all measures considered, we only calculated the difference in life cycle embodied GHG emissions with the base case.

$$LCEGHG_b = \sum_{m=1}^{M}\left(Q_{m,b} \times GHGC_m\right) + \left(TGHGIRBS - \sum_{m=1}^{M} TGHGI_m\right) \times C_b + \sum_{m=1}^{M}\left[\left|\frac{POA}{SL_m} - 1\right| \times \left[\left(Q_{m,b} \times GHGC_m\right) + \left(TGHGIRBS - TGHGI_m - NATGHGI_m\right) \times C_{m,b}\right]\right] \quad (1)$$

Where: $LCEGHG_h$ is the life cycle embodied GHG emissions of the building in $kgCO_2e$; M is the total number of materials in the building; $Q_{m,b}$ is the quantity of material m in the building b (e.g. tons of steel); $GHGC_m$ is the EPiC GHG emissions coefficient of material m in $kgCO_2e$ per functional unit; $TGHGIRBS$ is the total GHG emissions intensity of the Australian residential building sector, in

$kgCO_2e$/AUD; $TGHGI_m$ is the total GHG emissions intensity of the input-output pathway representing material m, in $kgCO_2e$/AUD; and C_b is the cost of the building b in AUD; POA is the period of analysis, in years; SL_m is the service life of the material m, in years; $NATGHGI_m$ is the total GHG emissions intensity of all input-output pathways not associated with the installation or production process of material m being replaced, in $kgCO_2e$/AUD, e.g. pathways representing concrete production when replacing aluminium frames; and $C_{m,b}$ is the cost of the material m in AUD in the building b.

2.4. Quantifying operational greenhouse gas emissions

The energy use associated with heating, cooling, lighting, hot water, cooking and appliances are calculated over a time period of 50 years. The energy demand for each end-use is first calculated in final energy terms, converted to delivered energy terms using the efficiency of the appliance and then to primary energy terms using the primary energy conversion factors calculated in [9] in Appendix B. Heating and cooling are modelled using the dynamic energy simulation software DEROB-LTH, developed by the University of Texas and Lund University. DEROB-LTH uses an hourly timestep and a detailed solar radiation model and has been used in the two previous studies of the authors. The energy demand of non-thermal end-uses are calculated based on the power rating and hours of operation of lighting, cooking and appliances and on the daily hot water demand for the latter.

Solar thermal collectors are installed on the roof to reduce the hot water and heating energy demand. All end-uses are electrified in the zero GHG emissions scenario in order to be able to cover their energy demand with solar photovoltaic panels (see Section 2.5).

Operational energy is converted to operational GHG emissions by multiplying the primary energy demand by a relevant emissions factor, according to the energy source. The emissions factors are taken from [16]. For electricity in Lebanon, we use a hybrid coefficient composed of 75% heavy fuel oil (the fuel used by state-operated power plants), i.e. 73.13 $kgCO_2e/GJ^{PRIMARY}$ and 25% diesel, i.e. 69.5 $kgCO_2e/GJ^{PRIMARY}$, used by privately-operated electricity generators, i.e. 72.22 $kgCO_2e/GJ^{PRIMARY}$. The GHG emissions factor for gas is 60.2 $kgCO_2e/GJ^{PRIMARY}$, from [16].

2.5. Quantifying greenhouse gas emissions offsets

Since it is impossible to reach zero life GHG emissions as long fossil fuels are used at any point of any supply chain involved in the building, the embodied GHG emissions need to be offset, on top of operational emissions. This is done by installing solar photovoltaic panels on the roof and the south façade in order to generate more energy than what the building requires and to payback the embodied energy and emissions of the building over its life cycle. The additional electricity generated by the solar panels is multiplied by the primary energy conversion factor for electricity in Lebanon and converted to GHG emissions as if that electricity came from the grid. This enables us to quantify how much GHG emissions have been avoided by producing this electricity with photovoltaic panels. We assume that all additional electricity can be sold back to the grid, which is not the case in Lebanon — Only selected areas are equipped with smart metering and if this is the case, these meters can only go down to zero, i.e. additional electricity is not paid for by the state electricity Electricité du Liban.

2.6. Quantifying life cycle cost

In order to provide a more pragmatic perspective on the feasibility of achieving zero life cycle GHG emissions apartment buildings in Lebanon, we calculate the associated life cycle cost associated. We only capture the difference in capital cost and add the energy savings in USD2020. We also take into account the annualised cost of offsetting GHG emissions through tree planting.

$$NPV_M = \sum_{y=0}^{50} \frac{\left(\Delta Capex_y + ES_y - GHGO_y\right) \times \left(1+CPI\right)^y}{\left(1+r\right)^y} \quad (2)$$

Where:

NPV_M = The net present value of measure M compared to the base case BC over 50 years, in USD2020; y = a specific year; $\Delta Capex_y$ = the capital expenditure in year y, which is the difference between the investment for the considered measure M minus the investment for the base case BC on that specific year y, in USD2020; ES_y = the delivered electricity savings in year y, which are the difference between the electricity spending for the considered measure M minus the electricity spending for the base case on that specific year y, in USD2020; $GHGO_y$= the annualised cost of GHG emissions offsetting through tree planting for year y, in USD2020; 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 civil war and return to normality, based on data from IMF and the Central Administration of Statistics; and r = the discount rate of 12.2%, as calculated in [10].

It is assumed that the residual value of all the building materials and appliances is nil after 50 years, at the end of the period of analysis.

3. Results

Figure 3 depicts the life cycle GHG emissions profiles of the base case and of the net zero life cycle greenhouse emissions building. It reveals that it is possible to offset the entirety of the life cycle operational GHG emissions as well as all embodied emissions of the building if 6.25 kWp of solar panels are installed for each of the 8 units (50 kWp in total), and all other measures are implemented. From a life cycle cost perspective, the combination of all measure requires an additional 83 176 USD in capital cost and results in a net present value of 42 928 USD, over 50 years. This means that implementing these measures never pays back from a financial perspective and therefore, financial support in the form of subsidies, renewable energy buy-back schemes or other forms, is required to be able to achieve net zero life cycle GHG emissions buildings in a Lebanese context.

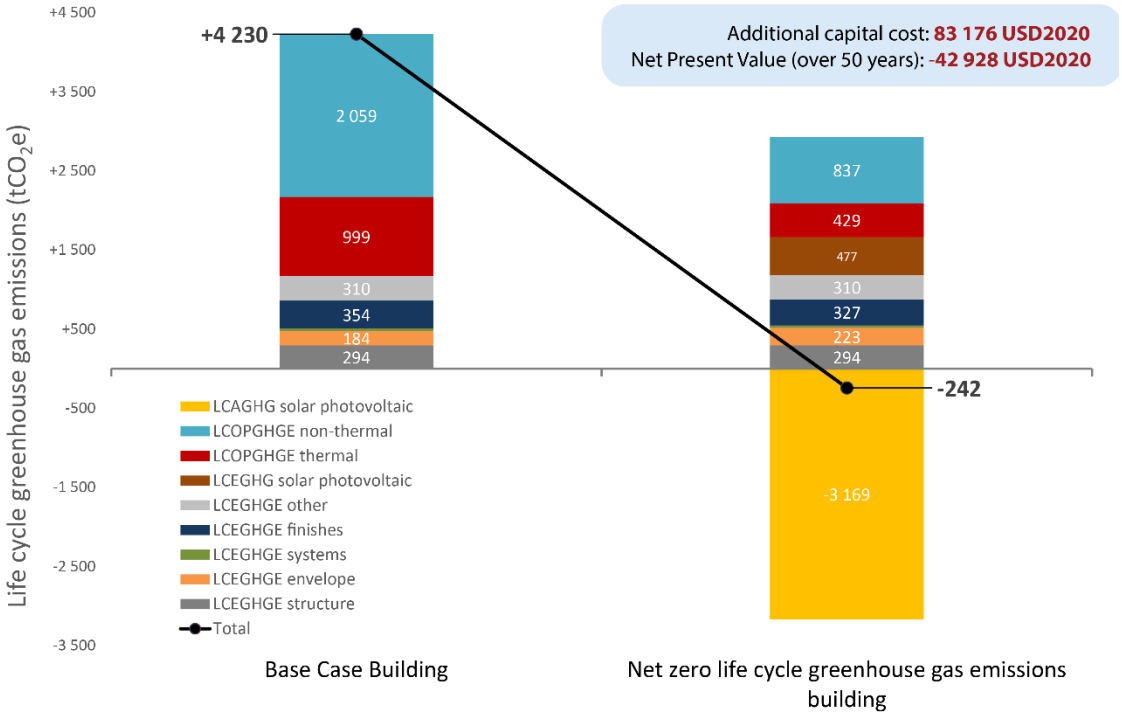

Figure 3: Life cycle greenhouse gas emissions profiles of the base case building and the net zero life cycle GHG emissions building, by use. Note: LCEGHG = life cycle embodied greenhouse gas emissions, LCOPGHGE: life cycle operational greenhouse gas emissions, LCAGHG: life cycle avoided embodied greenhouse gas emissions.

The implications of these findings are discussed in the following section. Note that the zero life cycle GHG emissions building offsets more GHG emissions than needed to reach net zero over 50 years. This margin of 242 tCO_2e is maintained as a buffer to compensate for parameters that were not modeled, such as the decay of the power output of the photovoltaic array over time.

4. Discussion and conclusion

This study demonstrates the feasibility of achieving zero life cycle GHG emissions apartment buildings in a Lebanese context through a range of measures, notably achieving a high energy efficiency and the installation of large photovoltaic arrays to offset both operational and embodied GHG emissions. The additional capital cost to achieve this performance is of 83 768 USD2020 or 10 471 USD2020 per apartment unit, which is not a substantial cost (it is equivalent to the construction cost of 15 additional m²).

This environmental performance is only possible because the solar photovoltaic array is replacing a very emissions-intensive electricity sector (emissions factor of 72.22 $kgCO_2e/GJ^{PRIMARY}$). Should the Lebanese grid witness the installation of large scale renewable energy sources, the array size needed to offset life cycle GHG emissions will increase beyond the physical capacity available on the building (on the roof and the south façade). There is therefore a direct relationship between the GHG emissions intensity of the electricity grid and the ability to achieve zero life cycle GHG emissions buildings through the installation of solar photovoltaic arrays. This relationship has been highlighted before in terms of the emissions payback time of photovoltaic arrays [17]. An interesting indirect relationship can also be established between the GHG emissions intensity of the electricity grid and the number of storeys in apartment buildings in order to achieve zero life cycle GHG emissions. In the Lebanese context, and with the studied typology (two units per storey), the four-storey mark seems to be the threshold that enables achieving this performance. The same building, from five-storeys upwards would not have enough space on the roof and the south façade to offset all embodied GHG emissions over 50 years.

These results have complex implications in terms of urban design recommendations in order to achieve zero life cycle GHG emissions. The announced increased reliance on renewable energy sources for electricity generation globally complicates the use of photovoltaic arrays to offset embodied GHG emissions as each locally produced kWh replaces an increasingly less emissions-intensive grid kWh. This dictates what (residential) building typologies are able to meet zero life cycle GHG emissions as the amount of available area for solar arrays decreases with taller buildings.

This study has limitations, as in any scientific inquiry. Most notably, the limited space available prevented us from expanding on the intricacies of the results and from including a much needed uncertainty analysis section. The latter needs to consider multiple grid decarbonisation scenarios, the influence of the number of storeys, and variability in the operational energy demand. Additional discussion is also needed on the practical policy implications that stem from this study. Finally, to be more holistic, GHG emissions through land-use change need to be taken into account, as called for by Allacker, Souza et al. [18]. Addressing these limitations in future research will further expand the robustness of this study and enable its findings to guide decision-making for a less GHG emissions intensive built environment.

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