

Life cycle energy and cost analysis of embodied, operational and user-transport energy reduction measures for residential buildings

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Abstract

Few studies have evaluated the overall life cycle energy demand of residential buildings, including their embodied, operational and user-transport requirements. To our knowledge, none has quantified the life cycle cost associated with reducing each of the aforementioned energy demands. It is critical to evaluate both energy and financial requirements in order to provide effective energy saving solutions for actors of the built environment.

This study quantifies the life cycle energy and cost requirements associated with 22 different energy reduction measures targeting embodied, operational and user-transport requirements. It evaluates a case study apartment building in Sehaileh, Lebanon. Embodied, operational and transport energy requirements are calculated over 50 years using a comprehensive approach. Life cycle costs are quantified using the net present value technique.

Results identify the most cost effective energy reduction measures and discard some others which are financially prohibitive, namely the installation of photovoltaic panels and the use of hybrid cars. A number of recommendations for building designers, occupants, urban designers and planners and decision makers are provided based on the quantified benefits of each measure. This demonstrates

the need for assessments with a broad scope and their potential to inform energy reduction strategies in the built environment.

Keywords: Life cycle energy analysis; Life cycle cost analysis; Energy efficiency; Residential buildings; Lebanon; Mediterranean.

1 Introduction

The operation of buildings alone is responsible for 30-40% of total energy use, globally [1]. If embodied requirements associated with the production of building materials and transport requirements associated with the mobility of building users are taken into account, the building sector can be considered as the dominant driver of energy use and greenhouse gas emissions [2].

For these reasons, reducing energy use and greenhouse gas emissions across a building's life cycle has been the focus of a large number of studies. However, according to major reviews on the topic [3-7], the majority of existing studies quantify embodied and operational energy use only, omitting transport requirements. In addition, most existing building life cycle energy analysis studies rely on the process analysis technique to quantify embodied energy, resulting in a significant underestimation of the latter [8, 9]. As demonstrated by Stephan et al. [10] and Anderson et al. [2], including embodied, operational and transport requirements as well as relying on comprehensive quantification techniques are key to effectively measure energy use across different scales of the built environment and to provide effective solutions to reduce it. The inclusion of user-transport requirements captures the context of the residential building and links it to the surrounding urban form. Although transport is affected by socio-economic characteristics [11], it is highly conditioned by the urban fabric [12-15], and is therefore directly related to the spatial context of the building. The attribution of user-transport energy to the household is further discussed in Section 3.2. Once the overall energy profile of a residential building is evaluated, it is critical to evaluate the net energy and financial repercussions of various improvement measures in order to provide feasible solutions to the industry [16].

Few studies have quantified the life cycle energy use of buildings across different scales of the built environment or combined life cycle energy and cost analyses. Norman et al. [17] have compared the life cycle energy use of low and high density residential buildings around Toronto, Canada, including

transport requirements. However, their study significantly underestimates embodied requirements. Fuller and Crawford [18] have evaluated the life cycle energy use and greenhouse gas emissions of different housing patterns in and around Melbourne, Australia. While they rely on the comprehensive hybrid analysis to quantify embodied energy, their study does not evaluate specific energy reduction strategies and their financial feasibility. Stephan et al. [10, 19, 20] and Stephan and Crawford [21, 22] have evaluated the overall life cycle energy profile of various residential buildings in Australia, Belgium and Lebanon, including embodied, operational and transport requirements. However, they do not consider financial requirements in their studies.

Kneifel [16] has evaluated the life cycle greenhouse gas emissions and cost of a number of improvement strategies for commercial buildings across the USA. While his study combines both energy and financial requirements, it does not include the transport requirements of building occupants and it underestimates embodied greenhouse gas emissions. Morrissey and Horne [23] have quantified the life cycle cost benefits of the Australian building energy efficiency regulation. They determine the net present value of different thermal performance levels and their financial benefits. While their study contributes to the building energy policy debate, it does not evaluate a range of energy mitigation strategies across the scales of the built environment nor does it consider embodied energy. The latest energy performance of buildings directive (EPBD) in Europe [24] enforces the adoption of so-called 'cost optimal' measure, i.e. measures that result in the lowest life cycle cost. However, this directive focuses solely on operational energy and does not take embodied or user transport energy into account.

To our knowledge, none of the existing studies has evaluated the life cycle energy and cost repercussions of various energy reductions strategies across the different scales of the built environment. In order to effectively reduce energy use in the built environment, it is critical to provide actors of the industry with robust and cost-effective solutions.

1.1 Aim and scope

The aim of this study is to quantify the overall life cycle energy benefits and cost requirements of various energy reduction measures targeting embodied, operational and user transport energy, over the service life of the building. This will identify the most cost effective measures that yield the highest

energy savings and will provide an unprecedented insight into reducing the overall energy use of residential buildings.

This paper focuses on building embodied and operational energy use as well as user-transport energy. It considers the energy demands that can be directly targeted by building designers, occupants, urban planners and designers and decision makers. It does not consider the energy use associated with goods, food and other activities which can also significantly contribute to the overall energy use of a household [25, 26].

The study builds upon the authors' previous work [27] on a case study building located in Sahaileh, Lebanon (see Section 2) to evaluate the cost effectiveness of energy reduction strategies. The previous study has determined the overall life cycle energy profile of a representative new residential building in Lebanon. This study focuses on evaluating the effectiveness of energy reduction solutions, from both life cycle energy and cost perspectives for similar new buildings. The scope of this study is depicted in Figure 1.

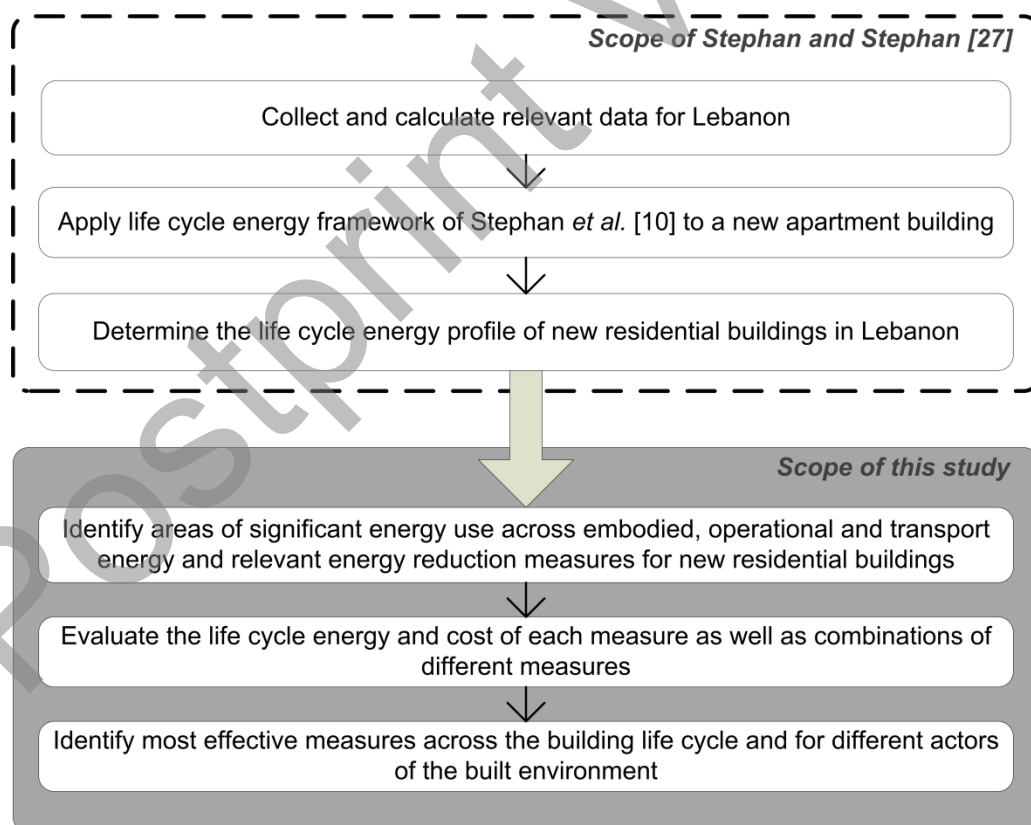


Figure 1: Scope of this study

1.2 Structure

This paper is structured in 6 Sections. Section 2 describes the previous study by Stephan and Stephan [27]. It briefly presents the case study building and its life cycle energy profile. Section 3 describes the method used and the quantification of life cycle energy requirements and life cycle cost. It also describes the investigated energy reduction measures to improve the life cycle energy profile of the base case apartment building presented in Section 2. Supplementary data complementing Section 3 are found in Appendices A, B and C. Section 4 presents the results of the life cycle energy and cost analyses of each energy reduction measure as well as their combination. A sensitivity analysis of the results to the inflation and discount rates is also conducted. Section 5 discusses the findings before concluding in Section 6.

2 Previous study

The previous study by the authors [27] has evaluated for the first time the total life cycle energy demand of a representative case study apartment building in Lebanon over 50 years. It has also quantified the primary energy conversion factor for electricity in Lebanon.

The case study building used in this study is the same as in Stephan and Stephan [27] for consistency. It is a new four-storey apartment building located in the residential town of Sehaileh, on the western side of the Mount-Lebanon ranges in Lebanon, 25 km North of the capital Beirut, at 515 m above sea level. The building is South-oriented and each storey comprises two apartments of 154 m² gross floor area and 113 m² of usable floor area (see Figure 2). It accommodates eight households of four persons or a total of 32 occupants. The building has a reinforced concrete structure with cast *in situ* reinforced concrete slabs which incorporate hollow core concrete blocks. Outer walls are double concrete block (2x100 mm) with an air blade (100 mm) and are stone-clad. Double-glazed windows with aluminium frames and external aluminium roller sunshades are installed. Ceramic floor tiling is used in all rooms. Each apartment is equipped with a central gas heating system (efficiency of 95%) and air conditioning units for cooling (COP of 2.5). Four occupants live in each apartment and each household owns two cars that are driven an average of 20 000 km per year each. No public transport is used trains and tramways are not in operation in Lebanon anymore. 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 [27]. Most of the information on

the building was sourced directly from the construction company [28], resulting in reliable data for many significant variables such as the bill of material quantities, building systems installed and their efficiency. The company also provided access to the tenants and buyers who were interviewed to obtain their average annual car travel distances. The main characteristics of the base case study building are summarised in Table 1 below.



Figure 2: South elevation and floor plan of case study apartment building in Sehaileh, Lebanon.

Note: GFA = Gross floor area. Based on Technical Enterprises Co. [28].

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 m ²
Useful floor area per apartment	113 m ²
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
Roof	Aerated concrete blocks
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%)
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Primary energy conversion factors	Electricity: 3.8 , Gas: 1.1
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Average car travel distance apartment per year (no public transportation)	40 000 km (for two cars and based on interview of inhabitants)
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Average occupancy rate of cars	1.6
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Average fuel economy of cars (direct energy intensity)	10 L/100km (2.13 MJ/pkm)
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Average indirect energy intensity of car transport	2 MJ/pkm
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Total energy intensity of cars	4.13 MJ/pkm
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Note: See Stephan and Stephan [27] for details on all the values in the table

^aCOP = Coefficient of performance

The overall life cycle energy demand of the case study building was evaluated in Stephan and Stephan [27]. This includes:

- the initial embodied energy associated with the production, manufacture, processing, transport and construction of all building materials;
- the recurrent embodied energy associated with the production and replacement of building materials over 50 years;
- the primary operational energy used for heating, cooling, hot water, lighting, appliances and cooking, over 50 years;
- the direct transport energy contained in the fuel burned to drive cars over 50 years; and
- the indirect transport energy required for automobile transport in terms of insurance, registration, advertisement, car manufacture and other indirect activities over 50 years.

In addition to the above, the recurrent embodied energy of nearby infrastructures was quantified but it represented less than 0.3% of the life cycle energy use and is not further considered in this study.

Figure 3 illustrates the life cycle demand of the studied building over 50 years, from the most significant contributor to the lowest. Three main observations can be made.

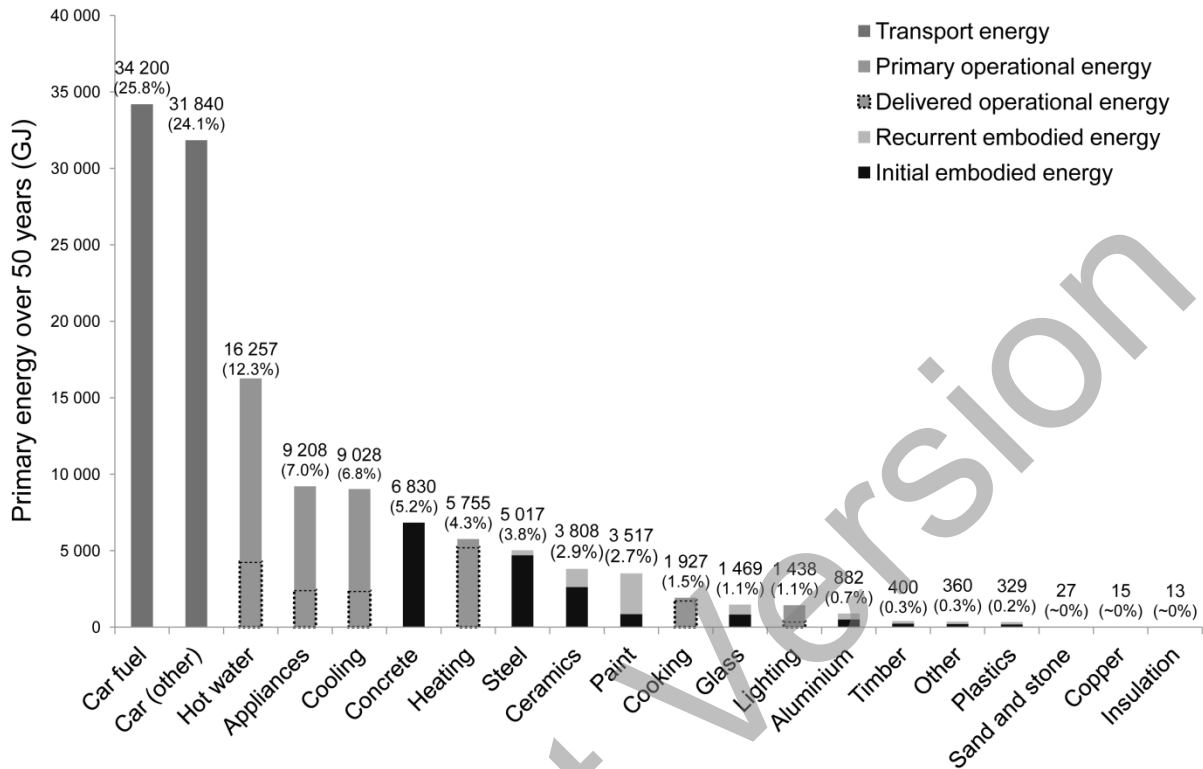


Figure 3: Life cycle energy demand of the case study apartment building in Sehaileh, Lebanon, over 50 years, by use. Based on Stephan and Stephan [27].

Firstly, transport energy is the most significant contributor with 49.9% of the total energy demand over 50 years. This is due to the sole reliance on cars with a relatively poor fuel efficiency (10 L/100km) and long travel distances (40 000 km per year for each household/apartment). Reducing transport energy is therefore a priority.

Secondly, operational energy end uses relying on electricity are the most significant contributors after transport. This is mostly due to the very high primary energy conversion factor (PEF) for electricity in Lebanon (3.8). The significance of the PEF is visible in Figure 3, when comparing delivered to primary energy use for gas heating (PEF = 1.1) and electric cooling (PEF= 3.8). Reducing the operational energy demand therefore requires finding alternative energy sources to electricity where available; relying on energy efficient systems and appliances to counter balance the high PEF of electricity; and reducing the energy demand (for e.g. by installing insulation).

Thirdly, the embodied energy demand is dominated by concrete and steel, the two main structural materials, followed by ceramics, and paint which is replaced every 10 years and results in a significant recurrent embodied energy demand. The embodied energy of ceramics is associated with the floor tiling in the entire apartment. Stephan et al. [20] have shown that ceramic tiles result in the lowest life cycle embodied energy demand compared to other flooring materials such as carpet or parquet because of their long service life. There is therefore little scope in reducing the life cycle embodied energy associated with ceramics and the focus of reduction strategies should be minimising the quantities of concrete and steel in the building as well as reducing the area of painted surfaces.

3 Quantifying the life cycle energy and cost requirements of energy reduction measures

This section describes the overall research method, the quantification algorithms used and the various energy reduction strategies considered. These are presented last so that specific details pertaining to the quantification of life cycle energy and cost can be described and referred back to the quantification algorithms. The base case apartment building is referred to as BC in the text.

3.1 Overall research strategy

Figure 4 depicts the overall research strategy in this paper. After the most significant areas to reduce energy use are identified (see Section 2), targeted energy reduction measures are proposed and their life cycle energy repercussions evaluated. If a measure does not result in an actual reduction of energy use, it is discarded and another measure is investigated. The life cycle cost of effective energy reduction measures is evaluated and effective measures are combined. The life cycle energy and cost of combined measures is re-evaluated because of possible interactions. Finally, a sensitivity analysis of the results to the uncertainty in the data and the assumptions made is conducted.

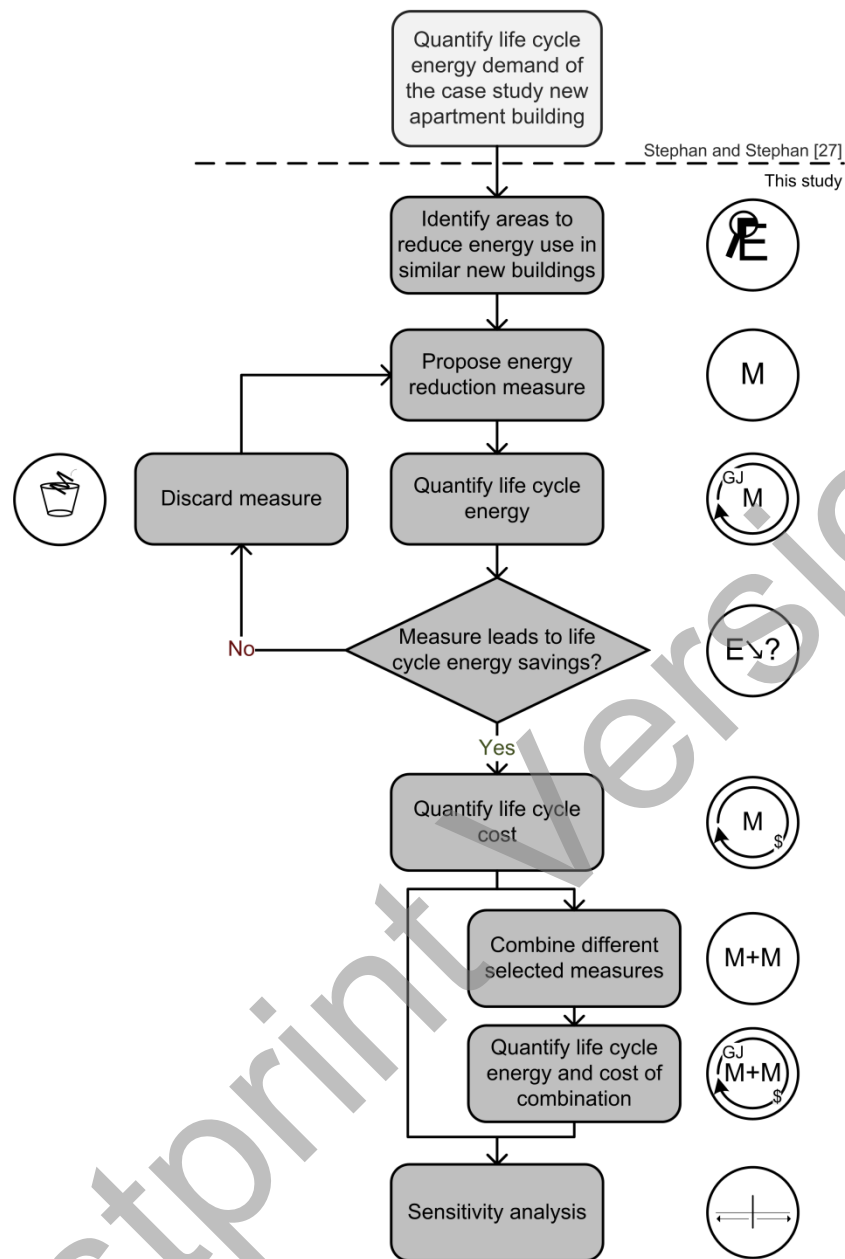


Figure 4: Overall research strategy

3.2 Life cycle energy requirements

Life cycle energy requirements are quantified using the same algorithms as in Stephan and Stephan [27] and explained in detail there. This ensures the comparability of the results. A summary of the life cycle energy quantification approach is given below.

Embodied energy is quantified using the comprehensive input-output-based hybrid analysis technique developed by Treloar [29] and validated by Crawford [8]. This technique combines industrial bottom-up data and economic top-down data. The quantity of each construction material is multiplied by a hybrid embodied energy coefficient from Treloar and Crawford [30] and the resulting embodied

energy is summed to obtain the total initial embodied energy of the building. A so-called input-output remainder which covers non-material energy inputs across the supply chain is added to this value to account for services such as insurance, advertisement, management and others. Energy used during the construction process is taken into account. These comprehensive boundaries explain why input-output-based hybrid analysis generates embodied energy figures that are up to 3-4 times higher than a traditional process-based analysis [20, 31, 32]. Hybrid analysis should therefore be preferred to other life cycle inventory techniques [9, 33, 34]. The recurrent embodied energy 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 [35] and NAHB [36].

Thermal operational energy requirements are computed using DEROB-LTH, a dynamic energy simulation software that includes a detailed solar radiation model [37]. DEROB-LTH uses an hourly timestep and takes into account thermal mass and building occupancy. Non-thermal operational energy requirements are calculated by multiplying the power rating of the system/appliance by its operating hours over the period of analysis. Final energy requirements 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 cooling coefficient of performance of the air conditioning unit). Delivered energy is then converted to primary energy using the primary energy conversion factors for gas (1.1) and electricity (3.8), determined in Stephan and Stephan [27].

Transport energy requirements comprise both direct energy (i.e. burning fuel in the car engine) and indirect requirements (e.g. energy requirements for insurance, registration and car manufacturing). Indirect requirements are based on figures from Lenzen [38] which rely on input-output analysis as in Jonson [39] or Chester and Horvath [40]. The average travel distance per household is multiplied by the average occupancy rate of the cars to obtain the amount of passenger kilometres per year. This is then multiplied by the total energy intensity of car transport (see Table 1). As highlighted by the studies mentioned above [38-40], it is critical to include indirect requirements for a comprehensive assessment of transport energy requirements.

It is important to briefly discuss the allocation of user-transport energy solely to the household. The allocation of indirect energy requirements is problematic in any process that could be attributed to different factors, as discussed in Cleveland [41] and Dixit *et al.* [42]. In this case, it could be argued that the location of the dwelling is not the sole driver of user transport energy and that the location of

other buildings, such as offices, retail and others also affect travel distances. A share of the transport energy use could then be allocated to other building types. The issue arises in how this energy should then be allocated, which is a highly subjective matter. In this study, the entirety of the transport energy is allocated to the dwelling and its occupants for three main reasons. Firstly, the dwelling is the origin and destination of most trips (occupants return home). Secondly, building occupants are the ones using energy for their mobility, even if they travel between different buildings. Thirdly, for life cycle costing purposes, building occupants are paying for the majority of direct and indirect energy requirements. The allocation of transport energy requirements could be further investigated in future research.

Life cycle energy requirements are calculated as the sum of embodied, operational and transport energy requirements over 50 years. The net life cycle energy difference between a scenario with an energy reduction measure M and the BC is given by Equation 1.

$$\Delta LCE_{M|BC} = (LCEE_M - LCEE_{BC}) + (LCOPE_M - LCOPE_{BC}) + (LCTE_M - LCTE_{BC}) \quad (1)$$

Where: $\Delta LCE_{M|BC}$ = the difference in life cycle energy demand between a scenario with an energy reduction measure M and the base case scenario BC , in GJ; $LCEE$ = life cycle embodied energy, in GJ; $LCOPE$ = life cycle operational energy demand, in GJ; and $LCTE$ = life cycle transport energy demand in GJ.

3.3 Life cycle cost requirements

The life cycle cost requirements are calculated in net present value (NPV) terms. For each energy reduction measure considered, the NPV is computed over 50 years, as per Equation 2. The NPV of each measure is calculated as the net difference with the base case scenario. A positive NPV means that the measure is economically worth pursuing.

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

Where:

NPV_M = The net present value of measure M compared to the base case BC over 50 years, in USD; 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 USD; 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 USD; GS_y = the delivered gas savings in year y , which are the difference between the gas spending for the considered measure M minus the gas spending for the base case on that specific year y , in USD; FS_y = the delivered fuel savings in year y , which are the difference between the fuel spending for the considered measure M minus the fuel spending for the base case on that specific year y , in USD; 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. It is calculated as described in Appendix A and has a value of 12.2%.

It is assumed that the residual value of all the building materials, appliances, cars, etc. is nil after 50 years, at the end of the period of analysis. 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, cars and other components are sourced from a market study conducted in March 2015 in Lebanon and are based on average retail prices from major suppliers. 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 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 [27], based on figures from the Lebanese Ministry of Energy and Water [43].

All prices are tax-inclusive and are corrected over the 50 years period of analysis for inflation. 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 fridge replaced every 15 years is the sum of its current price, its price in 2030, 2045 and 2060 as well as the associated electricity use.

Table 2: Average monthly electricity prices in Lebanon as of 2015, in USD/kWh.

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

Table 3: Average generator monthly fee for a 5 A connection in Zouk-Mosbeh, Lebanon for 2014, in USD

Month of 2014	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
Average price for a 5 A connection (USD)	66	67	67	47	47	84	93	97	90	90	66	57
Average (USD)	72.6											
Specific price ^a	0.275 USD/kWh											

Note: ^aThe specific price is based on the assumption of full capacity use (5 A = 1.1 kW) for the entire time the generator is on over 30 days (8 h/day as in Stephan and Stephan [22]). This gives: $1.1 \times 8 \times 30 = 264$ kWh of generator energy per month. The price is therefore: $72.6/264 = 0.275$ USD/kWh.

3.4 Selected energy reduction measures

As discussed in Section 2 and depicted in Figure 3, transport is the most energy intensive use, followed by electrical operational end-uses, heating, and finally concrete and steel that contribute most to the embodied energy demand. Measures aiming at reducing each of these energy uses are described below, by priority. While measures are presented for one household/apartment, results are calculated at the whole building level. These measures are based on existing studies and available technologies. Redesigns to the building floor plan are not considered in order to maintain the same functional unit and ensure the comparability of results. All measures, their acronyms and the relevant assumptions and calculations as summarised in Table C.1, Appendix C.

3.4.1 Reducing transport energy use

Transport is the most significant contributor to the overall energy demand of the studied building and depends mostly on the location of the building and the mobility choices of its occupants. Transport energy could be reduced by relying on public transport instead of using cars. Indeed, Lenzen [38] and Chester and Horvath [40] have demonstrated that public transport can use less than 50% of the

energy needed for petrol cars, per passenger-kilometre. However, the inexistence of alternative transport modes in Lebanon significantly restricts the possible alternatives to automobiles. Evaluating the life cycle energy implications of implementing a railway transit system along the Lebanese coast to link the capital to the other main cities would constitute a major future research but is out of the scope of this study.

Three main measures focusing on reducing car transport energy will be investigated in this study and all of them depend directly on the decisions of building occupants. Firstly, the standard petrol cars used by the occupants will be replaced by hybrid cars (petrol/electric) in the H_CARS measure. Hybrid cars can use much less fuel than current petrol cars used in Lebanon, i.e. 3 L/100km compared to 10 L/100km. Plug-in hybrid cars are not considered because of the very high primary energy conversion factor for electricity in Lebanon (which is detrimental to their performance) as well as their higher price compared to standard hybrid cars. Also, Sharma *et al.* [44] have found that hybrid vehicles have lower life cycle greenhouse gas emissions compared to plug-in hybrid vehicles or purely electric vehicles due mostly to the higher embodied energy of batteries in the latter. They also found that the embodied greenhouse gas emissions of non-plug-in hybrid vehicles (13.7-13.8 tCO₂-e) are only slightly higher than those of conventional petrol vehicles (13.2 tCO₂-e). For this reason, the H_CARS scenario assumes that there is no increase in embodied energy compared to a standard petrol car.

Secondly, the travel distance of each household is reduced by 15% in the TD-15% measure. It is assumed that the annual travel distance can be optimised by combining trips for different purposes (e.g. work, school and grocery shopping). The 15% fraction is an assumption that estimates an average realistic reduction in travel distance based on combining trips. Further travel distance reductions by 10%, 20%, 30% and 40% have been investigated. These are not reported systematically but are discussed where relevant to nuance the findings.

Thirdly, a final measure (CAR_POOL) is considered where the main income earner travels 15 000 km per year using car pooling with neighbours or other workers along the route. This would translate into raising the average car occupancy from 1.6 [27] to 4 and significantly reducing the energy intensity per passenger-kilometre (pkm) over the 15 000 km. The transport energy associated with the remaining 25 000 km is the same as in the base case. It is assumed that each household needs one car instead of two in this measure.

All of the above scenarios are combined in a single scenario (ALL_TE) where occupants reduce their travel distance from 40 000 km to 34 000 km per year. They use one hybrid car for 19 000 km and the remaining 15 000 km, associated with the work-related travel of the main income earner, are travelled by car pooling. The household owns one car in this measure.

3.4.2 Reducing operational energy use

Operational energy is the second largest contributor to the life cycle energy demand and is affected by both the energy efficiency of the building and its systems and the occupants' behaviour. Most measures investigated in this study focus on the choice of systems from a building designer's perspective. Six different measures are investigated.

Firstly, the domestic hot water primary energy use, which represents the most significant primary operational energy use (16 257 GJ, 12.3%) is reduced by installing solar hot water collectors (SOLAR_COLL). Crawford and Treloar [45] have demonstrated that solar collectors result in significant life cycle energy savings in Melbourne's climate which has a lower annual solar irradiation than Sehaileh, Lebanon. In addition, Ruble and El Khoury [46] have clearly highlighted the potential of solar hot water collector in the Lebanese context. A vacuum tube collector of 4.8 m² with a gas auxiliary system is considered for each apartment. The system is tilted at 70° to the South in order to maximise mid-season output and cover part of the heating demand. This system provides 90% of the annual hot water demand of each apartment.

The second investigated measure is the replacement of all conventional appliances by energy efficient appliances (EFF_APP) because the primary operational energy use for appliances represented 9 208 GJ or 7% of the total energy demand. Ruble and Karaki [47] have investigated the cost benefits of implementing mandatory energy efficiency levels for appliances in Lebanon. They have found that energy efficient air conditioning units, fridges/freezers, washing machines and lighting systems can result in significant energy savings. In this study, some of the most energy efficient fridges/freezers, washing machines and televisions are installed instead of the appliances considered in the BC. The price of new appliances is obtained from current retailers in Lebanon. However, the price of the appliances in the BC could not be obtained as most of these are not available on the market anymore. It has been assumed that the BC appliances cost 15% less on investment than their energy efficient counterparts based on the average current price difference between a standard

appliance and a very energy efficient appliance on the Lebanese market. This is also assumed for future appliance replacements where the most energy efficient type would be about 15% more expensive than the less efficient one. Efficient cooling and lighting are investigated separately. Details regarding the efficiency of the appliances can be found in Table C.1, Appendix C.

Thirdly, the cooling energy demand is reduced by using a highly efficient air conditioning unit with a coefficient of performance (COP) of 5.9 (compared to 2.5 in the BC) in the EFF_AC scenario. This efficiency rating is based on the manufacturer's specifications. This replacement falls in line with the studied energy efficient appliance of Ruble and Karaki [47].

Fourthly, the heating and cooling energy demands are reduced by adding 50 mm of expanded polystyrene (EPS) insulation in the walls and the roof in the INSUL+ scenario. This insulation layer can be easily added in the current 100 mm air blade of the outer wall assembly. The benefits of increasing building insulation to reduce heating requirements (notably compared to non-insulated buildings) have been demonstrated by a number of studies in different countries, e.g. [48-53]. The effect of insulation on the cooling demand is less clear. Indeed, Masoso and Grobler [54] and Li *et al.* [55] show that additional insulation does not always result in its reduction, depending on the desired indoor temperature and the type of climate. Nevertheless, insulation is still considered in this study because the majority of new apartment buildings in Lebanon are not insulated at all. The insulation thickness of 50 mm is chosen to ensure that it can be easily installed in buildings with a narrower air blade in their cavity outer walls (compared to the case study building).

The fifth measure to reduce operational energy is the installation of energy efficient light emitting diodes (LED) lighting in the LED scenario. The BC already uses compact fluorescent light bulbs (CFL) but LED lights can further reduce the lighting energy demand by more than 43% during the use phase [56].

The sixth measure targets all operational energy end-uses running on electricity and consists of installing photovoltaic panels on the roof in the PV scenario. While Kinab and El Khoury [57] have found that photovoltaic panels are too costly to be considered in Lebanon in 2011, they are taken into account in this study because their price has sharply decreased since then and also because they can provide significant life cycle primary energy savings. A 3 kWp monocrystalline photovoltaic system, comprising 9 panels of 388 Wp, 1 inverter and 24 tubular gel batteries of 800 Ah each is

considered for each apartment. The system is sized in order to cover 65% of the annual electricity demand. Note that the installation of batteries is a significant handicap to the large scale deployment of PV systems in Lebanon both from a cost and embodied energy points of view as well as disposal and related environmental impacts which are not considered in this paper. If no batteries are installed, a consistent electricity supply cannot be guaranteed without a connection to a local generator because of the systematic daily electricity shortage from the state electricity EdL. In addition, EdL's current grid state does not allow private parties to feed electricity back in most locations in Lebanon. The grid cannot therefore be used for storage and batteries are required.

All the above measures are combined in a single ALL_OPE measure where cumulative benefits and synergies can be assessed. For example, the cooling demand could be reduced by additional insulation and the installation of a high COP air conditioning unit. This would lead to a reduced electricity demand which in turns would lead to a smaller photovoltaic system that can cover a larger solar fraction. Combining different measures together can multiply their individual benefits, notably from a system sizing point of view.

3.4.3 Reducing embodied energy use

Embodied energy contributes the least to the life cycle energy demand of the studied building. This is due to a combination of factors, notably the relatively low recurrent embodied energy due to the durability of the materials used (e.g. stone cladding, ceramic tiles) and the small living area per capita which directly affects the contribution of embodied energy to the total. Indeed, a significant part of operational energy (hot water, appliances and cooking) and the entirety of transport energy are based on the number of occupants and not on the floor area. Conversely, embodied energy is directly associated to the quantities of different materials and therefore to the living area. In their comparison of the life cycle energy profile of dwellings in Australia, Belgium and Lebanon, Stephan and Crawford [22] found that the contribution of embodied energy to the total was the lowest for the Lebanese apartment due to its much smaller living area per capita (28 m² compared to 60 m² and 82 m²).

In this study, since the floor plan cannot be modified, the major means to reduce embodied energy is to either seek alternative construction materials or to adopt a design with a reduced quantity of materials. (Even if the floor plans could be altered, it would be hard to reduce the living floor area per capita below the 28 m² mark.) The only two measures considered to reduce embodied energy target

the reduction of the quantities of steel and concrete, the top two contributors to embodied energy (see Figure 3). The focus on reducing steel and concrete is supported by Huberman and Pearlmutter [58] and Huberman *et al.* [59] who find that ~66% of the initial embodied energy of a typical concrete frame and block construction (such as the case study apartment building) results from its reinforced concrete structure.

The structural system used in the BC and in most new apartment buildings in Lebanon and many other countries is a typical reinforced concrete (RC) structure. This structure has shallow foundations lying on rocky ground in which columns are anchored. These support RC slabs with incorporated beams within the slab thickness (typically 250 mm). Slabs are constituted of hollow core concrete blocks aligned perpendicularly to the beams and intermittently separated by RC ribs. The latter typically have an inverted triangle section and are assembled on site, resulting in significant amounts of waste.

Firstly, the steel ribs assembled *in situ* are replaced by prefabricated ribs in the PREFAB_RIBS measure. Prefabricating ribs results in less waste and therefore less material use and associated embodied energy. In addition, prefabricated ribs are prestressed, resulting in increased strength and an additional reduction in material use. A 22% reduction of steel in each rib was obtained based on detailed structural calculations that ensure the same service and ultimate limit states as the original structure.

The second measure consists of replacing the hollow core concrete blocks which represent the bulk of the slab by expanded polystyrene blocks (EPS) in the EPS_FILL scenario. While an EPS block has a slightly larger embodied energy than a hollow core concrete block of the same volume, the use of EPS blocks results in a significant reduction in the overall weight of the slabs. This in turn leads to a reduction of 15% in the steel reinforcement of beams and columns while maintaining compliance with the Lebanese seismic requirements.

These two measures are combined in a single ALL_EE scenario. This scenario cannot currently be applied in Lebanon as the available EPS fillings on the market are not compatible with the prefabricated ribs. It is considered nonetheless to investigate its potential.

3.4.4 Reducing life cycle energy

All the energy reduction measures above are combined. Two versions of this combination are generated, one comprising the installation of PV panels (ALL) and one without (ALL_NO_PV). This is due to the significant investment cost of PV and the potential unavailability of roof space.

Table C.1, Appendix C summarises all studied measures and indicates for each measure its acronym, the targeted and affected energy uses as well as details pertaining to life cycle energy and cost calculations. Data from [27, 56, 57, 60] are used in the calculations.

4 Results

The life cycle energy analysis of the measures is first described in Section 4.1. The life cycle cost results are then combined with the life cycle energy analysis in Section 4.2. Section 4.3 evaluates the impact of the inflation and discount rates on the results by conducting a sensitivity analysis. All numbers are calculated for the entire building (comprising 8 apartment units, each housing 4 occupants). Results are expressed in GJ, GJ/m² and in GJ/capita where relevant. The base case is referred to as BC.

4.1 Life cycle energy analysis

Figure 5 presents the life cycle energy repercussions of each investigated measure. Measures targeting the life cycle embodied, operational, transport and total energy demands are discussed below, in this order.

Embodied energy is the hardest energy demand to reduce while conserving the same functional unit. Indeed, typical embodied energy reduction measures involve the use of radically different materials which in turn often require significant modifications to the design. As this was not considered in this study, the limited remaining choices focused on reducing concrete and steel quantities. A number of other embodied energy reduction measures involving the replacement of building materials did not yield significant savings and even resulted in increased life cycle embodied energy. These are described in Appendix B. The life cycle embodied energy savings associated with PREFAB_RIBS and EPS_FILL are 320 GJ and 312 GJ, respectively. Their combination results in total savings of 812 GJ or less than 1% of the total life cycle energy demand of the BC. Measures targeting operational energy use result in much more significant reductions.

The ALL_OPE scenario results in a net life cycle energy demand reduction of 31 650 GJ (-23.5%) compared to the base case and represents the most significant reduction in a particular energy category. This is almost equal to the total life cycle energy demand of two of the eight apartments in the building. Installing solar vacuum tube collectors for domestic hot water and a part of the heating demand (SOLAR_COLL) contributes most to this reduction (45%) followed by installing a very efficient air conditioning machine (EFF_AC; 15%), efficient appliances (EFF_APP; 14%) and reducing the heating and lighting demands. Figure 5 also shows that the additional embodied energy for solar thermal collectors (452 GJ) is insignificant compared to the resulting solar thermal energy produced (16 642 GJ). This is however not the case for photovoltaic panels in the PV scenario where the additional embodied energy (13 090 GJ) represents 56% of the solar energy produced (23 357 GJ). It is important to note that this embodied energy figure covers the original panels as well as their replacement and the replacement of batteries and the inverter (as presented in Table C.1, Appendix C). This results in an energy payback time of 13.8 years for the system which is higher than in other studies such as Halasah *et al.* [61]. This is due to the reliance in this study on the comprehensive input-output-based hybrid analysis for the quantification of embodied energy (see Section 3.2) and the consideration of large batteries and their replacement over time.

The ALL_TE scenario can reduce the life cycle energy demand by 26 134 GJ (-19.5%) compared to the base case. As for operational energy, the combination of H_CARS, TD-15% and CAR_POOL results in less overall energy savings compared to the sum of the parts. This is because the targeted energy demand is already reduced by another measure when a new one is applied.

The total energy demand of the BC can be reduced by 58 236 GJ or up to 43% (ALL). This means that the current life cycle energy demand of new residential buildings in Lebanon could be almost reduced by half if energy reduction measures, targeting mostly operational energy and transport energy uses, are introduced. The resulting reduced energy demand over 50 years would be 2 381 GJ/capita. This is almost half the energy requirements over 50 years for the inhabitants of a suburban single family Passive House in Belgium or a recent Australian suburban house determined by Stephan and Crawford [22] using the same technique. The financial cost associated with these energy reduction measures over 50 years is quantified in the following section.

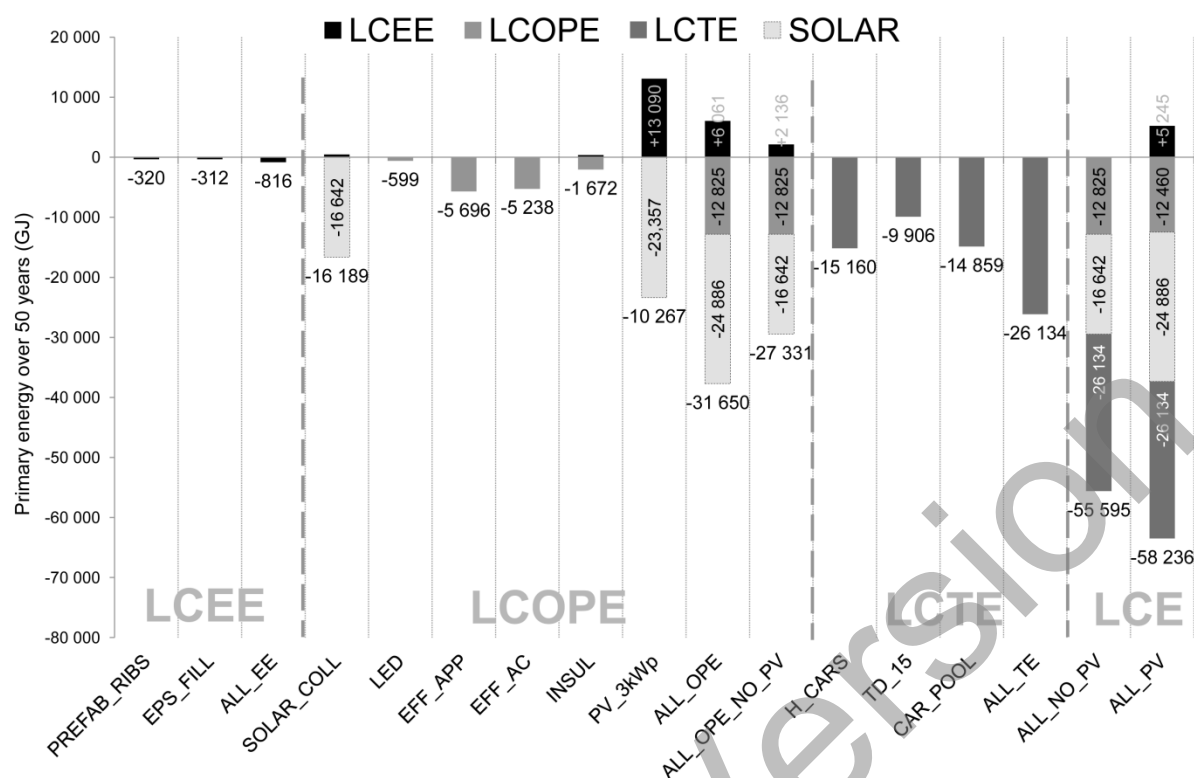


Figure 5: Life cycle energy analysis of the proposed energy reduction measures over 50 years, by use. Note: LC = life cycle, EE = embodied energy demand, OPE = operational energy demand, TE = transport energy demand, SOLAR = solar energy from solar collectors or photovoltaic panels; faded acronyms indicate the targeted energy use for the measures beneath; all measures are detailed in Table C.1.

4.2 Life cycle energy and cost analyses

The life cycle energy analysis presented in Section 4.1 is complemented by a life cycle cost analysis. In this regard, three additional scenarios are added, namely ALL_OPE_NO_PV, ALL_TE_NO_HYB and OPTIMUM. The three scenarios correspond to the combination of all operational energy reduction measures except installing photovoltaic panels; all transport energy reduction measures except the use of hybrid cars; and all scenarios that present a positive NPV, respectively. The first two were added because the excluded measures resulted in a large negative NPV. Results are discussed by targeted energy flow as in Section 4.1.

Figure 6 shows the reduction in life cycle energy demand (in grey) on the left axis and the associated NPV (in red/green) on the right axis, over 50 years, for each energy reduction measure. Only the net overall energy balance has been depicted in this graph, for more details on the energy savings, refer

to Figure 5 and Section 4.1. All investigated measures aiming at reducing embodied energy requirements result in a negative NPV due to the additional investment cost for prefabricated ribs and expanded polystyrene blocks for the slabs that are more significant than the reduced cost of steel.

On the contrary, all operational energy reduction measures except PV result in a positive NPV. This is because the reduction in energy costs is more significant than the initial capital cost and the recurrent costs. For instance, SOLAR_COLL has an NPV of +18 770 USD compared to the BC while simultaneously reducing total energy use by 12%. The installation of PV panels requires significant investments, both upfront and throughout the 50 years period of analysis. These costs are mostly associated with the replacement of the batteries and the panels themselves. This study does not take into consideration a possible reduction in the price of panels or batteries in the future due to technological breakthrough and this could significantly affect the results. Nevertheless, given the current economic situation in Lebanon and current photovoltaic and energy storage prices, installing PV panels is not financially beneficial. This confirms the findings of Kinab and Elkhoury [57]. The ALL_OPE_NO_PV scenario results in an NPV of +41 223 USD while yielding significant primary energy savings (27 331 GJ). While the combination of energy reduction measures yield lower total energy savings than the sum of those associated with each measure (see Section 4.1 and Figure 5), the NPV does not follow the same trend. As can be seen in Figure 6, the NPV of ALL_OPE is higher than the sum of the NPV of each scenario. This is because a reduced electricity demand associated with the use of efficient appliances, lighting and air conditioning system requires a smaller photovoltaic system, which in turn costs less money. The reduction in system sizes associated with a lower load and demand can result in significant cost savings.

The highest NPV among all investigated measures is associated with car pooling. This is because not only car pooling does not require any investment cost but it also allows each household in the building to own one car instead of two and to therefore halve costs associated with car purchase, maintenance and insurance. While CAR_POOL has the highest NPV and yields significant energy savings (14 859 GJ or -11% compared to the BC), it is also one of the hardest measures to implement since it is a behavioural change. The same holds true for reducing the travel distance by 15% which results in an NPV of +32 707 USD (4 090 USD/household), or 80% of the NPV of ALL_OPE. Note that reducing the travel distance by 10%, 20%, 30% and 40% resulted in an NPV of +21 805 USD, +43 609 USD, +65 414 USD, +87 218 USD, respectively. In other words, reducing the travel distance by 40% results

in significant money savings to each household (10 902 USD) and is the second single most effective measure after CAR_POOL. Using hybrid cars instead of regular petrol cars results in significant costs and a negative NPV of almost 1 000 000 USD for the 8 households of the building. This negative return on investment explains why hybrid cars have been phased out from the Lebanese market and why a separate scenario, ALL_TE_NO_HYB has been investigated. The latter results in a large positive NPV (+413 127 USD).

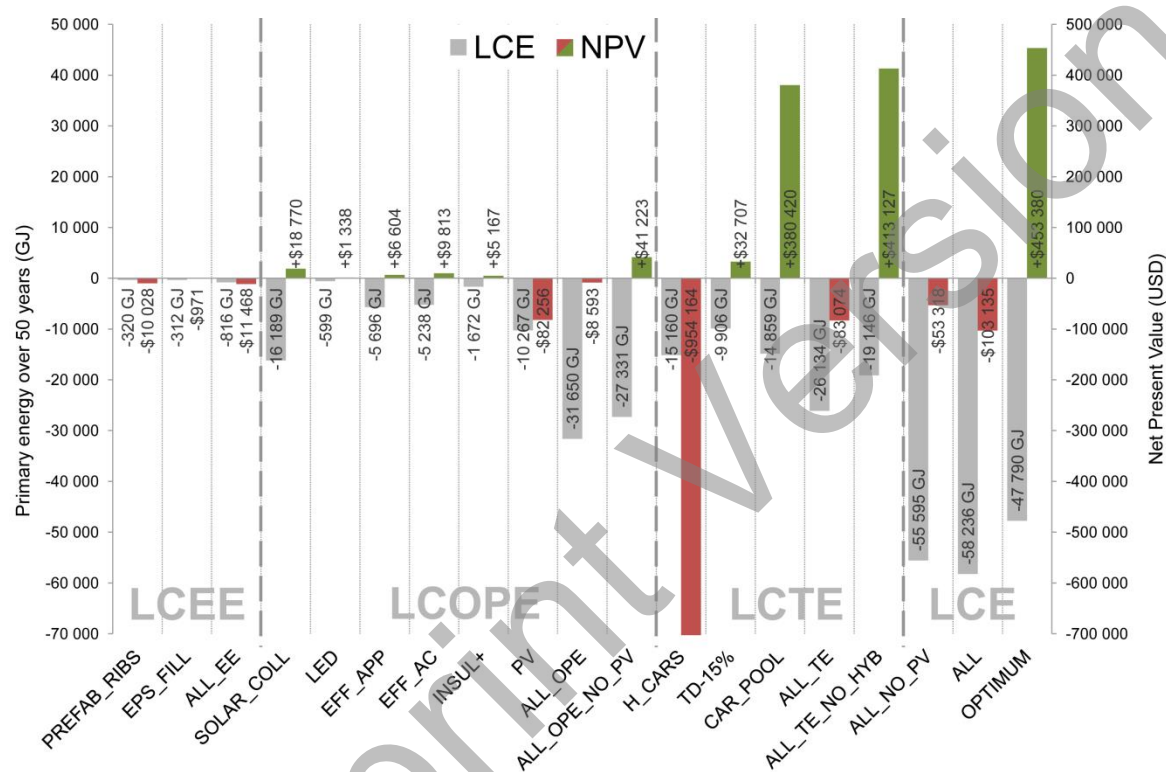


Figure 6: Life cycle energy and cost analysis of the proposed energy reduction measures over 50 years. Note: LCE = life cycle energy demand (in grey, on the left axis) and NPV = net present value (in red for negative values and green for positive values, on the right axis); faded acronyms indicate the targeted energy use for the measures beneath; all measures are described in Table C.1

Both ALL_NO_PV and ALL have a negative NPV because of the use of hybrid cars and photovoltaic panels and hybrid cars, respectively. The OPTIMUM measure yields 47 790 GJ of energy savings, reducing the life cycle energy demand of the building and its occupants by 35.5% over 50 years. It also results in a positive NPV of 453 380 USD, most of which is associated with the car pooling strategy which reduces the number of cars by 8 (down from 16).

It is crucial to mention that the very high discount rate of 12.2% is very unfavourable and penalises strategies with high investment costs. These same strategies could yield a positive NPV should the discount rate be lower. This is investigated in Section 4.3.

4.3 Sensitivity analysis

Any life cycle cost study suffers from a high level of uncertainty due to the unforeseeable nature of financial indicators [62]. In this study, the calculated real discount rate (see Equation A.1, Appendix A) is significantly higher than in previous studies using NPV to evaluate the life cycle cost of building energy reduction measures because of the much higher investment risk in Lebanon compared to developed economies. For instance, Morrissey and Horne [23] use a discount rate of 3-3.5% over 50 years for their study in Melbourne, Australia. Similarly, Leckner and Zmeureanu [63] use a discount rate of 4% for their life cycle cost analysis of solar systems in a net zero energy house in Montréal, Canada. The calculated 12.2% discount rate for Lebanon is however in line with the values of other economies with similar risk profiles such as Turkey (12.4% average over 2010-2014), Egypt (9.4% average over 2010-2014) or Pakistan (10.3% average over 2010-2014) based on data from the International Monetary Fund [64].

In order to evaluate the impact of the discount rate and to broaden the relevance of the results to other economies with similar prices, two other discount rates of 3% (D1) and 15% (D2) are considered. For consistency, these two discount rate values are coupled with different inflation values of 2% (as in [63]) and 4.1%, respectively. The 4.1% inflation rate is a linear extrapolation based on the discount rates for 3% and 12.2%.

In addition, this paper assumes an energy inflation rate that is similar to the general inflation rate. However, it is likely that these two rates are not coupled over the 50 years period of analysis. In this regard, another sensitivity analysis decouples the general and energy inflation rates. Decoupling the general inflation rate from the energy price inflation rate is common in combined life cycle energy and cost analyses such as Copiello and Bonifaci [65]. This decoupling assumes a variability of an additional $\pm 2\%$ on the energy inflation rate, compared to the general inflation rate over 50 years. This broad variability is in line with the investigated scenarios in Copiello and Bonifaci [65] who evaluate a higher inflation rate, a higher inflation rate for a few years with no inflation over the rest and an energy inflation rate similar to the general inflation rate. Also, the International Energy Agency future oil prices

fluctuate greatly depending on the policy scenario investigated [66]. This is captured by considering the broad range of possible energy inflation rate in this study. Practically, the sensitivity analysis evaluates the effect of the two following sets of values E1 inflation rate: 3.9%; energy inflation rate: 1.9% and E2) inflation rate: 3.9% and energy inflation rate: 5.9%. This variability ensures that different forecasts are envisaged such as higher energy prices in the future due to the depletion of resources or war and lower energy prices due to deregulation, low commodity prices, etc. The discount rate is not modified in this analysis.

The life cycle analysis can also suffer from a high level of uncertainty, notably uncertainty in the data used. However, contrarily to life cycle cost which relies on the same variable in every calculation, i.e. discount and inflation rates (see Equation 2), the life cycle energy demand is an addition of rather independent variables, such as the embodied energy of locally produced concrete, the embodied energy of imported photovoltaic panels, the operational energy for lighting (which depends on the efficiency of the fixture installed and the primary energy conversion factor for electricity) and the transport energy requirements associated with a car (depending on travel distance, fuel economy and indirect energy intensity). This means that a significant number of variables can affect the life cycle energy demand and that there is no single variable that intervenes in all calculations. This joins the findings of Blengini and Di Carlo [67] that find that when energy reduction measures are applied, there is not one single energy demand that dominates the life cycle energy use of a house. In this study, an evaluation of the effect of modifying every variable intervening in the calculation of the life cycle energy demand was not conducted as this was out of scope. Instead, a sensitivity analysis was performed on the primary energy conversion factor for electricity (PEF_{el}) as it intervened in the largest number of energy reduction measures (11 out of 19). The PEF_{el} was modified from 3.8 to 3.4 ($PEF1$: -10%) and 4.2 ($PEF2$: +10%). This is to account for possible errors in the quantification of the PEF_{el} which was undertaken in Stephan and Stephan [27]. The $\pm 10\%$ range is based on an estimation of the overall potential error margin. For instance, Stephan and Stephan [27] have estimated that fuel transportation would result in a 5% increase of the PEF_{el} if these were taken into account. The larger interval considered here attempts to account for further upstream losses in the energy supply chain and for a potential overestimation of losses in energy supply grid. The possible evolution of PEF_{el} in time was not evaluated as it depends on a range of factors such as policy, political stability and energy generation technology that fall outside of the scope of this work.

629 Results of the sensitivity analysis on the net present value are shown in Table 4 and those associated
630 with both the net present value and the primary energy demand are depicted in Figure 7.

631 *Table 4: Sensitivity of the net present value results to the discount rate and energy inflation rate for*
632 *the investigated measures.*

Measure acronym ^a	No variation	D1	D2	EI1	EI2
	NPV ^b (USD)	NPV (USD)	NPV (USD)	NPV (USD)	NPV (USD)
	(r ^c = 12.2%, CPI ^d = 3.9%)	and (relative difference) (r = 3%, CPI = 2%)	and (relative difference) (r = 15%, CPI = 4.1%)	and (relative difference) (CPI = 3.9%; EI ^e = 1.9%)	and (relative difference) (CPI = 3.9%; EI = 5.9%)
PREFAB_RIBS	-10 028	-10 028 (0%)	-10 028 (0%)	-10 028 (0%)	-10 028 (0%)
EPS_FILL	-971	-971 (0%)	-971 (0%)	-971 (0%)	-971 (0%)
ALL_EE	-11 468	-11 468 (0%)	-11 468 (0%)	-11 468 (0%)	-11 468 (0%)
SOLAR_COLL	+18 770	+92 018 (+390%)	+11 282 (-40%)	+11 343 (-40%)	+29 819 (+59%)
LED	+1 338	+5 208 (+289%)	+938 (-30%)	+1 051 (-21%)	+1 765 (+32%)
EFF_APP	+6 604	+26 572 (+302%)	+4 600 (-30%)	+4 404 (-33%)	+9 877 (+50%)
EFF_AC	+9 813	+33 015 (+236%)	+7 456 (-24%)	+7 642 (-22%)	+13 043 (+33%)

INSUL+		+28 363	+2 802	+3 083	+8 267
	+5 167	(+449%)	(-46%)	(-40%)	(+60%)
PV		-83 549	-81 751	-91 023	-69 213
	-82 256	(-2%)	(+1%)	(-11%)	(+16%)
ALL_OPE		+114 479	-20 922	-25 910	+17 167
	-8 593	(+1 432%)	(-143%)	(-202%)	(+300%)
ALL_OPE_NO_PV		+171 917	+27 913	+28 203	+60 593
	+41 223	(+317%)	(-32%)	(-32%)	(+47%)
H_CARS		-1 965 012	-845 122	-965 091	-937 908
	-954 164	(-106%)	(+11%)	(-1%)	(+2%)
TD-15%		+105 131	+25 324	+26 201	+42 386
	+32 707	(+221%)	(-23%)	(-20%)	(+30%)
CAR_POOL		+929 911	+322 900	+370 661	+394 939
	+380 420	(+144%)	(-15%)	(-3%)	(+4%)
ALL_TE		-8 919	-89 140	-101 000	-56 407
	-83 074	(+89%)	(-7%)	(-22%)	(+32%)
ALL_TE_NO_HYB		+1 035 042	+348 224	+396 862	+437 324
	+413 127	(+151%)	(-16%)	(-4%)	(+6%)
ALL_NO_PV		+151 530	-72 695	-84 265	-7 282
	-53 318	(+384%)	(-36%)	(-58%)	(+86%)

ALL		+94 092	-121 530	-138 377	-50 708
	-103 135	(+191%)	(-18%)	(-34%)	(+51%)
OPTIMUM		+1 205 988	+375 167	+424 094	+496 946
	+453 380	(+166%)	(-17%)	(-6%)	(+10%)

Note:

The PEF1 and PEF2 sensitivity analysis variations are not displayed in the table because they do not affect the NPV, only the life cycle energy demand.

^aAll measures are described in Table C.1.

^bNPV = net present value.

^cr = discount rate, calculated as per Equation A.1 and artificially set to 3% and 15% in the sensitivity analysis.

^dCPI = Inflation rate (see Equation 2) which is artificially set to 2% and 4.1% for discount rates of 3% (D1) and 15% (D2) in the sensitivity analysis, respectively.

^dEI = Energy inflation rate which is artificially set to 1.9% (EI1) and 5.9% (EI2) in the sensitivity analysis, respectively.

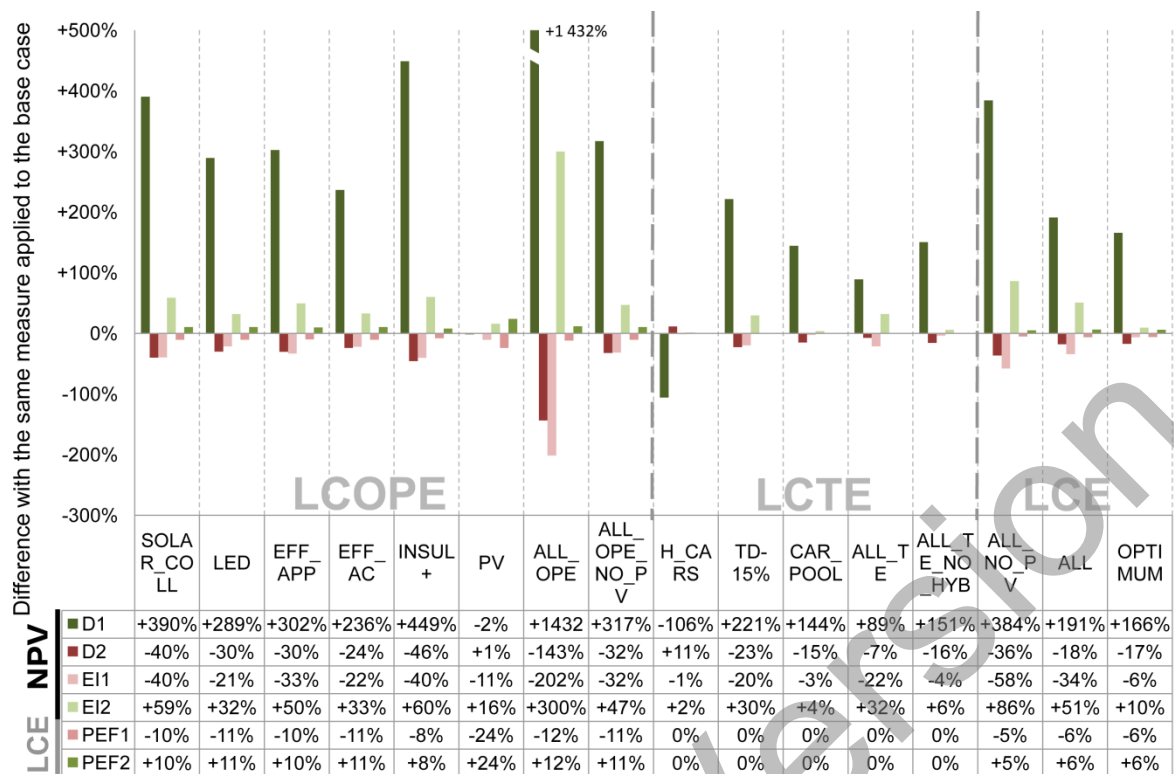


Figure 7: Relative difference between reductions in net present value (D1, D2, EI1 and EI2) and life cycle energy demand (PEF1, PEF2) for the investigated measures. Note: Embodied energy measures have been omitted since they are not affected.

The D1 and D2 sensitivity analyses show that the results are significantly affected by the discount rate and are penalised by the current high discount rate in Lebanon. The most significant changes are observed within the operational energy reduction measures where the NPV increases by a significant amount when a discount rate of 3% is applied (e.g. SOLAR_COLL: +390%, INSUL+: +449%). The significantly higher NPV of individual operational energy reduction measures explains why the NPV of ALL_OPE, which was -8 593 USD with a discount rate of 12.2% reaches +114 479 USD for a discount rate of 3%. These larger cost savings can allow the installation of photovoltaic panels since their negative NPV is more than compensated by the other operational energy measures. These panels can shelter the occupants from a potential significant energy price increase in the future (in this study, the average inflation rate is used for energy prices). Economies with a lower discount rate are therefore more favourable for energy reduction measures to be deployed. Because the current discount rate is already very high, a discount rate of 15% does not significantly alter the findings, as clearly depicted in Figure 7. Investigated embodied energy reduction measures are not affected by the discount rate as their entire cost is paid upfront and lasts the entire 50 years.

The effect of decoupling the energy inflation rate from the general inflation rate (EI1 and EI2) also affects the results, but to a lesser extent. The most significant changes occur in the measures that reduce delivered energy requirements. INSUL+ and SOLAR_COLL are therefore the most affected with +60% or -40% in their NPV. The NPV of the ALL_OPE measure, which reduces most delivered energy requirements is increased by 300% in case of an average energy inflation rate of 5.9% and reduced by 202% when energy prices increase at a slower rate than the rest of the economy (1.9% compared to 3.9%). Transport measures that reduce fuel usage have a higher or lower NPV depending on the future energy prices. The NPV of TD-15% and ALL_TE is either increased by 30% and 32% or reduced by 20% and 22%, respectively. The OPTIMUM measure is only slightly affected by decoupling the energy inflation rate, with a variation of -6%-+10%.

It is important to note that variability in the primary energy conversion factor for electricity (PEF_{el}) does not significantly affect the life cycle energy demand ($\pm 5\text{-}6\%$ in the combined measures). Also, the variability in the PEF_{el} does not affect the NPV of any measure since it is calculated based on delivered energy savings (see Equation 2) which are not affected by the PEF_{el} . The single most affected measure by a potential variation in the PEF_{el} is the PV measure because of the high initial embodied energy of the panels. A small difference in the PEF_{el} makes a significant difference from a life cycle energy perspective.

5 Discussion

The discussion is divided into three sections. Section 5.1 presents the contribution of this paper in comparison to previous studies combining building life cycle energy analysis and life cycle cost analysis. Section 5.2 discusses the practical implications of the findings and the role of different actors of the built environment to reduce the overall life cycle energy demand of residential buildings while relying on financially sound measures. Section 5.4 presents the limitations of this study and outlines future research directions.

5.1 Contribution

This study has quantified for the first time the life cycle energy and cost implications of a large number of residential building energy reduction measures, across the different scales of the built environment. It has evaluated the energy reduction potential of measures targeting embodied, operational and user-transport energy use while determining their associated life cycle cost using the net present

value approach. In comparison, most existing studies focus mostly on building operation, notably heating and cooling (e.g. Morrissey and Horne [23], Ozel [50] or Kneifel [16]). The broad range of measures investigated covers a large number of actors of the built environment and identifies better the roles of each as well as the incentives needed to reduce energy use and associated environmental impacts in residential buildings. This type of assessment can effectively inform future policies that aim at reducing the life cycle energy demand of residential buildings.

Within the Lebanese context, this study complements existing studies on the financial and energy benefits of deploying efficient household appliances [47] and on the barriers and solutions for solar [46] and renewable energy [57]. It broadens the spectrum of energy reduction measures by including embodied and occupant-related transport energy requirements and identifies the energy reduction measures that yield the highest NPV while achieving significant life cycle energy savings.

5.2 Reducing the overall life cycle energy demand of residential buildings

A large number of actors are involved in reducing the total life cycle energy demand of buildings. Among the most prominent are building designers, occupants, urban planners and designers and decision makers. The breadth of energy reduction measures investigated in this study involves these actors. The role of each in contributing to the reduction of the life cycle energy demand of residential buildings is highlighted for the case of Lebanon.

5.2.1 What can building designers do?

Building designers have a direct influence on embodied and operational energy use. As shown in Sections 4.1 and 4.2, reducing embodied energy is extremely hard if traditional construction materials and designs are used. Indeed, the largest reduction in embodied energy was 812 GJ or ~3% of the life cycle energy demand of the case study building. The difficulty to reduce embodied energy confirms the findings of Stephan *et al.* [20]. More radical changes to the design of the building and choice of materials should be investigated to significantly reduce embodied energy as demonstrated by Tibi *et al.* [68]. Huberman *et al.* [59] also show that radically different non-flat vaulted reinforced concrete roofs can reduce both embodied and thermal operational energy requirements. However, the fundamental issue with reducing embodied energy is the lack of incentive for building designers. Apart from a specific client demanding a low embodied energy project, the mainstream market has

very little motivation to reduce embodied energy, especially if this comes at a higher cost (e.g. the PREFAB_RIBS or EPS_FILL scenarios).

In addition, the building designer options are limited by the available construction materials on the market. This is a significant limitation in economies with little demand for renewable and low embodied energy materials such as Lebanon. In contrast, the European Union is supporting the widespread use of environmental product declarations [69] for construction materials to favour the use of more environmentally friendly choices. Design solutions, such as designing smaller spaces which results in a smaller living area per capita are a viable alternative to material choices [22, 70]. In this study, the living area per capita is already very low, at 28 m²/capita (compares to an average of 40 m²/capita for all Belgian dwellings [71] and 77 m²/capita for new US dwellings [72]).

Reducing the embodied energy of new residential buildings is therefore hard to achieve in Lebanon if a business as usual approach is adopted and considering that the case study building is representative of the average. A more thorough investigation of different construction materials, such as insulation from recycled materials, concrete with limestone filler [73] and others, should be conducted.

Operational energy use can be significantly reduced by building designers, notably through the selection of building systems and insulation. As depicted in Figure 5, installing vacuum tube collectors (see SOLAR_COLL) can not only significantly cover a significant share of the hot water demand (which represents the bulk of the primary operational energy demand, as shown in Figure 2) but also results in life cycle cost savings. This confirms the findings of Ruble and El Khoury [46]. Similarly, installing a high efficiency air conditioning system (see EFF_AC) results in both energy savings and a positive NPV. Insulating buildings can help reduce both heating and cooling demands and is economically viable through the induced cost savings. Installing photovoltaic panels is too expensive in Lebanon at the moment because of the cost of batteries and the very high discount rate. Decision makers could however influence this result as discussed in Section 5.2.4.

The incentive for building designers to invest in operational energy reduction measures is a higher selling price of the property. Indeed all the operational energy reduction measures considered have a positive NPV only over the entire life cycle of the building (or, at least, after several years). They all induce an additional extra cost that has to be borne by the developer while the savings are harvested

by the occupants. The only way the initial investor would be willing to spend these extra dollars is by being able to sell at a higher price in order to obtain a positive return on his investment. However, this is not guaranteed in the Lebanese market where a significant number of buyers have little interest in energy efficiency and care mostly about aesthetics (based on data from more than 40 buyers from Technical Enterprises Company). Raising awareness about cost savings induced by energy efficiency measures is crucial in order to support the deployment of such measures in the Lebanese market. Studies such as this one can help provide the needed scientific evidence. Regardless, the role of occupants remains the most determining factor in reducing the life cycle energy use in residential buildings.

Another way to deal with this mismatch between payer and beneficiary, without increasing the selling price of properties, is to let the occupant invest while facilitating the process. For example, the developer could install the necessary piping for the solar hot water collector without installing the solar system itself. That would come at almost zero additional cost for the builder while making it very straight forward to the occupant to make the investment and take advantage of the savings. Another example is the appliances, lighting or cooling units, where the developer could do all the wiring and pre-installation requirements while allowing the occupants to install the final systems themselves. However, this approach is limited both in scope, as it cannot apply to all measures (embodied energy measures, insulation) and in efficiency, as the occupants could choose to install inefficient fixtures and thus reduce the overall energy performance of the building.

5.2.2 What can occupants do?

While occupants have a limited impact on the building's embodied energy (apart from a recurrent embodied energy perspective in terms of material replacement frequency), they play a determining role in terms of operational and transport energy use. Reducing each of these energy demands is discussed below, respectively.

When old appliances need to be replaced, occupants should target the very high energy efficiency appliances as a replacement (see EFF_APP). Because of their generalisation in the recent years, the price of energy efficient appliances has significantly fallen. For a small extra investment cost (+15%), occupants can save significant amounts of energy (5 696 GJ of primary energy over 50 years) and save money (NPV of +6 604 USD over 50 years). The high primary energy conversion factor for

electricity makes this investment even more significant from a primary energy saving perspective. Another measure is to replace old light bulbs with LED lights (see LED). Occupants who own their property can also implement the same operational energy saving measures as building designers and are actually more prone to, as revealed by a recent study of OECD economies [74].

The total transport energy demand can also be significantly reduced by occupants if these are willing to modify their behaviour. Relying on car pooling for the main income earner (see CAR_POOL) yields the highest NPV (by far) among all investigated single measures (see Figure 6). This is because the household does not need to own and maintain two cars. Car pooling companies that can match different commuters together and ensure a safe environment could significantly support the uptake of this behavioural change in Lebanon. Car sharing, which was not investigated in this study, could also potentially yield significant energy and cost savings as demonstrated in the case of Ireland by Rabbitt and Ghosh [75]. The other behavioural change would be to reduce travel distance by optimising trips. Purchasing hybrid cars leads to significant financial losses over time and is not viable with the current prices of hybrid cars and fuel in Lebanon. This explains why these cars have been removed from the market (they are not imported to Lebanon anymore).

The incentive for occupants to invest in energy saving measures is the reduction of their energy bills and associated financial benefits. However, while the upfront costs are not very significant when it comes to installing energy efficient appliances, those associated with installing solar hot water collectors can be dissuasive. The micro loans with 0% interest offered by a range of Lebanese banks to install solar hot water systems can significantly help support the uptake of such systems, as in other countries [74].

5.2.3 What can urban planners and designers do?

Urban planners and designers have a major role to play in reducing the energy use associated with the mobility of building users. This is particularly true in Lebanon where the centralisation of jobs in the capital Beirut and the absence of public transport systems results in significant traffic congestions due to the sole reliance on cars as a transport mode. Creating more jobs in other cities and focusing on urban design elements that support walkability can significantly reduce car travel [76]. Reducing the car travel distance of households by 40% in the case study building would yield a reduction of 26 416 GJ over 50 years, reducing the life cycle energy demand by 20%, and resulting in an NPV of

+10 902 USD per household (+87 216 USD at the whole building level). Urban designers at the municipality level can significantly improve the walkability of urban and suburban neighbourhoods in Lebanon in order to encourage people to walk instead of using their cars for proximity trips.

The incentive for urban planners and designers is to improve the use of infrastructures and the quality of life. Reducing traffic and travel distance can not only reduce air pollution [77-80] but also frees more time for the inhabitants and reduces stress levels [81].

5.2.4 What can decision makers do?

Within the scope of this study, decision makers could focus on financially supporting energy reduction measures that yield significant energy savings but are financially unattractive. The most notable of these measures is the installation of photovoltaic panels (as depicted in Figure 6). The major impediment to the deployment of photovoltaic panels in Lebanon is currently the need to have local electricity storage because the surplus production cannot be fed back to the grid in most locations. If decision makers would upgrade the existing Lebanese electricity grid which is in poor condition [82] and enable consumers to feed surplus electricity to the grid, the cost of batteries (which represents the bulk of the negative NPV in the PV scenario) could be removed. The PV scenario without batteries requires a reduction of the discount rate (i.e. to 7.3%) to have an NPV of 0. If other operational energy reduction measures are deployed and the necessary photovoltaic system reduced in size (see ALL_OPE), the discount rate should only be lowered to 11% to reach an NPV of 0. Transiting to a smart grid would significantly impact the NPV of PV scenarios because no batteries would be needed and the surplus electricity could be sold on the grid, generating further financial profits. Potential state subsidies for photovoltaic systems could further increase their profitability and reduce overall installation costs because of increased deployment, similarly to the German and Chinese experience [83]. Another solution would be to increase energy prices (given that the population will tolerate this measure). This will incentivise the deployment of onsite renewable energy generation as revealed by imposing a higher inflation rate on energy in the sensitivity analysis. In addition, savings resulting from operational energy reduction measures and fuel savings would also be more significant. These incentives would significantly facilitate the deployment of renewable energy sources in the currently fossil-fuel-dominated electricity mix in Lebanon [43] and help reduce greenhouse gas emissions and air pollution.

5.3 Applicability of the results in other countries

Despite the fact that this study is applied to the Lebanese context and is therefore relevant to its particular economic situation and its energy mix, a number of results can be applied to different countries. First of all, the life cycle energy profile of the case study building as well as the significance of transport energy requirements are very likely to be representative of a number of other Mediterranean countries (*inter alia* Greece Israel, Italy, Spain, Tunisia and Turkey), with a mild climate, masonry and reinforced concrete construction and a relatively significant car usage. Secondly, while the financial repercussions of the energy reduction measures depend significantly on the inflation and discount rates, the sensitivity analysis conducted in Section 4.3 widens the applicability of results to a broad range of economies. Since the Lebanese economy suffers from a relatively high discount rate, the financial soundness of most investigated measures is very likely to be guaranteed in other economies with lower discount rates. In this regard, the H-CARS measure would be worthy of investigation in a number of different economical contexts as it resulted in a very high financial loss over time. Non-technological measures such as car pooling and reducing the travel distance are surely applicable in other contexts as their financial soundness and potential energy savings are very likely to be guaranteed. Besides a direct application of the results, the life cycle energy analysis method developed by Stephan [84], applied by Stephan and Stephan [27] and complemented in this study by a life cycle cost analysis is applicable in any country, given that data is available. This application would allow a future comparison with the Lebanese case.

5.4 Limitations and future research

This study suffers from a number of limitations. Firstly, future technological breakthroughs are not modelled and can significantly influence the results. Further research, using a 'what if' scenario approach could investigate the potential influence of improvements of appliances, photovoltaic panels, car fuel efficiency, energy systems and other aspects. Secondly, the recurrent price of the investigated measures suffers from a high degree of uncertainty, notably many years into the future. This limitation is inherent to life cycle cost analysis and to forecasting future expenditure. Thirdly, this study relies on Australian hybrid data for embodied energy. While embodied energy savings are minor in this work, it is important to highlight the potential high source of error in embodied energy calculations, due to the reliance on Australian data. This is discussed thoroughly in Stephan and

Stephan [27] who demonstrate that it is extremely difficult to quantify building embodied energy in a Lebanese context due to the majority of construction materials being imported from a range of different countries. The best approach would be to rely on a multi-regional-input-output-based hybrid analysis database of embodied energy coefficients for construction materials. This database would combine multi-regional input-output data (see Lenzen *et al.* [85] for an example of a multi-regional input-output database) with location-specific process data. However, this database does not exist yet and in its absence, the most comprehensive embodied energy database for construction materials [30] was chosen. Another limitation is related to the variability of operational energy use between households. Gram-Hanssen [86] and Steemers and Yun [87] have demonstrated that the operational energy use of different households living in the same dwelling could differ by more than 300%. While an average energy use has been adopted in this study to be representative of the average Lebanese household, results are valid for the case study building only. Metered post-occupancy energy use would help validate the simulated energy use. Despite these limitations, this study provides an unprecedented insight into reducing the overall energy use associated with residential buildings and the accompanying life cycle cost.

6 Conclusion

This study has quantified the life cycle energy and cost of various energy reduction measures targeting embodied, operational and transport energy requirements. This comprehensiveness ensures that the various actors involved in reducing energy use and associated environmental impacts in the built environment are captured at the same time. It allows a screening of different energy reduction measures and the identification of the most cost-effective and significant measures. By providing energy reduction guidelines for each actor of the built environment based on quantified benefits, this study provides a basis to discuss future energy reduction strategies for residential buildings. This will ultimately contribute to reducing the environmental impact of buildings and create a healthier built environment.

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Appendix A Discount Rate Calculations

The discount rate is calculated using the Capital Market Model (CAPM) as presented in Berk and DeMarzo [62]. Under the CAPM assumptions, the discount rate can be computed using the following equation [62]:

$$r = r_E \frac{E}{E+D} + r_D \frac{D}{E+D} (1 - \tau_D) \quad (\text{A.1})$$

Where: r is the discount rate; r_E = cost of equity; r_D = cost of debt; E = project equity value; D = the project debt value; and τ_D = the effective tax rate.

The cost of equity (r_E) can be computed also using the CAPM model with Equation A.2 [62]:

$$r_E = r_f + \beta(r_M - r_f) \quad (\text{A.2})$$

Where: r_E = discount rate; r_f = risk free rate; r_M = market return; and β = investment risk premium compared to the market.

The risk free rate r_f is taken as the average over the last 10 years of the Lebanese banks' creditor interest rate on US dollars deposit and has a value of 4.2%. This is based on data from the National Lebanese Bank or Banque du Liban (BdL) [88].

The market return (r_M) is taken as the Beirut Stock Exchange average yearly return starting in 2006 (over 9 years). This cut-off date has been chosen because this is when dividends data became available. The market opened in 1996 (after the Lebanese civil war) and the first 10 years are irrelevant as no dividends data is available. The value of r_M is 15.9% based on data from Bloomberg [89].

The investment risk premium of real estate compared to the market in Lebanon (θ) is unavailable because of the lack of data. However, the β of the real estate sector in other economies such as the USA [90] or Turkey [91] is very often close to 1 (between 1 and 1.05). Based on that value and given the absence of any data from which this factor could be determined, a unitary β ($\beta = 1$) is assumed. This safe assumption means that the real estate sector risk is perfectly correlated with the broader market risk.

Based on the figures above, the cost of equity r_E , calculated as per Equation A.2, is 15.9% (equal to r_M). The values of the remaining terms of Equation A.1 are presented below.

The cost of debt (r_D) is taken as the average over the last 10 years of the interest rate charged by the banks for corporate loans in US dollars. Its value is 9.1% based on BdL data [92].

The proportion of debt and equity (E and D) in a typical real estate project in Lebanon varies wildly and, again, no data is available. The financial structure of Technical Enterprises Company (which has constructed the case study building) has been adopted as a proxy. The profile of Technical Enterprises Company is also in line with the usual leverage ratio the Lebanese banks adopt for financing real estate developments. The proportions are 55% equity (E) and 45% debt (D).

The effective corporate tax rate for companies in the real estate sector in Lebanon (τ_D) is 15% flat.

In light of the above values, Equation B1 generates a discount rate value (r) of 12.2%.

Appendix B Discarded measures

As depicted in Figure 4, some measures are discarded in the process because they do not actually yield significant energy savings. All the discarded measures in this paper were related to reducing embodied energy.

The first measure attempted to reduce the painted surfaces indoors by fixing oriented strain boards (OSB) on 20% of internal walls. Reducing painted surfaces reduces recurrent embodied energy. In this case, this measure only yielded a reduction of 120 GJ of energy over the life cycle of the entire building. It was therefore discarded.

The second discarded measure removed non-essential walls partitions in order to reduce material quantity and associated embodied energy. In the particular plan layout of the case study building (see Figure 2), the only internal wall that could be removed was the partition between the kitchen and the dining room. This resulted in an energy reduction of 16 GJ only.

The third discarded measure investigated was to replace the 100 mm concrete masonry internal walls with 100 mm EPS sandwich panels (2x18 mm oriented strand boards with a 64 mm EPS filling). This resulted in an actual increase of the life cycle energy demand of the building by 1 144 GJ, increasing its embodied energy by 4.6%. If these sandwich boards were left unpainted with a wood finish, (and assuming that occupants will accept this radical change from typical aesthetics on the market) the savings in terms of paint embodied energy over 50 years would result in a net life cycle energy reduction of 104 GJ (-0.4% in embodied energy). Not only is this negligible but this would significantly alter the design of the building and its indoor space, making it incomparable to other scenarios. It was therefore discarded.

Appendix C Calculation details for all investigated measures

Table C.1 summarizes all investigated measures and provides details regarding life cycle energy and cost calculations.

Table C.1: List of investigated energy abatement measures and associated calculation details

#	Acronym	Description	LCE details	LCC details
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#	Acronym	Description	LCE details	LCC details
1	H-CARS	Replace the conventional 2 cars of each household with hybrid cars. <u>Target energy use:</u> direct transport energy	A fuel economy of 3 L/100km is assumed based on the manufacturers' specifications and on the very hilly nature of Lebanon (charging batteries downhill and using them uphill).	The Toyota Prius is the only hybrid car model to have been available in Lebanon. It has been removed from the market due to its very high price for a car in this category. Nevertheless, the dealer provided a price of 52 000 USD without VAT and registration resulting approximately in 58 000 USD in total. This compares with a total average cost of 20 000 USD for a conventional car of the same size as considered in the BC. Apart from the fuel, recurrent costs, e.g. tire replacement, maintenance, etc. have been omitted since they are assumed to be the same as for conventional cars in the BC. Cars are replaced 4 times during the 50 years period of analysis (once every 10 years).
2	TD-15%	Reduce annual travel distance by 15%. <u>Target energy use:</u> transport energy	N/A	Assumed zero financial cost
3	CAR_POOL	Car pooling for the main income earner. <u>Target energy use:</u> transport energy	15 000 km out of 40 000 km are travelled with an occupancy rate of 4 users per car compared to the average of 1.6 used in Stephan and Stephan [27]. The DTE and ITE intensities per pkkm over this distance are reduced by 60% to 0.97 MJ/pkkm and 0.8 MJ/pkkm, respectively.	Assumed zero financial cost. On the opposite, it assumes that the household needs only one car since the main income earner uses car pooling for work-related travel. The household saves insurance and maintenance costs on one car. These costs are approximated at 900 USD/year. The household participates in 20% of these costs for the car used for car pooling.

#	Acronym	Description	LCE details	LCC details
4	ALL_TE	Combines H-CARS, TD-15% and CAR_POOL. Replaces the 2 conventional cars by 1 hybrid car, reduces the travel distance by 15% and assumes that the main income earner uses car pooling for 15 000km per year out of 34 000 km. <u>Target energy use:</u> transport energy	The TE intensities of H-CARS and CAR_POOL are used over 19 000 km and 15 000 km per year, respectively.	See H-CARS. Assumes that the household needs only one car since the travel distance is reduced and the main income earner uses car pooling for work-related travel. The car is replaced 4 times during the 50 years period of analysis (once every 10 years). In this case, the household saves insurance and maintenance costs on one car. These costs are approximated at 900 USD/year. It however participates in 20% of these costs for the car used for car pooling.
4A	ALL_TE_NO_HYB	Same as ALL_TE but excludes H-Cars.	Same as ALL_TE but excludes H-Cars.	Same as ALL_TE but excludes H-Cars.
5	SOLAR_COLLECTION	Installs a 4.8 m ² vacuum tube solar collector with an auxiliary gas boiler for each apartment. <u>Target energy uses:</u> hot water and heating. <u>Affected energy use:</u> embodied energy	The solar collector system is replaced once during the 50 period of analysis. The circulation pump is rated at 125 W and is assumed to operate 1 hour per day. The solar system covers 20% and 90% of the final annual heating and hot water energy demands, respectively.	The installation cost of the whole system is 2 300 USD based on three quotes from three different providers. The bulk 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, the price of the electric hot water cylinder should be deducted since it is not needed anymore in this system. This amounts to 250 USD which results in a final net cost for the solar collector system of 2 050 USD. The system (vacuum tubes and heat exchanger) is replaced once over 50 years.

#	Acronym	Description	LCE details	LCC details
6	EFF_AP	Replaces the fridge, washing machine and television (TV) with high efficiency A+++ EU-labelled appliances. <u>Target energy use:</u> appliances.	The annual delivered electricity use of the fridge, washing machine and TV are reduced by 77%, 55.7% and 77.5%, respectively. The power ratings of the new appliances (as specified by the manufacturers) is multiplied by their average operating time as in Stephan and Stephan [27]. The difference in embodied energy of appliances between EFF_AP and BC is neglected as conventional and efficient appliances are assumed to have the same embodied energy. In addition Treloar et al. [25] have shown that the embodied energy of appliances is very small compared to that of the building.	The cost of new appliances is obtained from a major electronic devices retailer. The most affordable models with the desired energy efficiency are selected. The prices of the fridge, washing machine and TV are 1 239 USD, 529 USD and 350 USD, respectively. The fridge and washing machine are replaced 2 times during the period of analysis. The TV is replaced 4 times (every 10 years).
7	EFF_AC	Replace the current split air-conditioning (AC) system with an energy efficient one. <u>Target energy use:</u> cooling.	The energy efficient AC system has a COP of 5.9 compared to the 2.5 used in the BC, based on manufacturer's specifications.	The price of the energy efficient AC 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. The AC system is replaced 2 times over the period of analysis of 50 years.
8	INSUL+	Install 50 mm of EPS insulation in the outer walls and roof. <u>Target energy uses:</u> heating and cooling. <u>Affected energy use:</u> embodied energy.	DEROB-LTH is used to simulate the reduced final heating and cooling demands. The additional embodied energy of EPS is associated with the additional 53 m³ of insulation needed for the building.	The price of EPS is 66 USD/m³ based on a quote from different suppliers. The installation cost is 35 USD/m³ based on internal data from Technical Enterprises Co.

#	Acronym	Description	LCE details	LCC details
9	LED	Replace compact fluorescent (CFL) light points with LED lights. <u>Target energy use:</u> lighting.	The 10 CFL light points operating at 12 W are replaced by LED lights operating at 7 W in each apartment. It is assumed that the difference in embodied energy is negligible.	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 once while CFL are replaced 9 times. These life expectancies are based on the average operating hours of 50 000 h and 10 000 h for LED and CFL [56].
10	PV	Install a 3 kWp monocrystalline photovoltaic system on the roof, covering 65% of the electricity needs. This avoids a connection to a local generator. <u>Target energy uses:</u> all electrically-operated operational end-uses. <u>Affected energy use:</u> embodied energy	The 3 kWp system comprises 9 panels rated at 388 Wp, one inverter and regulator and 24 tubular gel batteries of 2 V and 800 Ah. The embodied energy associated with the panels is based on Crawford et al. [60] who use a hybrid life cycle inventory. The life cycle embodied energy of the inverter and batteries represents less than 10% of the total for the system and is calculated using pure input-output analysis.	The price for the considered system is based on two quotes from two main suppliers. The solar panels cost 0.79 USD/Wp and 1 500 USD for installation. Each tubular gel battery costs 300 USD. The inverter and regulator cost 650 USD. The panels and heat exchanger are replaced once, while the inverter and batteries are replaced 4 times during the period of analysis of 50 years.

#	Acronym	Description	LCE details	LCC details
11	ALL_OPE	Combine SOLAR_COLL, EFF_APP, EFF_AC, INSUL+, LED and PV into a single scenario. Reduce the heating and cooling energy demand by increasing the insulation level, installs solar collectors and PV panels on the roof, replace major appliances, the air conditioning units and lights with energy efficient systems. <u>Target energy uses:</u> heating, cooling, lighting, hot water, appliances and cooking <u>Affected energy use:</u> embodied energy	The solar collectors cover 90% of the final hot water demand and 23% of the final heating demand. The PV panels are downsized to 1 kWp (3 panels) because of the much smaller electricity load installation of solar collectors, efficient appliances, air conditioning and lighting and the reduced cooling demand. The 1 kWp system covers 90% of the electricity demand.	All life cycle cost estimations are based on the individual measures. The only difference is with the PV system which is downsized. The new system cost is as follows: the solar panels cost 0.79 USD/Wp and 750 USD for installation. Each tubular gel battery (250 Ah) costs 175 USD. The inverter and regulator cost 250 USD. The panels and heat exchanger are replaced once, while the inverter and batteries are replaced 4 times during the period of analysis of 50 years.
11 A	ALL_OPE_NO_PV	Same as ALL_OPE but excludes PV.	Same as ALL_OPE but excludes PV.	Same as ALL_OPE but excludes PV.
12	PREFAB_RIBS	Replace reinforced concrete ribs by prefabricated ribs <u>Target energy use:</u> embodied energy.	The quantity of steel in the slabs is reduced from 7.3 kg/m² in the BC to 5.7 kg/m². The wastage coefficients of steel and concrete for the prefab ribs are reduced to 0.5% down from 5% and 10% for <i>in situ</i> construction, respectively.	Prices of steel and concrete are based on the current Lebanese market. Concrete 25 MPa costs 75 USD/m³, smooth reinforcement steel 6/8 mm ø costs 566.5 USD/t, twisted 8 mm ø costs 660 USD/t and twisted 10 mm ø and more 550 USD/t. The BC cost per square meter of floor (excluding main beams) is 20 USD compared to 28.1 USD for the PREFAB_RIBS case. The main beams and columns price remain the same.

#	Acronym	Description	LCE details	LCC details
13	EPS_FILL	Replace hollow core concrete blocks in slab with EPS blocks. <u>Target energy use:</u> embodied energy	Reduce quantities of steel in beams and columns by 15%.	Prices for steel and concrete are the same as in PREFAB_RIBS. The cost of EPS is 61.6 USD/m ³ . This translates into a cost per square meter of floor (excluding main beams) of 21.7 USD. The main beams and columns see their cost cut down since the steel quantity is reduced by 15%.
14	ALL_EE	Combines PREFAB_RIBS and EPS_FILL. Replace reinforced concrete ribs in slabs by prefabricated ones and hollow core concrete blocks by EPS blocks. <u>Target energy use:</u> embodied energy	See PREFAB_RIBS and EPS_FILL.	See PREFAB_RIBS and EPS_FILL.
15	ALL	Combines ALL_TE, ALL_OPE and ALL_EE in a single scenario.	See ALL_TE, ALL_OPE and ALL_EE.	See ALL_TE, ALL_OPE and ALL_EE.
16	ALL_NO_PV	Combine ALL_TE, ALL_OPE and ALL_EE but exclude the PV measure.	See ALL_TE, ALL_OPE and ALL_EE but exclude the PV measure.	See ALL_TE, ALL_OPE and ALL_EE but exclude the PV measure.
17	OPTIMUM	Combine ALL_TE and ALL_OPE but exclude measures resulting in a negative NPV: PV and H_CARS.	See ALL_TE and ALL_OPE but exclude measures resulting in a negative NPV: PV and H_CARS.	See ALL_TE, ALL_OPE and ALL_EE but exclude measures resulting in a negative NPV: PV and H_CARS.

957 Note: LCE = Life cycle energy demand, LCC = Life cycle cost, BC = Base case; ø = section; DTE =
958 direct transport energy; and ITE = Indirect transport energy.

959 References

960 [1] Perez-Lombard L, Ortiz J, Pout C. A review on buildings energy consumption information. Energy
961 Buildings. 2008;40:394-8.

962 [2] Anderson JE, Wulfhorst G, Lang W. Energy analysis of the built environment—A review and
 963 outlook. *Renewable and Sustainable Energy Reviews*. 2015;44:149-58.

964 [3] Ramesh T, Prakash R, Shukla KK. Life cycle energy analysis of buildings: An overview. *Energy*
 965 *Buildings*. 2010;42:1592-600.

966 [4] Sharma A, Saxena A, Sethi M, Shree V, Varun. Life cycle assessment of buildings: A review.
 967 *Renewable and Sustainable Energy Reviews*. 2011;15:871-5.

968 [5] Karimpour M, Belusko M, Xing K, Bruno F. Minimising the life cycle energy of buildings: Review
 969 and analysis. *Building and Environment*. 2014;73:106-14.

970 [6] Cabeza LF, Rincón L, Vilariño V, Pérez G, Castell A. Life cycle assessment (LCA) and life cycle
 971 energy analysis (LCEA) of buildings and the building sector: A review. *Renewable and Sustainable*
 972 *Energy Reviews*. 2014;29:394-416.

973 [7] Chau CK, Leung TM, Ng WY. A review on Life Cycle Assessment, Life Cycle Energy Assessment
 974 and Life Cycle Carbon Emissions Assessment on buildings. *Appl Energ*. 2015;143:395-413.

975 [8] Crawford RH. Validation of a hybrid life-cycle inventory analysis method. *J Environ Manage*.
 976 2008;88:496-506.

977 [9] Majeau-Bettez G, Strømman AH, Hertwich EG. Evaluation of process- and input-output-based life
 978 cycle inventory data with regard to truncation and aggregation issues. *Environ Sci Technol*.
 979 2011;45:10170-7.

980 [10] Stephan A, Crawford RH, de Myttenaere K. Towards a comprehensive life cycle energy analysis
 981 framework for residential buildings. *Energy Buildings*. 2012;55:592-600.

982 [11] Stead D, Williams J, Titheridge H. Land use, transport and people: identifying the connections. In:
 983 Jenks M, Williams K, Burton E, editors. *Achieving sustainable urban form*. London; New York: E & FN
 984 Spon; 2000. p. xii, 388 p.

985 [12] Newman P, Kenworthy JR. *Sustainability and cities: overcoming automobile dependence*.
 986 Washington, D.C.: Island Press; 1999.

987 [13] van de Coevering P, Schwanen T. Re-evaluating the impact of urban form on travel patterns in
 988 Europe and North-America. *Transp Policy*. 2006;13:229-39.

989 [14] Karathodorou N, Graham DJ, Noland RB. Estimating the effect of urban density on fuel demand.
 990 *Energy Econ*. 2010;32:86-92.

991 [15] Rickwood P, Glazebrook G, Searle G. Urban structure and energy - a review. *Urban Policy Res*.
 992 2008;26:57-81.

993 [16] Kneifel J. Life-cycle carbon and cost analysis of energy efficiency measures in new commercial
 994 buildings. *Energy Buildings*. 2010;42:333-40.

995 [17] Norman J, MacLean HL, Kennedy CA. Comparing high and low residential density: life cycle
 996 analysis of energy use and greenhouse gas emissions. *J Urban Plan Dev*. 2006;132:10-21.

997 [18] Fuller R, Crawford R. Impact of past and future residential housing development patterns on
 998 energy demand and related emissions. *Journal of Housing and the Built Environment*. 2011;26:165-
 999 83.

1000 [19] Stephan A, Crawford RH, de Myttenaere K. Multi-scale life cycle energy analysis of a low-density
 1001 suburban neighbourhood in Melbourne, Australia. *Building and Environment*. 2013;68:35-49.

- [20] Stephan A, Crawford RH, de Myttenaere K. A comprehensive assessment of the life cycle energy demand of passive houses. *Appl Energy*. 2013;112:23-34.
- [21] 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.
- [22] Stephan A, Crawford RH. A comparison of the life cycle energy profile of residential buildings in different countries. *World Sustainable Building Congress 2014: Are we moving as fast as we should?* Barcelona2014. p.8.
- [23] Morrissey J, Horne RE. Life cycle cost implications of energy efficiency measures in new residential buildings. *Energy Buildings*. 2011;43:915-24.
- [24] 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.
- [25] Treloar GJ, Fay R, Love PED, Iyer-Raniga U. Analysing the life-cycle energy of an Australian residential building and its householders. *Build Res Inf*. 2000;28:184-95.
- [26] Heinonen J, Jalas M, Juntunen J, K, Ala-Mantila S, Junnila S. Situated lifestyles: I. How lifestyles change along with the level of urbanization and what the greenhouse gas implications are—a study of Finland. *Environ Res Lett*. 2013;8:025003.
- [27] Stephan A, Stephan L. Reducing the total life cycle energy demand of recent residential buildings in Lebanon. *Energy*. 2014;74:618-37.
- [28] Technical Enterprises Co. *Le Peuplier - New Sehaileh*, Available from www.tecentlb.com, 2013 (Accessed 22/07 2013)
- [29] Treloar GJ. Extracting embodied energy paths from input-output tables: towards an input-output-based hybrid energy analysis method. *Econ Systems Res*. 1997;9:375-91.
- [30] Treloar GJ, Crawford RH. *Database of embodied energy and water values for materials*. Melbourne: The University of Melbourne; 2010.
- [31] Crawford RH. *Life cycle assessment in the built environment*. London: Spon Press; 2011.
- [32] Crawford R, 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.
- [33] Dixit MK, Culp CH, Fernández-Solís JL. System boundary for embodied energy in buildings: A conceptual model for definition. *Renewable and Sustainable Energy Reviews*. 2013;21:153-64.
- [34] Dixit MK, Fernández-Solís JL, Lavy S, Culp CH. Need for an embodied energy measurement protocol for buildings: A review paper. *Renewable and Sustainable Energy Reviews*. 2012;16:3730-43.
- [35] 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.
- [36] 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.
- [37] Bataineh KM, Fayez N. Analysis of thermal performance of building attached sunspace. *Energy Buildings*. 2011;43:1863-8.

- [38] Lenzen M. Total requirements of energy and greenhouse gases for Australian transport. *Transport Res D-Tr E*. 1999;4:265-90.
- [39] Jonson DK. Indirect energy associated with Swedish road transport. *EJTIR*. 2007;7:183-200.
- [40] Chester M, Horvath A. Environmental assessment of passenger transportation should include infrastructure and supply chains. *Environ Res Lett*. 2009;4.
- [41] Cleveland C. *Net Energy Analysis*, Available from <http://www.eoearth.org/view/article/154821>, 2013 (Accessed June 25 2015)
- [42] Dixit MK, Culp CH, Fernandez-Solis JL. Embodied Energy of Construction Materials: Integrating Human and Capital Energy into an IO-Based Hybrid Model. *Environ Sci Technol*. 2015;49:1936-45.
- [43] MEW. Policy Paper for the Electricity Sector - (COM#1-21/06/2010). Beirut: Ministry of Energy and Water; 2010.
- [44] Sharma R, Manzie C, Bessede M, Crawford RH, Brear MJ. Conventional, hybrid and electric vehicles for Australian driving conditions. Part 2: life cycle CO₂-e emissions. *Transportation Research Part C: Emerging Technologies*. 2013;28:63-73.
- [45] Crawford RH, Treloar GJ. Net energy analysis of solar and conventional domestic hot water systems in Melbourne, Australia. *Sol Energy*. 2004;76:159-63.
- [46] Ruble I, El Khoury P. Lebanon's market for domestic solar water heaters: Achievements and barriers. *Energy for Sustainable Development*. 2013;17:54-61.
- [47] Ruble I, Karaki S. Introducing mandatory standards for select household appliances in Lebanon: A cost-benefit analysis. *Energy Policy*. 2013;52:608-17.
- [48] Çomaklı K, Yüksel B. Optimum insulation thickness of external walls for energy saving. *Applied Thermal Engineering*. 2003;23:473-9.
- [49] Hasan A. Optimizing insulation thickness for buildings using life cycle cost. *Appl Energ*. 1999;63:115-24.
- [50] Ozel M. Cost analysis for optimum thicknesses and environmental impacts of different insulation materials. *Energy Buildings*. 2012;49:552-9.
- [51] Özkan DB, Onan C. Optimization of insulation thickness for different glazing areas in buildings for various climatic regions in Turkey. *Appl Energ*. 2011;88:1331-42.
- [52] Tettey UYA, Dodoo A, Gustavsson L. Effects of different insulation materials on primary energy and CO₂ emission of a multi-storey residential building. *Energy Buildings*. 2014;82:369-77.
- [53] Yu J, Yang C, Tian L, Liao D. A study on optimum insulation thicknesses of external walls in hot summer and cold winter zone of China. *Appl Energ*. 2009;86:2520-9.
- [54] Masoso OT, Grobler LJ. A new and innovative look at anti-insulation behaviour in building energy consumption. *Energy Buildings*. 2008;40:1889-94.
- [55] Li DHW, Yang L, Lam JC. Zero energy buildings and sustainable development implications – A review. *Energy*. 2013;54:1-10.
- [56] 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.

- [57] Kinab E, Elkhoury M. Renewable energy use in Lebanon: Barriers and solutions. *Renewable and Sustainable Energy Reviews*. 2012;16:4422-31.
- [58] Huberman N, Pearlmutter D. A life-cycle energy analysis of building materials in the Negev desert. *Energ Buildings*. 2008;40:837-48.
- [59] Huberman N, Pearlmutter D, Gal E, Meir IA. Optimizing structural roof form for life-cycle energy efficiency. *Energ Buildings*. 2015;104:336-49.
- [60] Crawford RH, Treloar GJ, Fuller RJ, Bazilian M. Life cycle energy analysis of building integrated photovoltaic systems (BiPVs) with heat recovery unit. *Renewable and Sustainable Energy Reviews*. 2006;10:559-75.
- [61] Halasah SA, Pearlmutter D, Feuermann D. Field installation versus local integration of photovoltaic systems and their effect on energy evaluation metrics. *Energy Policy*. 2013;52:462-71.
- [62] Berk JB, DeMarzo PM. *Corporate finance*. 2nd edition ed. Boston: Pearson Education; 2010.
- [63] 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.
- [64] IMF. *International Financial Statistics*. International Monetary Fund, Available from <http://data.imf.org/?sk=5DABAFF2-C5AD-4D27-A175-1253419C02D1&ss=1390030341854>, 13/05/2015, 2015 (Accessed 13/05 2015)
- [65] Copiello S, Bonifaci P. Green housing: Toward a new energy efficiency paradox? *Cities*. 2015;49:76-87.
- [66] IEA. *World energy outlook 2014*. Paris: International Energy Agency; 2014. p.748.
- [67] 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.
- [68] Tibi G, Ghaddar N, Ghali K. Sustainable design guidelines for detached housing in the Lebanese inland region. *International Journal of Sustainable Built Environment*. 2012;1:177-93.
- [69] International Standard 14025/TR. *Environmental labels and declarations -- Type III environmental declarations -- Principles and procedures*. Geneva: International Organization for Standardization (ISO); 2006. p.25.
- [70] Wilson A, Boehland J. Small is Beautiful U.S. House Size, Resource Use, and the Environment. *J Ind Ecol*. 2005;9:277-87.
- [71] IBSA. *Monitoring des quartiers*. Institut Bruxellois de statistiques et d'analyse; 2011.
- [72] U.S. Census Bureau. *American housing survey for the United States: 2013*. Washington: United States Census Bureau; 2013.
- [73] Carette J. *Towards early age characterization of eco-concrete containing blast-furnace slag and limestone filler [Ph.D. thesis]*. Brussels: Université Libre de Bruxelles; 2015.
- [74] Ameli N, Brandt N. Determinants of households' investment in energy efficiency and renewables: evidence from the OECD survey on household environmental behaviour and attitudes. *Environ Res Lett*. 2015;10:044015.
- [75] Rabbitt N, Ghosh B. A study of feasibility and potential benefits of organised car sharing in Ireland. *Transportation Research Part D: Transport and Environment*. 2013;25:49-58.

- [76] Pickett STA, Cadenasso ML, McGrath B. Resilience in ecology and urban design : linking theory and practice for sustainable cities. New York: Springer; 2012.
- [77] Steg L, Gifford R. Sustainable transportation and quality of life. *J Transp Geogr.* 2005;13:59-69.
- [78] Van Y-P, Senior M. The contribution of mixed land uses to sustainable travel in cities. In: Jenks M, Williams K, Burton E, editors. *Achieving sustainable urban form.* London; New York: E & FN Spon; 2000. p. xii, 388 p.
- [79] Newman P, Kenworthy JR. Sustainable urban form: the big picture. In: Jenks M, Williams K, Burton E, editors. *Achieving sustainable urban form.* London; New York: E & FN Spon; 2000. p. 109-20.
- [80] Dodman D. Forces driving urban greenhouse gas emissions. *Current Opinion in Environmental Sustainability.* 2011;3:121-5.
- [81] Gee GC, Takeuchi DT. Traffic stress, vehicular burden and well-being: A multilevel analysis. *Social Science & Medicine.* 2004;59:405-14.
- [82] Dagher L, Ruble I. Modeling Lebanon's electricity sector: Alternative scenarios and their implications. *Energy.* 2011;36:4315-26.
- [83] Grau T, Huo M, Neuhoff K. Survey of photovoltaic industry and policy in Germany and China. *Energy Policy.* 2012;51:20-37.
- [84] 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.
- [85] Lenzen M, Moran D, Kanemoto K, Geschke A. Building Eora: A Global Multo-Region Input-Output Database at High Country and Sector Resolution. *Econ Systems Res.* 2013;25:20-49.
- [86] Gram-Hanssen K. Residential heat comfort practices: understanding users. *Build Res Inf.* 2010;38:175-86.
- [87] Steemers K, Yun GY. Household energy consumption: a study of the role of occupants. *Build Res Inf.* 2009;37:625-37.
- [88] BDL. *Commercial Banks -US\$: Discount and Loans (Weighted Average).* Banque du Liban, Available from <http://www.bdl.gov.lb/webroot/statistics/table.php?name=t5273-1>, 01/01/2015, 2015 (Accessed 11/05 2015)
- [89] Bloomberg. *BLOM stock index Lebanon.* Bloomberg, Available from <http://www.bloomberg.com/quote/BLOM:IND/chart>, 11/05/2015, 2015 (Accessed 11/05 2015)
- [90] University of New York. *Cost of Capital by Sector (US),* Available from http://pages.stern.nyu.edu/~adamodar/New_Home_Page/datafile/wacc.htm, 01/01/2015, 2015 (Accessed 11/05 2015)
- [91] Ozgur A. Calculation And Application Of Risk Rates In Valuation Of Real Estates [MSc Thesis]. Istanbul: Istanbul Bilgi University 2011.
- [92] BDL. *Commercial Banks -US\$: Average Rate on Deposits (Weighted Average).* Banque du Liban, Available from <http://www.bdl.gov.lb/webroot/statistics/table.php?name=t5273-5>, 01/01/2015, 2015 (Accessed 11/05 2015)