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Reducing the total life cycle energy demand of recent residential buildings in Lebanon

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Abstract

Buildings require a substantive amount of energy for their operation. Recent studies have found that indirect requirements, such as the embodied energy associated with their construction and the transport-related energy of their users can be even more significant. A complete life cycle energy analysis of buildings in a Mediterranean context has seldom been undertaken.

This paper relies on a multi-scale life cycle energy analysis framework to determine the energy use profile of recent residential buildings in Lebanon by taking into account embodied, operational and user transport energy requirements. It studies a representative case study building in Sehaileh, a suburb of the capital Beirut, over 50 years and identifies the most effective ways to reduce energy use across the different life cycle stages and scales of the built environment.

Results show that the life cycle energy demand is dominated by transport energy (49%) followed by operational (33%) and embodied (18%) requirements. The main ways to reduce this life cycle energy demand comprise relocating jobs outside of the capital, putting in place an adequate public transport network, improving town planning to favour pedestrians and rely on gas or renewable energy sources instead of electricity when possible, notably for domestic hot water.

Keywords: Life cycle energy analysis; Lebanon; Apartment buildings; Embodied energy; Transport energy; Mediterranean

1 Introduction:

The construction and operation of buildings require significant amounts of energy and are responsible for huge environmental impacts [1]. A growing number of studies is investigating the life cycle environmental impact of buildings (often in terms of energy use only) [2, 3] or neighbourhoods in order to reduce them. These studies have covered a wide geographical range including Australia [4-6], Belgium [7, 8], China [9], Finland [10, 11], Italy [12, 13], Sweden [14, 15], Switzerland and the USA [16], the UK [17] and other locations. However, there is currently no study assessing the total life cycle energy demand of buildings in Lebanon despite the unprecedented number of new construction on its soil in recent years.

Lebanon has witnessed a construction boom, notably during the 2008-2011 period of relative stability. During this time, a large number of residential buildings has been erected, notably in Mount Lebanon, a district surrounding the capital Beirut. Mount Lebanon represented on average 62% of the new residential buildings' floor area during this period [18]. According to the same source, nearly 22.5 million square meters of residential buildings have been built between 2008 and 2012, the majority being low to medium rise apartment buildings (four to eight stories). Assuming an average apartment gross floor area of 160 m² (based on the average apartment size in recent buildings), this equates to ~140 000 apartment units, far more than the actual need for residential units. There is therefore a mismatch between supply and local demand. Also, a substantial share of this housing stock consists of large, luxurious apartments with a price tag well above the average local residents' means. For this reason, a significant share of these apartment units is bought by Lebanese expatriates and, to a lesser extent, foreigners, especially Arab nationals. This explains why up to 50% of these apartment buildings can remain unoccupied. The construction of such a housing stock in a short period of time and the operation of the occupied units can have great environmental repercussions, notably in terms of energy use.

Most studies about the energy efficiency of the building stock across the world focus on their operational energy, notably in terms of thermal efficiency. A clear indicator of this trend is the emergence of policies aimed at improving the thermal efficiency of buildings, such as the European Directive for the Energy Performance of Buildings (EPBD) [19]. In Lebanon, such directives do not exist, but other instruments have recently been implemented to favour thermal performance. The most notable of these incentives is the law regarding the construction of double concrete walls (with an air blade) and the use of double glazing. A developer or client that uses double walls and double glazing does not take the thickness of the building envelope in the allowed constructible area. Therefore, the developer or client can benefit from a larger area for resale or use. This incentive is behind the notable increase in the use of double walls and double glazing in new residential buildings in Lebanon. Yet, the additional use of materials is not considered while the additional energy required to produce these materials might counterbalance the savings in terms of heating and cooling energy demand. The embodied energy in building materials, which is the energy required to produce these materials, across their entire supply chain, needs to be taken into account for a comprehensive assessment [20].

At a different scale of the built environment, land scarcity and increasing plots and property prices are pushing residential developments further away from the capital Beirut, the major working, administrative, social and cultural hub of Lebanon. Moreover, the very inefficient and unregulated public transport system, relying solely on road vehicles (shared taxis, small vans, buses) leaves the dominant majority of the Lebanese population with no choice but to rely on private cars for mobility. These two factors are responsible for larger travel distances and an increased energy use for transport which needs to be taken into account to provide an overall picture of the energy demand [21].

To date, most studies on the energy efficiency of the building stock in Lebanon focus solely on the operational energy aspect, e.g. Chedid and Ghajar [22] and Ruble and El Khoury [23]. The embodied energy is seldom mentioned [24], and rarely quantified. A study taking into account the transport energy demand of building occupants as well as embodied and operational requirements has not been found. There is therefore a pressing need for a comprehensive energy assessment of the growing building stock in Lebanon.

1.1 **Aim**

The aim of this paper is therefore to conduct a comprehensive energy analysis of recent low-rise residential buildings in Lebanon in order to determine their energy use profile and to identify the most appropriate means to reduce their energy demand.

1.2 **Scope**

This work focuses solely on energy, as Junilla [25] and Allacker [7] have proven that it is the most significant indicator regarding the environmental impact of buildings. In order to provide a comprehensive assessment, wide system boundaries are chosen, spanning the life cycle of the building across the different scales of the built environment. The embodied energy in building materials is taken into account as well as the energy required to replace them across the useful life of the building. The operational energy demand, in terms of heating, cooling, ventilation (if present), domestic hot water, appliances, lighting and cooking is considered. Energy requirements for user transportation are also within the system boundaries, in order to evaluate their significance and include the location and context of the building. The different energy demands taken into account are depicted in Figure 1.

2 Method

Buildings are the constituting brick of the built environment. They can be seen as a combination of various materials and assemblies, generating indoor and outdoor spaces in which the occupants live. At a larger scale, these buildings generate the urban fabric. Whether for the production of building materials, their construction, the operation of buildings or at a larger scale the mobility of their occupants, a significant amount of energy is associated with buildings. In Europe, the operation of residential buildings is responsible for 26% of the final energy demand [26]. In Lebanon, Mourtada [27] has estimated this figure at 35% (including commercial buildings) and Kampet et al. [28] have identified the residential sector as the largest electricity user with 38.5% of the demand. If so-called indirect requirements are taken into account (embodied and user transport energy) these figures are likely to increase significantly.

As demonstrated by Stephan [29], it is essential to consider very wide system boundaries when assessing the life cycle energy demand of residential buildings in order to ensure that a reduction at one stage of the life cycle or one scale of the built environment does not result in an offset at another stage or scale. Life cycle assessment (LCA) methods and requirements have been formalised in the international standard ISO 14040 [30] which describes the different steps involved in conducting a life cycle assessment. These include the goal and scope definition, the life cycle inventory (where methods are defined, including quantification algorithms for assessed flows), the life cycle impacts assessment (where quantified flows are converted to environmental impacts) and the interpretation. Conventional LCA takes into account a range of different inputs and environmental impacts. In this work, only energy use is considered in a streamlined LCA also called life cycle energy analysis (LCEA). This simplifies the LCA procedure as the life cycle impact assessment stage is not needed.

This work relies on the framework and software tool described in Stephan and Crawford [31] which takes into account the following life cycle stages: raw material extraction, manufacturing, construction and operation (including user mobility) and maintenance. The end of life stage is not considered as Crowther [32] and Winistorfer et al. [33] have demonstrated that it often represents less than 1% of the total energy requirements. These life cycle stages are considered both at the building and at the urban scales. The system boundaries of the framework used are depicted in Figure 1.

The functional unit in this work is a recently constructed multi-storey residential building in Sehaileh, Lebanon (described in Section 2.1 and in Appendix A), including the infrastructures that are essential to its functioning. Results of the LCEA are provided in absolute terms, per square meter of usable floor area and per capita to facilitate the comparison with other studies.

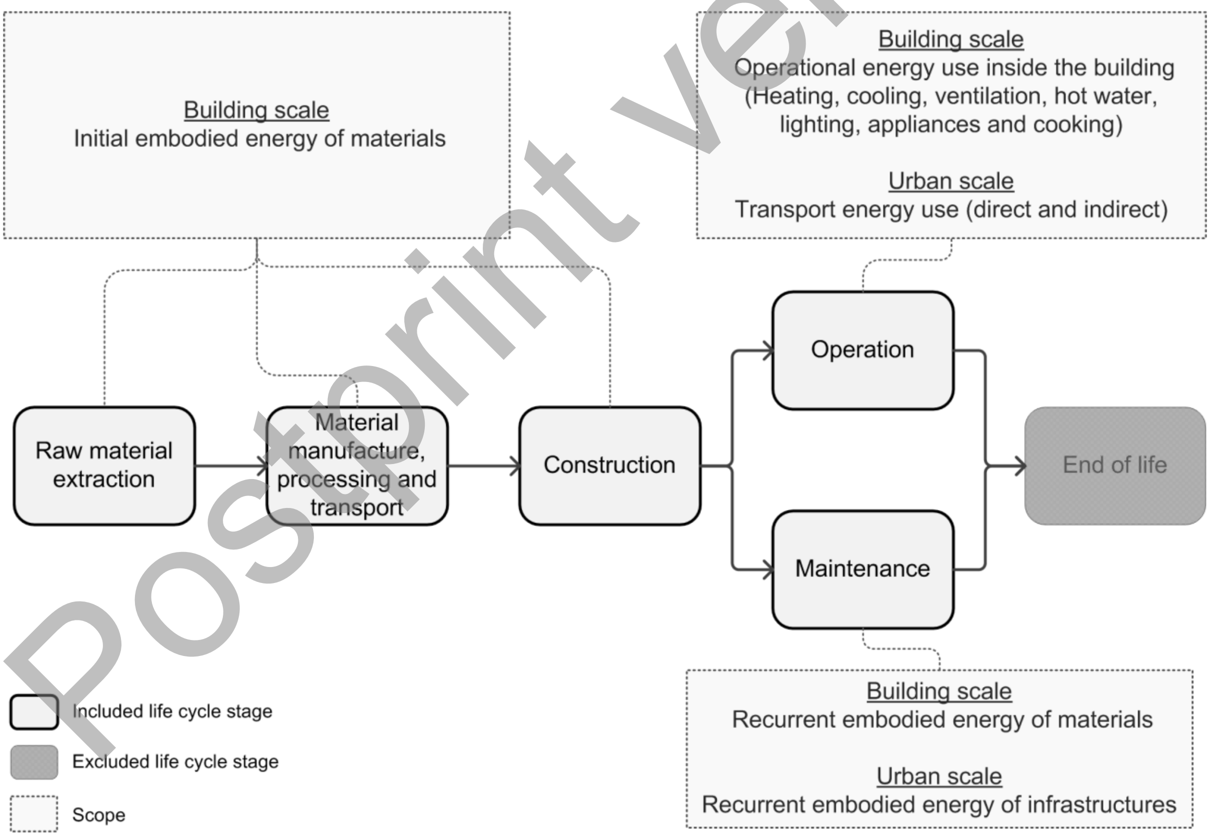


Figure 1: System boundaries of the life cycle energy analysis framework

Section 2.1 first describes the case study building used in this work. Sections 2.2 to 2.6 present the life cycle inventory used to quantify energy use over the period of analysis. Section 2.7 provides an overview of two scenarios applied to the base case.

2.1 **Case study building**

In order to evaluate the life cycle energy demand of recent residential buildings in Lebanon, a representative case study apartment building, built between 2008 and 2010 (at the heart of the construction industry boom) is assessed. This building is located in the Mount Lebanon district, at 515 m above sea level, in the town of Sehaileh, in the region of Kesrwan, 25 km North of the capital Beirut. Sehaileh is a residential town on the western side of the Mount-Lebanon mountain range. Its population density is 1 860 inhabitant/km², based on figures from the municipality. The building is studied over 50 years, a typical period of analysis used in life cycle energy analyses of buildings. The building is assumed to last through the whole period.

The building comprises eight apartments and is four-storeys tall. The ground floor comprises car parks and storage rooms while the higher floors comprise the apartment units (see Figure 2). Each apartment has a gross floor area of 154 m² (see Figure 3). This results in a net liveable area of 113 m². Detailed information about the building is provided in Appendix A. Table 1 summarises the building characteristics.

Figure 2: South elevation of the case study apartment building, in Sehaileh, Lebanon

Source: Technical Enterprises Co. [34]

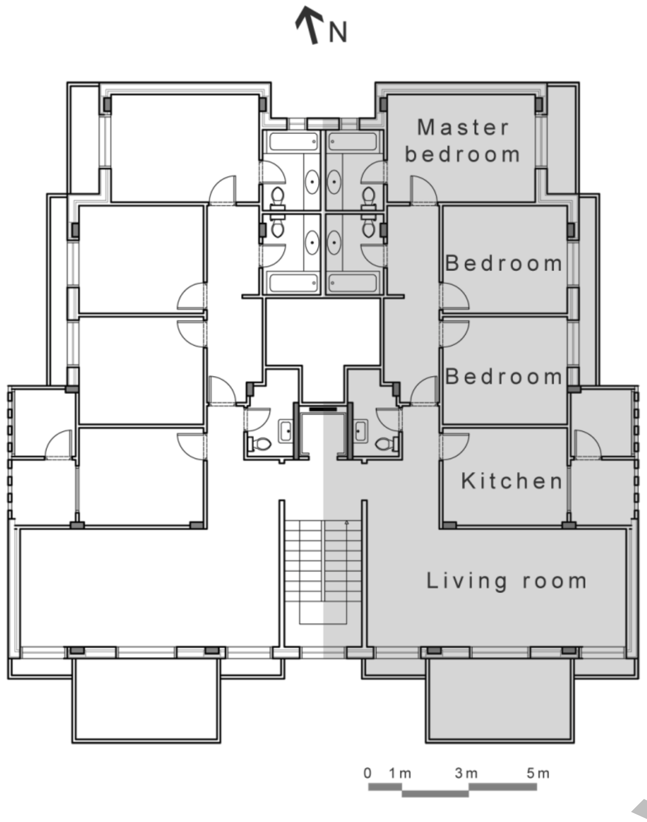


Figure 3: Plan view of a typical floor of the case study apartment building in Sehaileh, Lebanon. Note: The shaded area represents a gross floor area of 154 m².

Source: Technical Enterprises Co. [34]

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

Characteristic	Value
Building useful life (years)	50
Gross floor area per apartment (m²)	154
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
Construction price (USD/m² GFA)	550

Operational energy sources	Gas heating (eff. 90%) and cooking (eff. 90%); Electrical cooling with a heat pump (eff. 250%); Electric domestic hot water system (eff. 100%)
Primary energy conversion factors	Electricity: 3.8 , Gas: 1.1 (see Appendix B for more information)
Average car travel distance per year (km) (no public transportation)	40 000 (two cars and based on interview of inhabitants, see Appendix A)
Average occupancy rate of cars	1.6 (assumed)
Total energy intensity of cars (MJ/pkm)	4.13 (See Appendix A)

Note: GFA = Gross floor area

2.2 Embodied energy calculations

2.2.1 Quantification algorithm

Embodied energy is the amount of energy required, across the whole supply chain, to manufacture a product. Embodied energy can be divided into two components: initial embodied energy and recurrent embodied energy. The first represents the embodied energy of the building as-built, prior to its use. The latter represents the accumulated embodied energy over the building (or infrastructure) useful life, accounting for the replacement of materials such as paint, carpets, asphalt and others.

In this work, embodied energy is quantified using the comprehensive input-output-based hybrid analysis technique developed by Treloar [35]. This technique relies on the so-called 'input-output analysis' to cover all material and non-material inputs across the whole supply chain. Examples of studies relying on input-output analysis to assess direct and indirect energy requirements of buildings include Cellura et al. [13, 36], Nässén et al. [37], Säynäjoki et al. [11] and Junnila [25]. This technique has also been used to determine the total energy requirements of households [5, 38]. This work also uses so-called 'process data', that is, data acquired from the manufacturers regarding the average energy intensity of specific production processes. By combining input-output and process figures, a hybrid approach ensures systemic completeness while using the most reliable figures where available. More details about hybrid life cycle inventories can be found in Suh et al. [39] and Crawford [1].

The calculation of embodied energy is performed by multiplying the quantity of materials by their relevant embodied energy coefficient. The non-material inputs associated with these materials (e.g.

advertising) are added afterwards since the coefficient comprises only material-related inputs (e.g. iron ore extraction). Non-material inputs are quantified using a pure input-output approach by multiplying the price of the material by the energy intensity of the economic sector to which it belongs. The quantification of the embodied energy of the building is given in Equation 1 which is based on Stephan and Crawford [31].

The first part of Equation 1 calculates the initial embodied energy of the building (IEE_b). It multiplies the quantity of each material (Q_m) in the building by its hybrid embodied energy coefficient (EC_m) and sums the result. This provides the initial process-based hybrid embodied energy figure for the building to which the so-called 'input-output remainder' is added. The latter covers non-material inputs from economic sectors contributing to the building sector (TER_n) but not considered in process data for materials (TER_m). It is quantified by multiplying the price of the building (P_b) by the energy intensity of the sectors that are not covered by process data.

The second part of Equation 1 calculates the recurrent embodied energy (REE_b) by first determining the input-output-based hybrid energy requirements of each material by multiplying the material quantity by its hybrid coefficient and adding the input-output remainder at the material level. This is then multiplied by the number of replacements of the material which is obtained by dividing the useful life of the building (UL_b) by the useful life of the material (UL_m) and subtracting the initial use. The recurrent embodied energy of all materials is summed to obtain the recurrent embodied energy of the building.

$$LCEE_b = \underbrace{\sum_{m=1}^{M}\left(Q_m \times EC_m\right) + \left(TER_n - \sum_{m=1}^{M} TER_m\right) \times P_b}_{IEE_b} + \underbrace{\sum_{m=1}^{M}\left[\left(\frac{UL_b}{UL_m} - 1\right) \times \left[\left(Q_m \times EC_m\right) + \left(TER_n - TER_m - TER_{i \neq m}\right) \times P_m\right]\right]}_{REE_b} \quad (1)$$

Where: $LCEE_b$ = Life cycle embodied energy of building *b,* in GJ; Q_m = Quantity of material *m* in the building, in t, m³, m or another functional unit, EC_m = Hybrid energy coefficient of material *m,* in GJ per functional unit; TER_n = Total energy requirements of the building construction-related input-output sector *n,* in GJ per currency unit; TER_m = Total energy requirements of the input-output pathways representing the material production processes for which process data is available, in GJ/currency unit; P_b = Price of the building *b* in currency units; IEE_b = Initial embodied energy of the building in GJ;

UL_b = Useful life of the building *b,* in years; UL_m = Useful life of the material *m,* in years; $TER_{i \neq m}$ = Total energy requirements of all input-output pathways not associated with the installation or production process of material *m*, in GJ per currency unit; P_m = Price of the material *m* in currency units and REE_b = Recurrent embodied energy of the building in GJ.

The infrastructures embodied energy is calculated using a similar algorithm that attributes the infrastructures present in a one square kilometre around the building to the occupants, based on the average population density in this area. In this particular case, only the recurrent embodied energy is taken into account as the infrastructures in terms of roads and power and water distribution already exist in the area.

The one square kilometre area around the building is chosen based on the fact that the infrastructures closest to the building will be mostly used by the local residents. This area is chosen in particular as it matches the typical unit of population density and therefore facilitates not only calculations but also the comparison of different areas. Using the average infrastructure density and the average population density in on square kilometre, the average infrastructure quantity per capita can be computed and multiplied by the number of occupants. This allocation method implies that higher densities result in smaller infrastructure requirements per person, as found by Carruthers and Ulfarsson [40].

However, this allocation approach should be used carefully since there can be a great variability between the infrastructure systems next to a building. For instance, a residential building next to a major highway will have some of the embodied energy of the highway section present in the one square kilometre area allocated to it while the highway is used by many more people than the local residents. Also, this allocation method attributes the infrastructures embodied energy solely to the local residents and to residential buildings. In truth, infrastructures are also shared by non-residential buildings. A way of allocating infrastructures to both building types would be to consider both the occupancy density and the built area of each building type and to allocate infrastructures based on the number of people in each building type in the area. However, this approach requires a significant amount of data that is rarely available. In the case of a majorly residential suburban neighbourhood, such as the one in which the case study building is located, the chosen allocation method is expected to realistically attribute local infrastructure to the inhabitants.

2.2.2 Embodied energy database

Currently, there is no embodied energy database for Lebanon. While it would be ideal to rely on local material embodied energy intensities (for local materials), the development of an input-output-based hybrid analysis database for Lebanon is far beyond the scope of this work and requires a sustained research effort over many years. For instance, the current input-output matrix for Lebanon comprises only 20 sectors (compared to, for example, 101 in the Australian input-output matrix). Also, the reliability of statistical data in Lebanon is questionable. For instance, the last official population census dates back to 1932. For these reasons, a database of materials from outside Lebanon is used in this paper.

While there is a number of databases available (e.g. Ecoinvent, ICE), the only readily available hybrid database of construction materials has been developed for Australia by Treloar and Crawford [41]. This database has the widest system boundaries and includes the complete supply chain of materials across the whole economy. Moreover, the database used takes into account capital investments in the input-output framework but excludes personal consumption. This makes it ideal to use in this case since the energy associated with occupants transport is not considered in the input-output tables used for embodied energy and therefore double counting is avoided.

Since Lebanon's currency, the Lebanese Pound (LBP), is pegged to the United States Dollars (USD), and since both currencies are interchangeably used in the country, prices for the building and construction materials are expressed in United States Dollars (USD). These have been converted to Australian Dollars (AUD) for the relevant year of input-output data using a currency exchange ratio of 1.28 based on information from the World Bank [42]. The converted price was then used to compute non-material inputs (see Section 2.2.1 for more details).

Relying on Australian data to quantify the embodied energy of building materials in Lebanon, which are mostly sourced from overseas (see Section 4.3 and Figure 8) can result in a high uncertainty. The use of non-representative life cycle inventory data has been identified by Huijbregts et al. [43] and Weidema [44] as a major source of uncertainty in LCA studies. This can notably arise from technological differences in the manufacturing processes and electricity mix differences. At a whole economy level, local regulations and business habits can also affect embodied energy requirements when calculated using a hybrid approach. The use of Australian data to calculate embodied energy figures is a limitation of this study as it can diverge from actual figure for Lebanon, China and all the other countries that produce building materials for Lebanon. The use of the comprehensive Australian hybrid embodied energy database for Lebanon is thoroughly discussed in Section 4.3.

2.3 Operational energy calculations

Operational energy can be divided into two main categories: thermal and non-thermal requirements. The total operational energy demand can be derived from energy bills but these will not be used in this study since they provide only an aggregated figure, failing to present a detailed breakdown by use. Thermal requirements, namely heating and cooling, represent the overall energy demand associated with indoor thermal comfort, to adjust the indoor temperature to a suitable level, depending on the season. This work relies on the dynamic simulation software DEROB-LTH to determine thermal requirements.

DEROB-LTH originates from the University of Texas in Austin, USA. It was further developed by the department of energy and building design of the faculty of architecture at Lund's University in Sweden. It is a dynamic building energy simulation software for the calculation of heating and cooling demands, peak loads, indoor temperature, lighting level and other factors. DEROB-LTH operates in non-steady state conditions and uses a time step of one hour. It comprises a very detailed window and solar radiation model. The latter is based on the Hay radiation model that considers direct solar radiation (or beam radiation), diffuse radiation and a mix of direct and diffuse radiation in a halo around the sun. DEROB-LTH takes into account direct, diffuse and reflected radiation and considers refraction and scattering effects on surfaces outside and inside the building. An evidence of DEROB-LTH's advanced solar radiation model is its use to assess thermal comfort in sunspaces in Jordan [45]. It is therefore well suited for a country with high solar radiation levels such as Lebanon. The details regarding the actual modelling can be found in Appendix A.

Non-thermal requirements comprise the energy demand for domestic hot water, ventilation, lighting, cooking, and appliances. In this paper, non-thermal requirements are calculated based on the average power of the system, its operation time and the number of appliances in the apartment as per Equation 2 which formulates the approach of Ruble and El Khoury [23]. These have previously used this approach to determine the daily electricity use of a Lebanese household. The list of appliances and their average power and operating hours are presented in Table A.4, Appendix A.

$$DE_u = 365 \times 3.6 \times P_s \times OT_s \times N_s \quad (2)$$

Where: DE_s = Annual delivered energy of use u, in MJ; P_s = Power rating of system s, in kW; OT_s = Average daily operation time of system s, in hours; and N_s = Number of systems s owned by the household.

The final domestic hot water demand is determined based on an average daily use per capita of 50 L. This figure is derived from the 200 L per household per day used by Ruble and El Khoury [23] and the average household size of 4.07 in Lebanon [46]. The average water distribution temperature is assumed at 20ºC (293.13 K) [23]. The annual hot water final energy demand is determined as per Equation 3 which is based on the heat capacitance of water.

$$FE_w = 365 \times 10^{-3} \times NO \times m_w \times c_{pw} \times \left(T_f - T_d\right) \tag{3}$$

Where: FE_w = Annual hot water final energy demand in MJ; NO = Number of occupants in building b; m_w = Mass of hot water required per day, in L per capita; c_{pw} = Specific heat capacitance of water in kJ/(kgK); T_f = Final temperature of hot water in K; and T_d = Initial temperature of cool water, as delivered, in K.

Final energy use needs to be converted to primary energy figures in order to account for losses upstream in the energy supply chain. Primary energy conversion factors are usually provided by governmental bodies. However, these factors are not readily available for Lebanon. The primary energy conversion factor for gas will be assumed at 1.1, a figure similar to many European countries [47]. The primary energy conversion factor for electricity is calculated for Lebanon's unique situation and has a value of 3.8. All the information, equations and data related to the determination of primary energy conversion factors are provided in Appendix B.

The total life cycle primary energy demand is obtained by multiplying the annual primary energy requirements by the useful life of the building, as per Equation 4 [31] and assuming that energy use and the energy mix remain the same during the useful life of the building. A scenario modelling the potential evolution of the energy mix in Lebanon is considered in Section 2.7.1.

$$LCOPE_b = UL_b \times \sum_{u=1}^{U} \left(\underbrace{\frac{FE_u}{\eta_u} \times \left(1 - SF_u\right)}_{DE_u} \times PEF_u \right) \tag{4}$$

Where: $LCOPE_b$ = Life cycle primary operational energy of building *b*, in GJ; UL_b = Useful life of building *b*, in years; FE_u = Annual final energy demand of use *u*, in GJ, η_u = Efficiency of the system running use *u*; SF_u = Solar fraction of use *u* (share of the energy demand covered by solar panels in case these are installed); DE_u = Annual delivered energy demand of use *u*, in GJ; and PEF_u = Primary energy conversion factor of use *u*.

2.4 Transport energy calculations

Transport energy represents all the energy expenditure associated with the mobility of building users. This energy demand can be divided into two main components: direct and indirect requirements. Direct requirements are associated with the mobility process itself, i.e. burning fuel in the engine of a car. Indirect requirements are associated with all the processes supporting mobility, such as car registration, insurance, manufacturing the car itself, etc. Lenzen [48] and Jonson [49] have demonstrated that indirect requirements can represent 45% of the total energy intensity of car use. The direct energy intensity is calculated using the average fuel efficiency and occupancy rate of used vehicles while the indirect energy intensity is calculated using input-output analysis.

In order to calculate the annual transport energy demand, the energy intensity of each transport mode used, should be multiplied by the average travel distance of building occupants that use this mode. In Lebanon, public transport is virtually inexistent. The few buses that operate on the main highway are often in poor condition and bus stops are rare. The overall safety of the network is rather low. Also, because of these conditions, the vast majority of the population relies on gasoline cars for their mobility. Since trains and tramways no longer exist in Lebanon (following the 1975-1990 civil war and the previous removal of tramways in Beirut), the only transport mode considered in this work is the gasoline car. The life cycle transport energy demand is calculated as per Equation 5 [31] and includes both direct and indirect requirements. Travel distances, as well as energy intensities of transport modes are assumed to remain constant over the useful life of the building. In truth, these parameters are likely to evolve during this long time period and this may influence the results. This evolution depends on a range of factors such as technological breakthroughs, access to public transport and urban form for direct requirements and on many others for indirect requirements. These can be accounted for by relying on forecasting scenarios. However, estimating the evolution of travel distances and the energy intensity of transport modes in detail is beyond the scope of this paper.

$$LCTE_b = UL_b \times \sum_{c=1}^{C} \left(DEI_c + IEI_c \right) \times ATD_c \quad (5)$$

Where: $LCTE_b$ = Life cycle transport energy demand of the occupants of building *b*, in GJ; UL_b = Useful life of building *b*, in years; DEI_c = Direct energy intensity of car c, in GJ/km; IEI_c = Indirect energy intensity of car *c*, in GJ/km; and ATD_c = Average annual travel distance of car *c*, in km.

2.5 Life cycle energy calculations

The total life cycle energy demand is obtained by summing the embodied, operational and transport requirements, as per Equation 6 [31].

$$LCE_b = LCEE_b + LCEE_{\text{inf}} + LCOPE_b + LCTE_b \quad (6)$$

Where: LCE_b = Life cycle energy demand of building *b,* in GJ; $LCEE_b$ = Life cycle embodied energy demand of building *b,* in GJ; $LCEE_{inf}$ = Life cycle embodied energy demand of surrounding infrastructures, in GJ; and $LCOPE_b$ = Life cycle operational energy demand of building *b,* in GJ; $LCTE_b$ = Life cycle transport energy demand of the occupants of building *b*, in GJ.

2.6 Including uncertainty and variability

This work relies on a variety of data sets, on a dynamic simulation model, on average fuel intensities and on parameters that are related to industrial processes, the energy intensity of the economy, the energy supply system, the building's thermal envelope, the occupants' behaviour and other factors. All these parameters induce uncertainty in the model. Also, operational and transport energy demands present variability since they represent averages. For all these reasons, uncertainty and variability should be taken into account in the assessment.

Uncertainty in embodied energy figures is computed using ±20% of uncertainty for process data and ±50% of uncertainty for input-output data, based on Crawford [1]. Uncertainty in input-output data can be linked to price estimate errors, errors in the primary energy coefficients used, a low number of sectors and other factors. This often results in an overall ~±40% uncertainty for hybrid data. The variability level on operational energy is estimated at ±20%, based on Pettersen [50] and assumed to be similar for transport energy.

The uncertainty and variability are propagated using a simple interval analysis, in the sense of Moore et al. [51]. This means that instead of considering a single value, results provide the nominal value as well as a fluctuation range. While interval analysis is a simple way of considering uncertainty, it is more suitable in this case than probabilistic models or Monte Carlo analysis. Indeed the probabilistic distributions of most parameters considered are unknown.

2.7 **Other variations**

2.7.1 Temporal evolution of the primary energy conversion factor for electricity

In the base case scenario, the primary energy conversion factor for electricity is assumed to remain constant over a period of 50 years. This assumption is probably unrealistic, even if the electricity sector has not significantly changed in Lebanon for the last 20 years. It is probable that renewable energy plants will be installed in this coming period and therefore, the primary energy conversion factor for electricity is very likely to decrease. For instance, in their study on the potential evolution of the building sector in Lebanon, Dagher and Ruble [52] explore, among other scenarios, the penetration of wind turbine as a renewable energy source in the Lebanese electricity market.

A scenario, modelling the temporal evolution of the primary energy conversion factor for electricity is included in this paper. This scenario, named PEF_EVOL evaluates the impact of decreasing the factor by 20%, 30% and 50%, in 16, 32 and 50 years, respectively. The annual values in between are interpolated using a cubic function.

2.7.2 Empty apartments

As stated in Section 1, many apartments are bought by Lebanese expatriates and other foreigners who visit only occasionally. This results in up to 50% of apartments that remain empty. A scenario, named 50%_EMPTY, where 50% of apartments remain empty is therefore modelled in order to evaluate its repercussions on the life cycle energy demand profile of the building. Yet, there is a great uncertainty regarding how long these apartments will remain empty, especially with a period of analysis of 50 years. Therefore, this scenario will be assessed with 50% occupancy over 10, 20, 30, 40 and 50 years in order to better evaluate the effect on the contribution of each of the embodied, operational and transport energy requirements. These scenarios are named 50%_EMPTY_X where X is the number of years during which the building is 50% empty.

3 Results

This section presents the life cycle energy requirements of the case study apartment building. Embodied, operational, transport and total energy requirements are presented, in this order. The influence of the temporal evolution of primary energy conversion factor for electricity and the empty apartments scenario are described afterwards. Results are expressed in primary energy, in GJ/m² of usable floor area and in GJ/capita where relevant, for better comparison with other studies.

3.1 Life cycle embodied energy requirements

The life cycle embodied energy of the case study building represents 24 596 GJ (27.2 GJ/m²) and is divided into its initial (16 977 GJ, 69%) and recurrent (7 619 GJ, 31%) parts. This embodied energy is equivalent to the direct energy required to drive around the equator 160 times (with a gasoline fuel efficiency of 10 L/100 km) or to the moon and back 8 times. The ratio of recurrent to initial embodied energy (45%) is lower than in other studies relying on hybrid analysis for the quantification of embodied energy such as Crawford [53] (60%). This is due to the more durable nature of building materials in Lebanon. The reinforced concrete structure, the natural stone façade cover, the use of ceramic tiles for flooring; all result in long lasting assemblies.

Figure 4 shows the life cycle embodied energy requirements over 50 years, by material. The largest single contributing material is concrete (20.9%), followed by steel (15.6%), paint (13%), and ceramics (12.7%). The remaining materials, such as glass, aluminium timber, plastics and others represent 5% or less each. The use of concrete blocks for the outer and inner walls and of reinforced concrete for the structure and foundations results in the dominance of concrete and steel over embodied energy requirements.

Yet, the most significant contribution is from non-material inputs. These represent processes across the supply chain that support the manufacturing of the materials. These non-material inputs include advertising, insurance, logistics, management, and other services. Their significant contribution (24.4%) demonstrates the need to use the input-output-based hybrid analysis when calculating embodied energy. Indeed, the use of process data would not only omit non-material inputs but would also result in lower material embodied energy figures because of the truncation of the supply chain.

Figure 4 also reveals the large uncertainty present in the embodied energy database. On average uncertainty reaches 42%. This can greatly alter the results and hinder the reduction of embodied energy requirements as the most energy intensive materials cannot be reliably indentified. There is a great need for more reliable embodied energy databases that provide comprehensive and location specific data. This need has already been highlighted by several studies [39, 54-57].

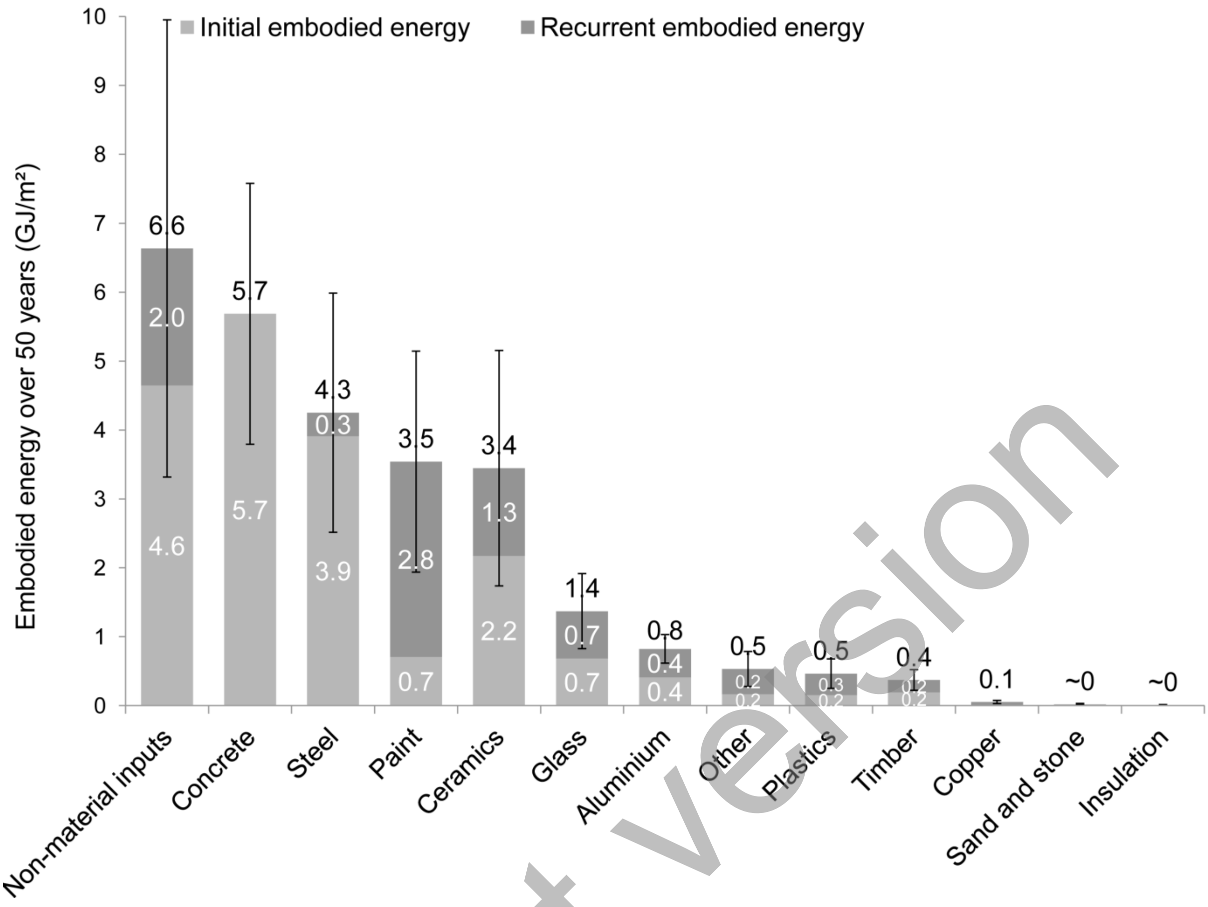


Figure 4: Initial and recurrent embodied energy requirements of the case study apartment building in Sehaileh, Lebanon over 50 years, per square meter of usable floor area, by material. Note: Figures may not sum due to rounding

In order to reduce embodied energy requirements, building designers could reduce the volume of concrete used, since this is the single highest contributor. Using aerated concrete blocks instead of a double concrete wall for the building envelope could provide a higher level of insulation and associated thermal comfort for a lower embodied energy. However, these aerated concrete blocks do not exist on the Lebanese market yet. Also, reducing the embodied energy requirements could be hard to achieve in this case. Indeed, the most efficient way of reducing the embodied energy requirements is often to reduce the living area per capita. Using less materials overall will logically lead to a reduction of embodied energy per capita. This has been quantified and demonstrated in various studies [58-60]. However, the net useful floor area per capita is already low in this case, i.e. 28.3 m² (compare to 35.6 m² for Brussels, Belgium [61], which is considered among the low figures, globally).

Another means to reduce material use and thus embodied energy is to limit the amount of waste generated on site. The concrete blocks partition works and the walls plastering using concrete mortar generate substantial amounts of waste (up to 30% as shown in Table A.2). By installing a small stone crusher on site, this neutral waste can be easily re-used as fill underneath the ceramic tiles (see Figure A.1) or even to cast small in-situ elements (lintels for example). This would not only recycle waste on site but would also spare the use of new materials, leading to double savings.

Nevertheless, a dramatic reduction of embodied energy figures seems unlikely to be achievable through simple solutions. A reduction of the primary operational energy demand might be easier to achieve.

3.2 Life cycle operational energy requirements

The life cycle primary operational energy demand of the assessed case study apartment building is 43 613 GJ (48.2 GJ/m²). As shown in Figure 5 this primary energy demand is mostly due to domestic hot water (37.3%) followed by appliances (21.1%), cooling (20.7%), heating (13.2%), cooking (4.4%) and finally lighting (3.3%). However, the breakdown of the delivered energy demand is more even with 26%, 14.7%, 14.5%, 31.8%, 10.7% and 2.3% for the same uses, in the same order as above. This difference leads to two observations.

Firstly, while delivered energy is a relevant metric when energy is assessed at the user endpoint, it becomes irrelevant when assessing the overall energy demand as it truncates a significant part of the energy supply system. By considering primary energy requirements the total raw energy content necessary to use is calculated. This has seldom been performed in previous studies on Lebanon.

Secondly, Figure 5 clearly depicts the significant effect of relying on electricity. Indeed, the very high primary energy conversion factor for electricity in Lebanon is responsible for the surge in the energy demand of electricity-operated end-uses such as hot water, appliances and cooling. This is contrasted by the space heating demand which is the highest delivered energy demand (5.8 GJ/m² or 31.8%) but only represents 13.2% of the primary energy demand. Substituting electricity with other energy sources such as solar or gas, should be a priority for end-uses that do not necessarily require electricity.

Another observation is the relatively low energy intensity of space heating. The improved thermal performance of the building compared to the existing Lebanese residential building stock, combined with Lebanon's mild weather (on average), results in a low annual space heating final energy demand

(104.2 MJ/m².a or 29 kWh/m².a). This figure is almost half the 50 kWh/m².a (180 MJ/m².a) requirement for low-energy buildings in Europe. Lebanon's Mediterranean climate requires little additional thermal performance components in order to reduce the space heating demand. This is clearly an advantage compared to countries with colder climates that need to install very thick insulations, mechanical heat recovery units on the ventilation system and a high air tightness in order to achieve a similar performance. The use of less material for such systems also reduces embodied energy.

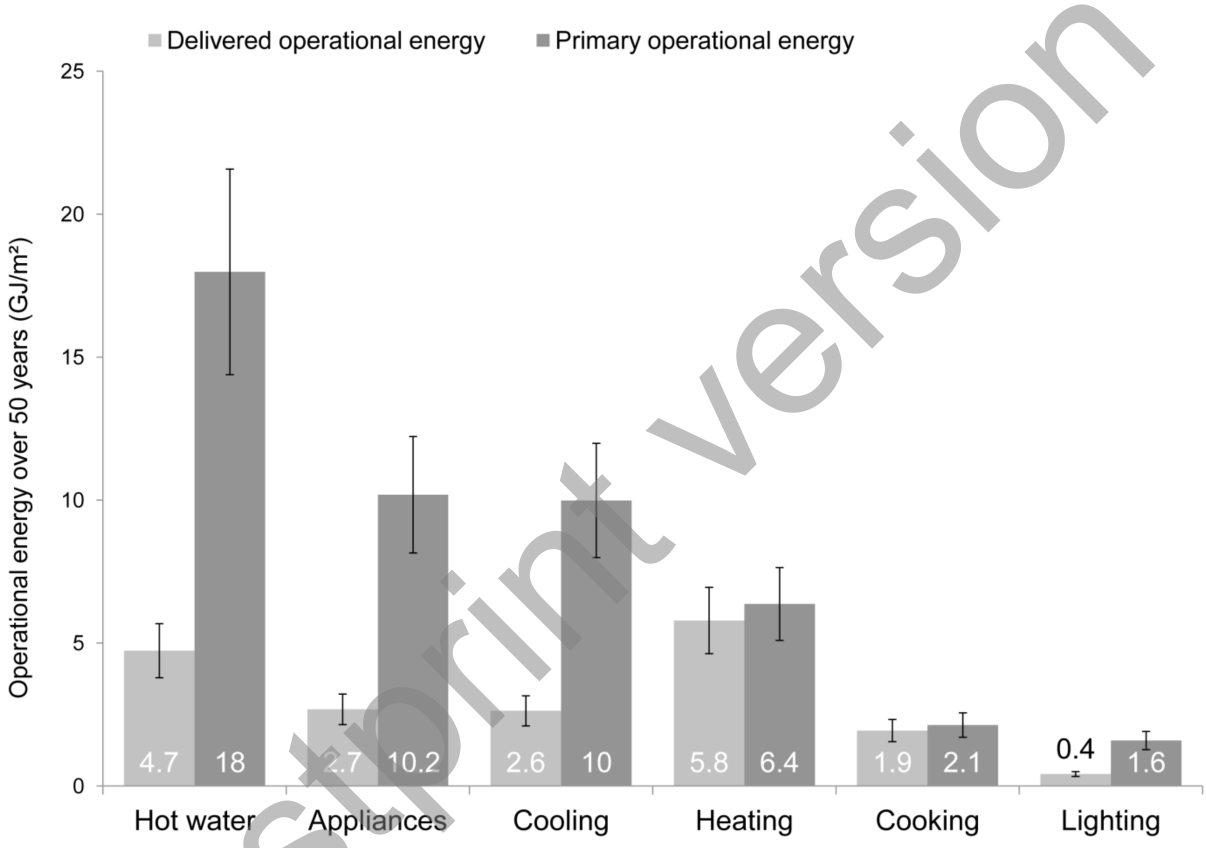


Figure 5: Final and primary life cycle operational energy requirements of the case study apartment building in Sehaileh, Lebanon over 50 years, per square meter of usable floor area, by use. Note: Figures may not sum due to rounding.

In order to reduce the primary operational energy demand, solar hot water systems are highly encouraged since a very large share of the demand (called 'solar fraction') can be covered by solar power in Lebanon [23]. For instance, installing a 2.16 m² solar flat plate solar panel, at 30° tilt towards the south can result in a solar fraction of 75%. If this system uses a gas boiler as an auxiliary heat source, operational primary energy demand can be reduced by 34.2%. This reduction requires a very small net increase in the embodied energy (20 GJ). This result joins the conclusions of Crawford and

Treloar [62] that demonstrated that solar hot water systems have a marginal embodied energy that is paid back very quickly.

Other ways of reducing the operational energy demand could be using more energy efficient appliances such as televisions, fridges, laptops, washing machines, etc. Also, the installation of photovoltaic panels should be considered, both in terms of energy and financial cost, as a measure to reduce the primary operational energy demand.

This section and the previous one have focused on the energy demand at the building scale; the next section presents the life cycle transport energy demand of the building occupants, at the city scale.

3.3 **Life cycle transport energy requirements**

The energy associated with the mobility of the building occupants, using gasoline cars, equates to 66 040 GJ (2 064 GJ/capita), over 50 years. This energy is split between direct requirements (1 069 GJ/capita; 51.8%) and indirect requirements (995 GJ/capita; 48.2%). Indirect requirements which are often not included in transport-related studies represent, alone, more than the embodied or operational energy demands. This clearly shows the need of including indirect requirements when assessing transport energy. Transport energy requirements are very significant and represent the largest share of the total life cycle energy requirements.

Reducing transport energy requires a planning approach at a regional scale. The huge centralisation of jobs, administration and social and cultural activities in Beirut, the capital of Lebanon, is a major driver for the use of cars and traffic congestion on the only coastal highway that connects major Lebanese cities. Also, the inexistence of national and local public transport systems, the often lacking sidewalks, the very pedestrian-unfriendly driving style and road design are all responsible for the reliance on cars at all times, even for proximity shopping. A general revision of the transport policy in Lebanon and associated jobs locations is needed to reduce the transport energy demand and also improve living conditions and reducing air pollution.

3.4 **Life cycle energy requirements**

The total life cycle energy requirements of the case study building represents 134 429 GJ (4 195 GJ/capita). This amount of energy is equivalent to the average solar irradiation on the roof of the building over approximately 71 years (based on an annual irradiation of 6 210 MJ/m².a). This life cycle energy demand is divided into its embodied (18%), operational (33%) and transport (49%)

requirements. As depicted in Figures 7 and 8, transport requirements dominate energy use. If only the building scale is considered (embodied and operational requirements), embodied energy represents 36% while operational energy represents 64%. This contribution of operational energy is higher than in other studies relying on the input-output-based hybrid analysis (IOBHA) [1, 4, 5, 63] due to the extremely high primary energy conversion factor for electricity (3.8) and the reliance on electricity for most operational energy end-uses. For instance, installing solar thermal collectors changes the contributions of embodied energy and operational energy towards the life cycle energy demand (excluding transport) to 46% and 54%, respectively. This result matches findings of the mentioned IOBHA studies.

As depicted in Figure 6, results suffer from a significant level of uncertainty and variability. Indeed, embodied, operational and transport energy requirements fluctuate between 439-1 098 GJ/capita, 1090-1 636 GJ/capita and 1 651-2 476 GJ/capita, respectively. The associated contributions towards total energy use fluctuate between 10-29%, 23-44% and 38-62% for the embodied, operational and transport requirements, respectively. Regardless of uncertainty in the data, indirect requirements, namely the embodied and transport energy demands, represent in all cases more than 50% of the total energy demand. Operational energy, which is the only focus of most building regulations and policies, represents less than half of the energy demand.

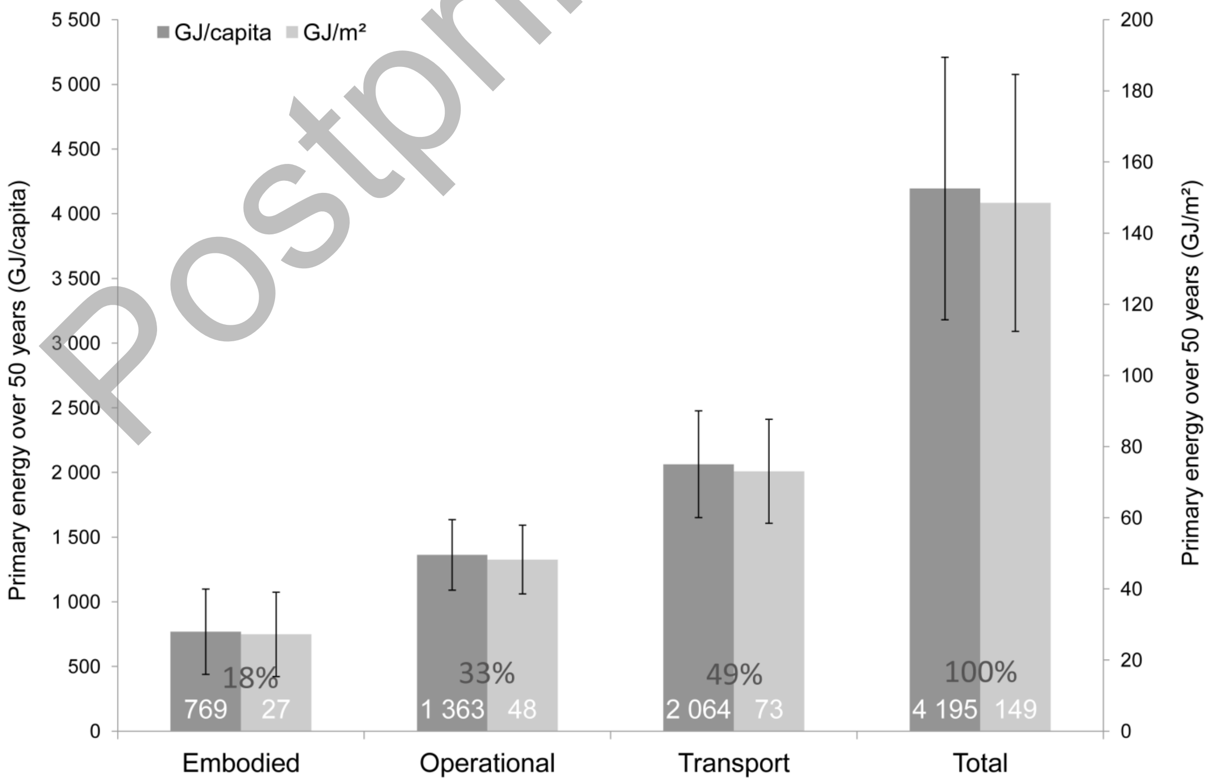


Figure 6: Life cycle energy demand of the case study apartment building in Sehaileh, Lebanon over 50 years, per capita and per square meter of usable floor area, by use.

Figure 7 shows the life cycle energy demand breakdown, by use. Direct and indirect transport energy requirements represent the highest contributions with 25% and 24% respectively. They are followed by domestic hot water (12%), appliances (7%), cooling (7%) and then multiple embodied energy categories such as finishings and shared areas (5%), structure (5%), non-material inputs (4%) as well as heating (4%). This diagram shows that at the building scale (excluding transport requirements), there is no single category that dominates the energy demand. Therefore, in order to reduce total energy requirements at the building scale, a holistic approach is needed, where building materials, construction assemblies, thermal performance, building systems and appliances are all tackled together using a life cycle approach.

It is important to highlight the small contribution of the infrastructure embodied energy. This is due to two main factors. Firstly, the high population density results in a small amount of infrastructure attributed to each occupant which in turn results in a low embodied energy per capita. Secondly, among the infrastructure types considered in the framework of Stephan et al. [64] the only types present in this case are roads, electric power lines and water distribution systems. Indeed, there are neither gas distribution systems nor sewage in the assessed area. The absence of these infrastructures results in a lower embodied energy. Yet, this is very likely to cause energy requirements that are out of the scope of this paper such as energy for delivering gas jars or energy for septic tanks and their maintenance.

The base case scenario relies on the assumption that the electricity generation infrastructure will be the same in 50 years. Also, 100% of the apartments are assumed to be occupied at all times. These two assumptions are probably unrealistic and it is therefore critical to assess the sensitivity of the results to a temporal evolution of parameters. This is presented in the following section.

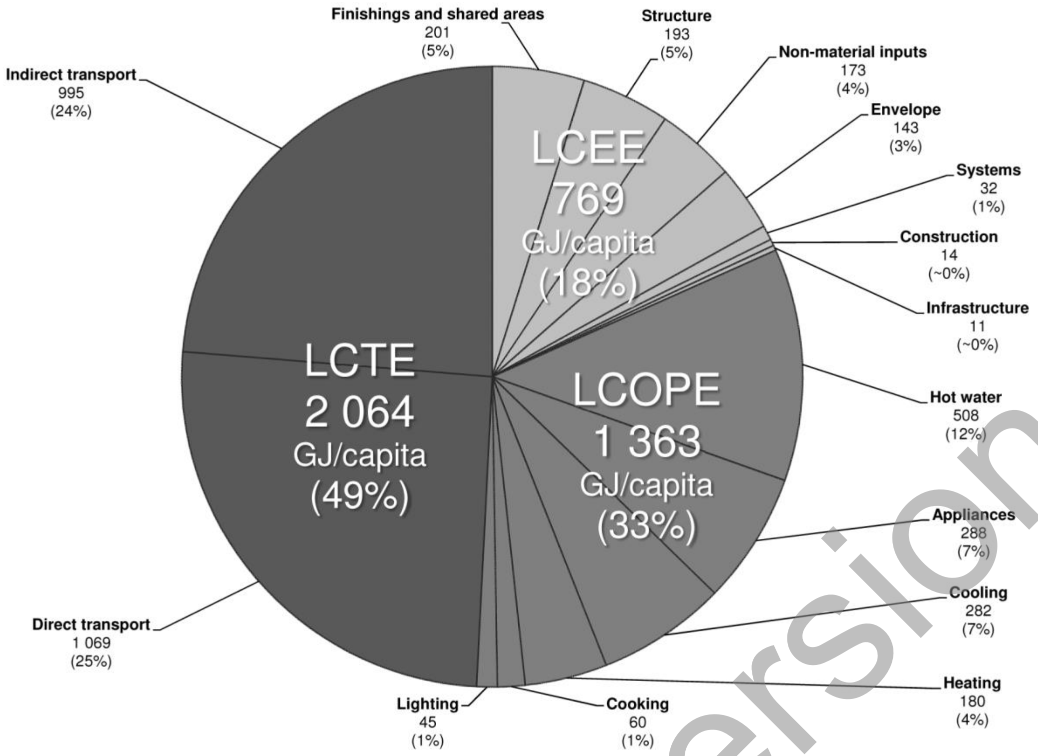


Figure 7: Detailed life cycle energy demand of the case study apartment building in Sehaileh, Lebanon over 50 years, per capita, by use. Note: figures may not sum due to rounding; LCEE = Life cycle embodied energy; LCOPE = Life cycle operational energy; LCTE = Life cycle transport energy.

3.5 Other variations

3.5.1 Temporal evolution of the primary energy conversion factor for electricity

The primary energy conversion factor for electricity represents the energy mix used to generate electricity. Hence, by reducing its value over time as described in Section 2.3.1, an alternative scenario regarding electricity generation is modelled. This factor is reduced to 50% of its value in 50 years, i.e. 1.9. This would be equivalent to shifting a considerable amount of the generation capacity to renewable energy sources such as solar, wind or hydraulic.

The PEF_EVOL scenario reduces the operational energy demand by 20.8% over 50 years. However, it does not affect embodied energy since a detailed embodied energy database for Lebanon that includes the energy mix breakdown for manufacturing processes is not available. Transport energy is not affected neither in the used model. The reduction of the operational energy by 20.8% results in a reduction of the total energy demand over 50 years by 6.8%.

This scenario shows that while it is crucial for Lebanon to shift to renewable energy sources and to provide an electricity supply that is reliable, this does not result in considerable energy savings within the scope of this paper. Yet, shifting to renewable energy for electricity generation has been identified by Heinonen et al. [65] as a very effective measure towards reducing the total primary energy demand of an economy and the associated greenhouse gas emissions. In the case of Lebanon, this has to be accompanied by a major revision of transport infrastructures and jobs locations.

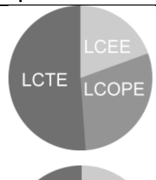
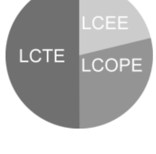
3.5.2 Empty apartments

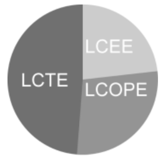
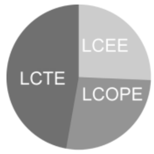
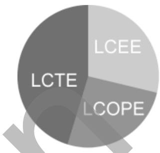
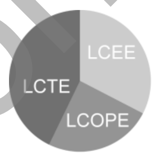
As described in Sections 1 and 2.3.2, a significant number of apartments in recently constructed buildings remain empty since they are bought by Lebanese expatriates and other foreigners who visit only occasionally. This aspect is modelled as five scenarios in which 50% of the apartments are empty over 10, 20, 30, 40 and 50 years, respectively.

Table 2 shows the influence of empty apartments on the life cycle energy demand, by use. A clear trend is visible as the apartments are empty for a longer period of time: the transport and operational energy contributions are reduced while the embodied energy remains constant. The empty apartments result in a lower overall energy demand (50%_EMPTY_50 has an overall energy demand 40.8% lower than the base case). Yet, this raises the question of building sustainably since roughly 50% of the building materials are not used but still wear in time.

Another important observation is that even in the extreme case where half the building remains empty over its whole useful life (i.e. 50 years), transport energy remains the largest contributor to the total life cycle energy of the building. This highlights the dire necessity to overhaul transport infrastructures and jobs locations, as already mentioned before.

Table 2: Influence of the 50% empty apartments scenarios on the life cycle energy demand profile of the case study apartment building in Sehaileh, Lebanon over 50 years.

Scenario	LCEE (GJ)	LCOPE (GJ)	LCTE (GJ)	LCE (GJ)	Graphical representation
BC	24 596 (18.3%)	43 613 (32.5%)	66 040 (49.2%)	134 249 (100%)	
50%_EMPTY_10	24 596 (20%)	39 252 (31.8%)	59 436 (48.2%)	123 284 (100%)	

50%_EMPTY_20	24 596	34 891	52 832	112 319	
	(21.9%)	(31.1%)	(47%)	(100%)	
50%_EMPTY_30	24 596	30 529	46 228	101 353	
	(24.3%)	(30.1%)	(45.6%)	(100%)	
50%_EMPTY_40	24 596	26 168	39 624	90 388	
	(27.2%)	(29%)	(43.8%)	(100%)	
50%_EMPTY_50	24 596	21 807	33 020	79 423	
	(31%)	(27.5%)	(41.6%)	(100%)	

Note: figures may not sum due to rounding; LCEE = Life cycle embodied energy; LCOPE = Life cycle operational energy; LCTE = Life cycle transport energy; LCE = Life cycle energy; BC = Base case. All other acronyms refer to Section 2.3.2.

4 Discussion

4.1 Contribution of the study

This paper has characterised the life cycle energy profile of recently built low-rise apartment buildings in Lebanon. The life cycle energy demand of these buildings is dominated by transport energy 2 064 GJ/capita (49%), followed by operational 1 363 GJ/capita (33%) and embodied 769 GJ/capita (18%) requirements. This repartition may be very similar to other Mediterranean regions with a similar urban context and energy supply system such as parts of Greece, Spain, Morocco, Egypt and Turkey. Yet, this energy breakdown is different from the average of seventy variations of three case studies in Belgium and Australia found by Stephan [29]. In his study, Stephan found that embodied, operational and transport requirements represented on average 34%, 33% and 33%, respectively.

Transport energy dominates the energy demand for several reasons. Firstly, the reliance on cars for mobility results in a high energy intensity per passenger-kilometre. Secondly, the high degree of centralisation of jobs in the capital Beirut results in long daily commuting distances and monster traffic jams on the only coastal highway. Thirdly, the poor pedestrian infrastructure and the unfriendly driving style and roads design greatly discourage walking to nearby destinations. Also, the very hilly nature of Lebanon's landscape is a barrier regarding the use of bikes for commuting.

Primary operational energy use is associated mostly with domestic hot water (37.3%), appliances (21.1%) and cooling (20.7%). The very high primary energy conversion factor for electricity (PEF_{el}) resulting from inefficient thermal plants and high distribution losses is responsible for the dominance of electricity-driven end-uses in the total primary operational energy use. The PEF_{el} in Lebanon has been estimated for the first time in this paper, allowing the measurement of the total raw energy requirements, unlike in previous studies [22, 23].

Embodied energy is dominated by concrete and steel (36.5%), the two structural materials. Non-material inputs represent around 24.4% of the embodied energy. This supports the use of the input-output-based hybrid analysis technique developed by Treloar [35] as it provides more comprehensive embodied energy figures compared to other methods [54].

4.2 Reducing the life cycle energy demand of buildings in Lebanon

Reducing the life cycle energy demand of this type of building in Lebanon requires the interaction of various players. Firstly, as transport dominates the energy demand, a more efficient urban planning is required. Decentralisation, coupled with improved public transport, proximity services and pedestrian friendly streets are potential keys to reduce the heavy reliance on cars and the long travel distances. This will also directly improve the urban air quality. Secondly, at the building scale, the reliance on renewable energy sources or gas instead of electricity, especially for domestic hot water, can significantly reduce primary energy use since electricity in Lebanon is generated with a mix of aging oil-based power plants and neighbourhood diesel generators. Thirdly, replacing concrete blocks in a building with a less energy intensive materials with improved thermal characteristics along with a better on-site waste management can reduce both embodied and operational energy requirements. Finally, by combining measures at different scales of the built environment while assessing their repercussions on the whole life cycle of the building, design guidelines that can yield a net reduction of energy use can emerge.

In this paper a temporal increase of the share of renewable energy sources in the Lebanese energy mix for electricity generation has been modelled through a reduction of the primary energy conversion factor for electricity. This evolution resulted in a 21% reduction of the operational energy demand and ~7% reduction of the total energy requirements since embodied and transport energy were not affected. While relying on renewable energy sources for electricity generation will undeniably result in a reduction of the overall primary energy use, its effect on embodied energy or indirect transport energy is not evident. Indeed, even if accurate figures regarding the use of electricity for embodied and indirect transport requirements were available for Lebanon, most building materials (see Section 4.3) and all cars are manufactured outside of Lebanon. The complexity of current supply chains that are spread across multiple countries requires a unified global database that connects all economies. This database can then be used to determine the influence of using renewable energy sources on a particular sector.

The other temporal evolution scenario modelled empty apartment buildings for different time periods. Results show that the significance of embodied energy increases when apartments are empty. Since most buildings comprise empty apartments, the contribution of embodied energy is likely to be higher than in the base case scenario while the operational and transport energy requirements would likely be lower. This poses a question regarding the use of empty apartment buildings and how economic and social concerns such as owning a foothold in your home country can have a very high environmental cost.

4.3 Using Australian hybrid data for embodied energy calculations

The use of Australian data for the determination of embodied energy in other locations (such as Lebanon) can result in errors. These can be due to different industrial processes, a different economic structure, differences in the energy mix and others. Yet, despite all these differences the use of the comprehensive input-output-based hybrid Australian database covers the complete supply chain of material production while simultaneously including process data collected from the industry. In the case of Lebanon, there is currently no existing embodied energy database for building materials. Using the most comprehensive database globally, even if it is not specific to Lebanon, is justified by the two following factors: (1) most of the embodied energy of the case study building, which is representative of recent apartment buildings in Lebanon, comes from imported materials (see Figure 8); and (2) embodied energy results calculated using process data are comparable, regardless of the origin of the database (see Figure 9).

In order to estimate how much of the embodied energy is associated with materials sourced in Lebanon, a detailed inventory of the origin of construction materials was established. This showed that aggregates and façade stone cladding are from Lebanese origin along with some minor contribution to other materials such as mixing paint ingredients imported mostly from Europe and the Middle East and extruding aluminium profiles using billets from China then assembling them into windows and doors frames. The rest of building materials are mainly sourced from China, notably: all steel elements including reinforcements, ceramic elements, granite and electricity wires. Other suppliers include Belgium for glass, Greece, Italy and Romania for timber, Iran for copper pipes, Jordan, France, the United Kingdom and the United States for paint ingredients, Portugal for roof tiles, Saudi Arabia for glass and plastic coatings in electric wires, Turkey for PVC pipes and the United Arab Emirates for insulation materials, plastic coatings in electric wires and some glass products. This non-exhaustive list clearly illustrates the global nature of the supply chain of recent residential buildings in Lebanon.

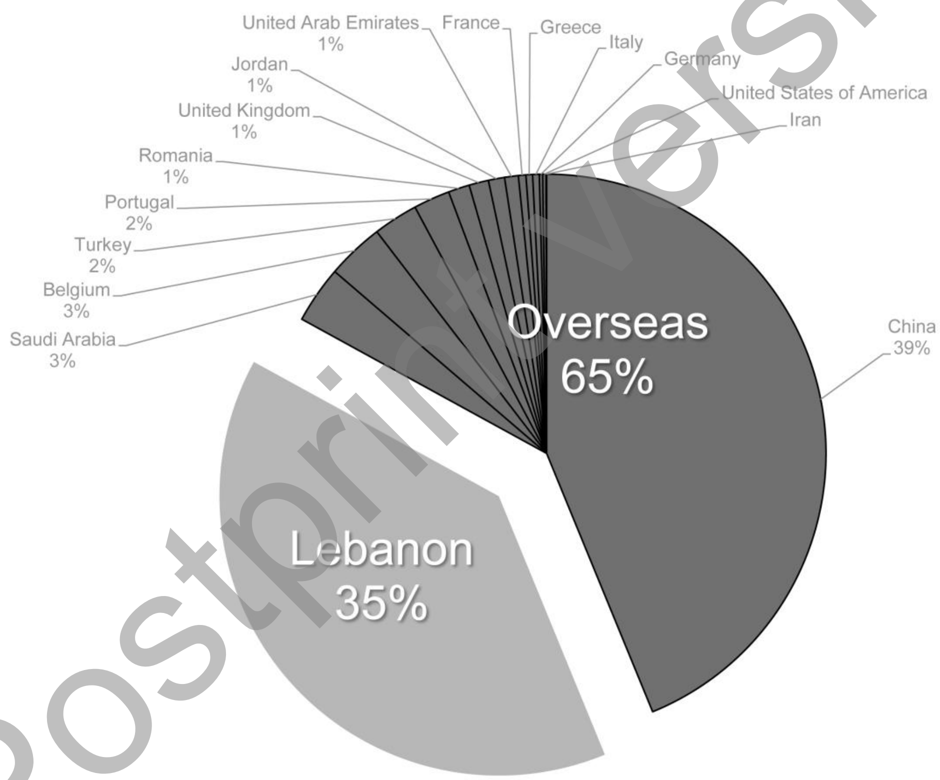


Figure 8: Breakdown of the life cycle embodied energy demand of the case study apartment building in Sehaileh, Lebanon over 50 years, by country of origin. Note: Figures may not sum due to rounding. The absence of a percentage indicates a contribution lower than 1%,

Figure 8 uses the material origins and represents the contribution of each country towards the embodied energy of the case study building. Only 35% of the embodied energy is attributed to materials sourced from Lebanon while 65% is associated with imported materials (dominated by China). This graph is a very simplistic representation of global supply chains since each manufacturer in each country relies in turn on other products and services that can be located in another country and so on. This leads to truly global supply chains stretching over thousands of kilometres. Figure 8 mainly shows that even if a Lebanese embodied energy database existed, it would only cover the embodied energy associated with 35% of the total (calculated using Australian data). For this reason, the comprehensive Australian hybrid database is chosen as it is the most comprehensive database for building materials, globally. In addition, the comparable energy mix of Australia and China (the main supplier of materials) which are both dominated by coal [66] is likely to diminish the influence of this significant factor on the results. Also, the higher primary energy factor for electricity in Lebanon (3.8 compared to 3.4 used in the Australian input-output model) supports similar energy intensities for electrically driven processes in concrete manufacture.

In order to verify if using Australian data results in significant errors in the quantification of embodied energy, results of this work are compared to figures from previous studies on residential buildings with a reinforced concrete structure and with a 50 years time frame. These figures are taken from Ramesh et al. [67] and Karimpour et al. [3], two major reviews of studies on the life energy demand of buildings. Where a gross floor area was used, it has been converted to a usable floor area using a coefficient of 0.9 as in Fay et al. [4]. Figure 9 compares the life cycle embodied energy of the case study building (excluding infrastructure) calculated using Australian process and hybrid data, to previous studies.

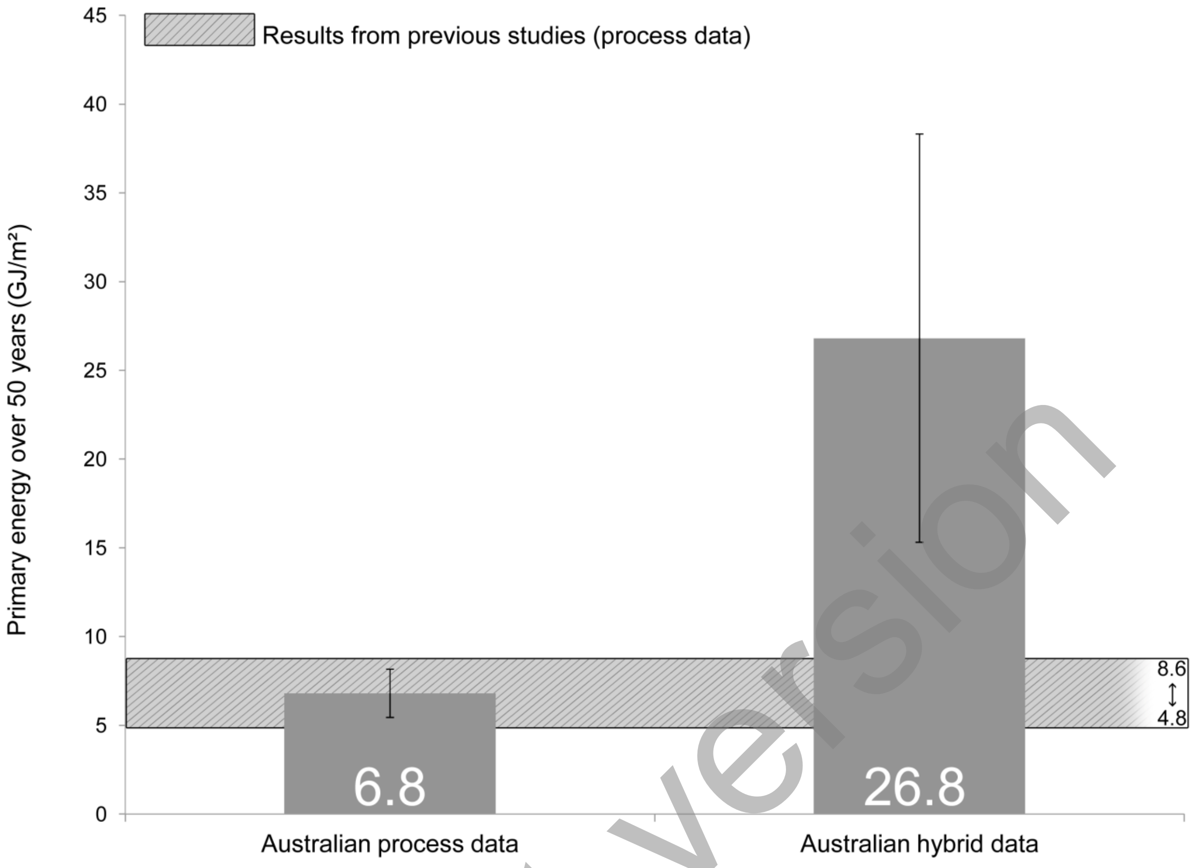


Figure 9: Comparison of life cycle embodied energy figures of the case study apartment building in Sehaileh, Lebanon, over 50 years, calculated using Australian data, to previous studies, per square meter of usable floor area.

Figure 9 shows that when calculated using Australian process data, the embodied energy intensity of the case study building (6.8 GJ/m²) falls within the range of values of previous studies (4.8-8.6 GJ/m²). Even with the 20% uncertainty on process data, the obtained figure remains within the range of previous studies. This shows that at the whole building level, the origin of the data does not seem to greatly affect the total life cycle embodied energy intensity of buildings when using process data.

However, a much more detailed comparison of the embodied energy results is required to validate the use of Australian data. This would require establishing a life cycle inventory that comprises process and input-output data for building materials in all the countries involved in producing building materials for Lebanon (see Figure 8). Such process data would comprise detailed information on raw material extraction processes for different materials, energy bills from material manufacturers (ideally for each manufacturing process), electricity mix and energy mix for each studied process and other data. Input-output data would rely on environmentally extended input-output matrices of countries where available. The absence of input-output data at a sufficient resolution for a country, such as in

Lebanon, would require developing a more comprehensive input-output matrix and more reliable national energy accounts. For all these reasons, a more thorough assessment of the compatibility of Australian hybrid embodied energy figures for the Lebanese situation falls out of the scope of this paper. Further research is needed in comparing life cycle inventories of different countries.

The calculated life cycle embodied energy figure in this paper (excluding infrastructures) is 26.8 GJ/m² and is significantly higher than in previous studies or when using Australian process data. The factor of four between the Australian process data figure and the Australian input-output-based hybrid figure is due to the more comprehensive nature of hybrid analysis and its systemic completeness. In their study of wind turbines in the UK, Wiedmann *et al.* [68] also found a factor of 3 difference between results calculated using process analysis and hybrid analysis. Even the lowest possible value of embodied energy calculated using Australian hybrid data which equates to 15.1 GJ/m² with 42.9% uncertainty (see Section 2.6) is still nearly twice as high as the highest intensity of previous studies. Relying on hybrid analysis is therefore highly recommended for future estimations of the embodied energy of buildings.

Results presented in Figure 9 highlight the urgent need for a comprehensive and global database of embodied energy coefficients for building materials. This need is underpinned by the increased globalization of supply chains and the fact that current embodied energy databases are not adapted to their global nature. Indeed, they either rely on process data or use hybrid analysis at a national level, treating all imports with the national energy intensity. A future development in this sense would be the development of a multi-regional input-output [69, 70]-based hybrid analysis (MRIOBHA) framework that combines average sectorial energy intensities at a national or subnational level with reliable process data collected from industries at the same level (national or subnational). This database would provide the necessary means to measure the embodied energy of building materials (and any other product or service) more accurately and comprehensively. This database could also automatically provide up-to-date figures based on the latest data figures as in the work of Dias and Poolyadda [71].

4.4 Other aspects

This study suffers from a number of limitations. Since input-output matrices are required to determine indirect transport energy intensities, the use of Australian figures are approximate in a Lebanese context, even if the low quality and resolution of input-output data in Lebanon (see Section

2.2.2) makes them unusable. The case study building is located in the Mount-Lebanon region which has accommodated most of the recent construction activity. Yet, other studies taking into account the other climatic conditions of Lebanon (e.g. Alpine in the mountains or dry in the North-East) should be undertaken. It is however expected that the main findings will still hold due to the small contribution of thermal requirements towards the total life cycle energy demand.

In this paper, thermal operational energy requirements have been modelled using a dynamic energy simulation program. This is more accurate than relying on static thermal equations as in previous studies using the same technique [8, 60, 64]. Also, the bill of quantities used in this work is more reliable than in previous studies since it is issued directly from the contractor.

Yet, this work has focused solely on energy demand while a range of other environmental impact categories should be considered in order to provide a complete estimation of the environmental impact of this building. These other categories include but are not limited to 'water use', 'toxicity', 'waste generation' and 'global warming potential'. For instance, while natural stones have a very low embodied energy, they are very likely responsible for a huge impact on the Lebanese ecosystems since stone extraction in quarries is undertaken in a very destructive and unregulated way. The same applies to the extraction of gravel and sand which are heavily used in the Lebanese building industry (notably for concrete manufacture) and which come at the expense of devastated mountainous areas. Also, even if the end of life stage requires a very small amount of energy, it is often responsible for large quantities of waste. With Lebanon's very low rate of recycling and its landfilling policy, waste generation is likely to result in a high environmental impact.

This study uses a single representative building to establish the life cycle energy demand profile of this building type. Yet a considerable variability can exist between buildings notably at the operational and transport energy level. The lifestyle of the occupants, their behaviour, their jobs location, their age and gender can all significantly affect the energy demand beyond the imposed 20% variability. The work of Burman et al. [72] is an example that focuses on reducing the gap between predicted and actual operational energy use in buildings.

Finally, it is hard to compare results from this study to the literature as there are very limited studies on the life cycle energy demand of buildings in Lebanon. Additional studies would allow a more robust contextualisation of the findings.

5 Conclusion

This paper has established that most of the energy used by occupants of recent low-rise apartment buildings in Lebanon is associated with mobility, followed by operational and embodied requirements. It has shown that a reduction of the total energy requirements is beyond the scope of any one actor of the construction industry and includes planners, regional managers, local municipalities, building designers and material manufacturers.

The recommendations based on this paper can be divided into immediate actions and long terms strategies.

Immediate actions:

- Strongly support the installation of solar thermal collectors with an auxiliary gas boiler for domestic hot water.
- Favour the use of small cars instead of sport utility vehicles (SUVs).

Long term strategies:

- Develop public transport infrastructures between the capital Beirut and other coastal cities.
- Implement policies supporting decentralization from Beirut and the development of peripheral areas.
- Support pedestrian friendly urban development and favour mixed-used neighbourhoods.
- Switch from fossil-fuel based electricity to renewable energy sources.
- Develop and implement a mandatory life cycle energy efficiency policy that considers at least embodied and operational energy.
- Favour the reuse and recycling of construction materials.

A limitation of this study is the reliance on Australian data for the calculation of embodied energy figures as this can result in a high uncertainty (see Sections 2.2.2 and 4.3). A global multi-regional-input-output-based hybrid analysis framework would be much more reliable to assess the embodied energy of building materials in Lebanon that are mostly sourced from global supply chains.

Future research comprises widening the system boundaries to include other environmental impact categories, the end of life stage, running sensitivity analyses on the effect of various measures towards reducing the energy use of buildings and assessing other buildings in other locations to verify the results. The development of a global database for embodied energy coefficients for building materials is also strongly needed to improve the robustness of life cycle energy analyses of buildings in Lebanon and elsewhere. These actions will ultimately contribute to reducing the environmental impact of buildings in Lebanon.

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Appendix A : Detailed description of the case study building

Detailed information about the case study building, including its construction characteristics, thermal performance, bill of material quantities, its dynamic energy simulation and the transport energy data are provided in this appendix.

Additional information on the case study building

The case study building is supported by a cast *in situ* reinforced concrete (RC) structure like most residential buildings of this type in Lebanon. The foundations are shallow consisting mainly of continuous footings and are relatively small compared to the size of the building as the ground in Mount Lebanon is almost always rocky and provides a very high bearing capacity. This avoids the need for deep foundations as in other countries with poor soil conditions, such as Belgium or the Netherlands. The foundations support RC columns and walls which support the slabs, typically about 250 mm thick. The latter are constituted by embedded primary beams (about 800 mm wide on average) resting on the RC columns and walls which in turn support secondary beams (called ribs) that run perpendicular to the primary beams. These ribs are about 150 mm wide and separated by 400 mm wide gaps filled with hollow concrete blocks 180 mm high topped by a 70 mm thick compressive slab. The hollow blocks and reinforcement steel are first placed on the wooden formwork before casting the ready mix concrete.

The outer walls are double concrete blocks walls with an air blade in between. They are stone-clad on the outside and rendered with a concrete mortar and painted on the inside. The double glazed windows are installed on an aluminium frame which is not thermally broken. This often leads to condensation on the frames in winter as a result of the thermal bridge. Window frames also comprise exterior aluminium sunshade rolls. The concrete lintels used and the RC columns and beams also represent thermal bridges as they are not insulated and they break the continuity of the air blade (see Figure A.1). In the case study building, a particular care has been taken in this regard as the lintels are cut in half along the axis of the wall and filled with insulation. Also, the columns are insulated with 20 mm of XPS to avoid the thermal bridge. However, this will not be taken into account in this paper as it is not a mainstream practice. The thermal characteristics of the building envelope are provided in Table A.1.

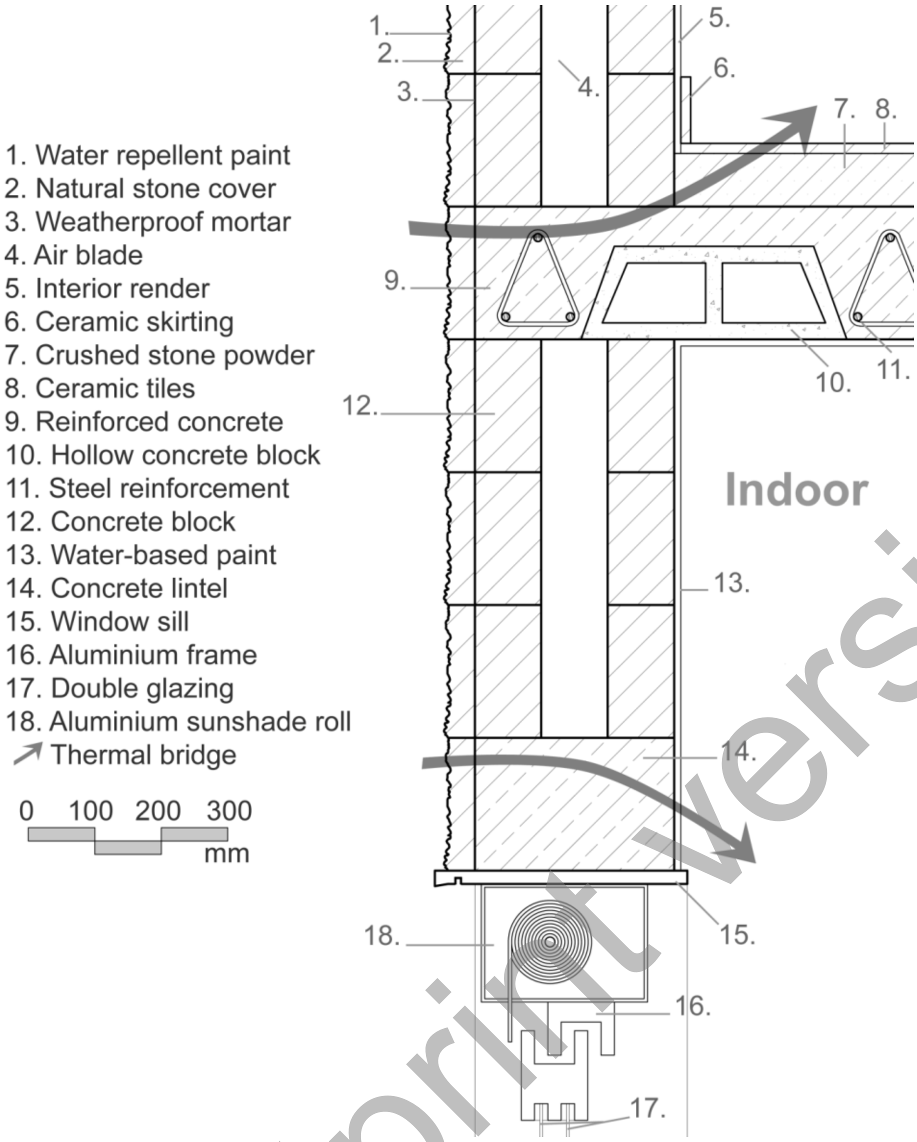

Figure A.1: Wall-slab junction detail of the case study apartment building in Sehaileh, Lebanon

Table A.1: Thermal characteristics of the envelope elements of the case study apartment building in Sehaileh, Lebanon

Envelope element	Composition	U-value (W/(m²K))	g-value ()
Outer walls	Double wall of concrete blocks (100 mm) with an intermediate air blade (100 mm)	0.78	N/A
Windows	Double glazing with aluminium frames (not thermally broken)	2.8	0.77
Roof	Hollow concrete blocks – Clay tiles	0.7	N/A

The interior finishes are of medium standard with large ceramic tiles in the living room, tiled walls to the ceiling in bathrooms, WCs and kitchens. The bedrooms are also clad with ceramic tiles.

The domestic hot water is provided by an electric hot water tank. Each apartment has a central heating system with radiators installed in each room. The heating system is operated by a gas boiler.

The detailed bill of material quantities of the building was obtained from the contractor. It has been used to adjust, where necessary, the automatic values produced by the software tool developed by Stephan [29]. The quantities of the main construction materials are given in Table A.2 along with the average useful life of these materials, based on NAHB [73] and Ding [74]. The design quantity of each material is augmented by a relevant wastage coefficient that accounts for the wastage on the construction site, during transport or during other activities. These wastage coefficients are based on Wainwright and Wood [75], on CSIRO [76] and on Crawford [77].

Table A.2: Bill of material quantities and average useful lives of main materials used in the case study apartment building in Sehaileh, Lebanon

Material	Delivered quantity	Wastage coefficient	Total quantity	Average useful life (years)
Concrete mortar	85.1 m^3	1.3	110.6 m^3	UL_b[a]
Concrete blocks 15 MPa	240.5 m^3	1.1	264.6 m^3	UL_b
Concrete 25 MPa	510.1 m^3	1.1	561.1 m^3	UL_b
Steel	38.6 t	1.05	40.4 t	UL_b
Ceramic tiles (10 mm thick)	1 507.2 m^2	1.05	1 582.6 m^2	UL_b
Roof tiles	327.8 m^2	1.1	360.5 m^2	UL_b
Natural stone	21.5 m^3	1.3	28 m^3	UL_b
Aluminium frames	522.2 m	1.05	548.4 m	40
Glass	348.2 m^2	1.03	358.6 m^2	40

Paint (water-based)	6 096.3 m²	1.05	6 401 m²	10

Note: $^{a}UL_{b}$ = Useful life of the building, i.e. 50 years

Thermal energy modelling of the case study building

The final heating and cooling demands are obtained with the DEROB-LTH model. A typical floor with a simplified geometry has been modelled, including two apartments, one facing east and the other west. This floor was then replicated three times and its elevation incremented by the height between the slabs to generate the building. Figure A.2 depicts the DEROB-LTH model. The average heating and cooling load of all units is presented in the results. The shading of overhanging balconies and flower trays as well as nearby buildings is taken into account. As depicted in Figure A.2, the underground parking volume has been removed and the building has been modelled directly on the ground. This, along with geometrical approximations, might have an influence on thermal energy requirements and is further discussed in Section 4.

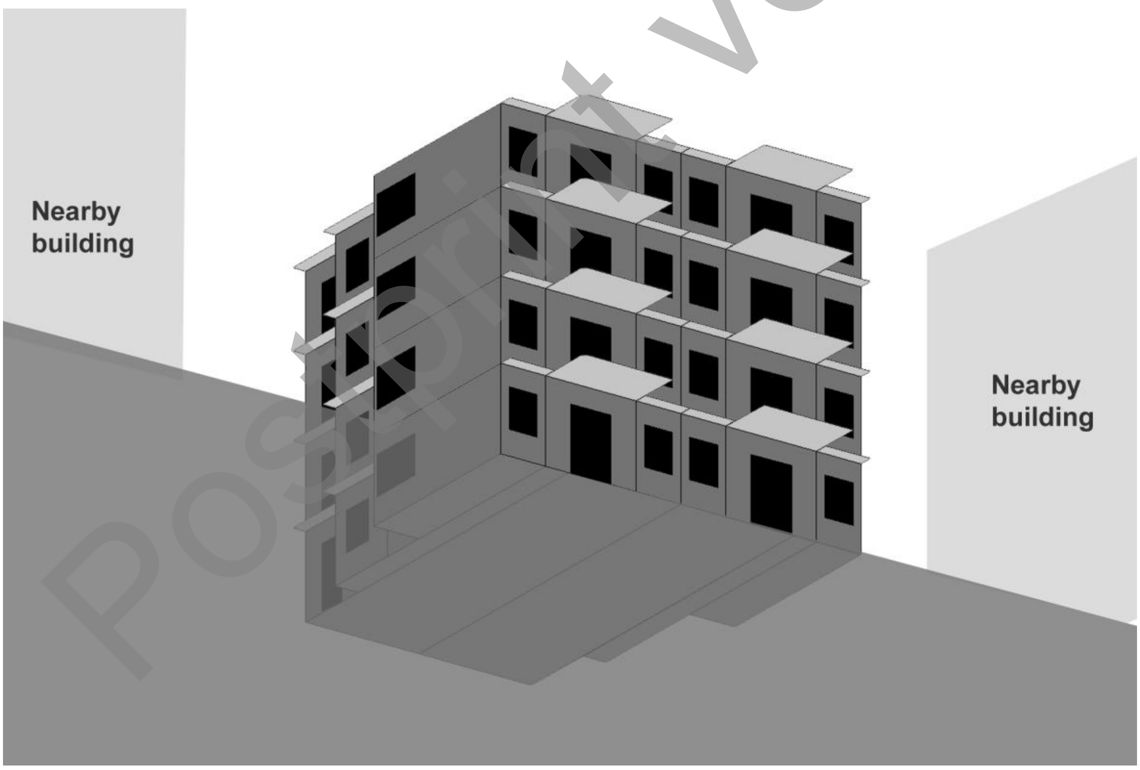

Figure A.2: South façade of the DEROB-LTH model of the case study apartment building in Sehaileh, Lebanon

The parameters used in this model are given in Table A.3. The typical apartment unit has been assumed to accommodate an average of four occupants based on the number of rooms. The final heating and cooling demands are converted to delivered energy figures based on a gas boiler efficiency of 90% and a coefficient of performance (COP) of 2.5, respectively. These figures are, in turn, converted to primary energy figures using the primary energy conversion factors for gas and electricity.

Table A.3: Main parameters used in the DEROB-LTH model of the case study apartment building in Sehaileh, Lebanon

Parameter	Value	Comment
Net indoor floor area	113 m²	Excludes wall thickness, balconies and common areas such as the staircase
Number of occupants	4	
Air temperature		
Heating	20ºC	
Cooling	26ºC	
n_{50} value (air leakage at 50 Pa pressure difference)	3 ach^{-1}	Average air leakage value for recent residential buildings
Occupancy		Based on an average timetable of residents
Weekday	16h→19h (3 occupants)	
	19h→07h (4 occupants)	
Weekend	16h→10h (4 occupants)	
Internal gains		
Occupants	100 W/occupant	Average metabolism
Appliances and others	3 W/m² (when apartment is occupied)	Adapted from the Passive House Planning Package figure of 2.1 W/m²
	1 W/m² (when apartment is empty)	Accounts for standby losses

Parameter	Value	Comment
Maximum simultaneous heating power	5 kW	Assuming that 3 radiators will be active at once
Maximum simultaneous cooling power	5.5 kW	Assuming that 2 out of the 4 installed air-conditioning machines operate at once.
Heating schedule		
Weekday	07h→08h 19h→23h	
Weekend	09h→11h 19h→23h	
Cooling schedule		
Weekday	07h→08h 16h→21h	
Weekend	09h→11h 16h→21h	
Windows	Open at 20% for two hours per day (all year long)	Windows are opened to renew the indoor air
Curtains	Interior curtains are closed at night all year long and additionally in the early afternoon in the three summer months	

Non-thermal energy modelling of the case study building

Non-thermal operational energy demands are based on figures from Ruble and El Khoury [23] which have been augmented to consider other requirements, such as electronic appliances. The power ratings of the latter are based on Blomsterberg and Avasoo [78]. The number of appliances in the household is based on a survey by Ipsos [79]. The data used for non-thermal operational energy demands is provided in Table A.4.

Table A.4: Estimated annual delivered energy use of household appliances and cooking for the case study apartment building in Sehaileh, Lebanon

Appliance	Power rating (W)	Operating time (hours/day)	Number of appliances	Estimated annual delivered energy use (MJ)
CFL lights	12	6	10	946
Fridge/freezer	300	6	1	2 365
Washing machine (7 kg)	1 800	0.65	1	1 537
LCD television	200	2	2	1 051
Router	5	24	1	158
Laptop	30	2	2	158
Other	100	6	1	788
Gas stove	3 000 (based on manufacturer)	1	1	3 942

Source: Adapted from Ruble and El Khoury [23], Power ratings based on Blomsterberg and Avasoo [78] unless specified otherwise. Number of appliances adjusted from Ruble and El Khoury [23] based on Ipsos [79].

Information regarding transport energy requirements of the case study building

The average household is considered to own two gasoline cars. Both are driven 20 000 km per year. These figures are based on an interview of the occupants. The direct energy intensity is based on a average fuel economy of 10 L/100 km, which is slightly less than in Australia (11.3 L/100 km) [80]. Indeed, although many cars in Lebanon have rather large engines for the very steep terrain and are equipped with air conditioning units for the warm summers, a significant number of smaller city cars is also used. Based on an average car occupancy rate of 1.6, this results in a direct energy intensity of 2.13 MJ/pkm. The indirect energy intensity is based on Lenzen [48] and equates to 2

MJ/pkm. The overall energy intensity of car travel is therefore 4.13 MJ/pkm. This figure is lower than the intensity used by Fuller and Crawford [58] in their study of residential buildings in and around Melbourne, Australia, in which they assume that only one person uses the car for work-related trips (7 MJ/pkm).

Appendix B : Primary energy conversion factors for Lebanon

This appendix explains how the primary energy conversion factor for electricity is derived for Lebanon. It provides a brief definition of primary energy conversion factors (PEF) as well as a review of the current state of PEF determination in Europe based on Molenbroek et al. [47]. All the information, algorithms and data used to determine the PEF for electricity in Lebanon are then given. These include plant efficiency, net calorific content of fuels, distribution losses and the characteristics of privately owned generators for electricity generation. Some upstream losses are taken into consideration and the inclusion of others is discussed.

Primary energy conversion factors

As described in EN 15603:2008 [81], a primary energy conversion factor converts the final or delivered energy to primary energy terms that represent the total raw amount of energy required upstream of the energy use process. Practically, a final energy demand would be augmented by the losses in the building depending on the efficiency of the system to obtain delivered energy. The latter would then be converted to primary energy terms by taking into account distribution and generation losses as well as losses further upstream (see Equation 4). However, quantifying upstream losses is extremely complex and seldom performed in practice as highlighted by Molenbroek et al. [47].

In one of the rare reports that investigate PEFs, Molenbroek et al. [47] review PEFs for seven European countries including France, Germany, the Netherlands, Poland, Spain, Sweden and the UK. They find that in at least three of the seven countries, upstream losses are not taken into account. Furthermore, the algorithms and the data used to determine PEFs is not clearly indicated for the majority of countries. Also, the values of PEFs in some countries, such as the Netherlands and Sweden, are politically motivated, greatly reducing the scientific validity of the calculated value. Therefore, based on Molenbroek et al. [47] a significant share of existing PEFs for European countries do not take into account upstream losses, are irreproducible due to lack of transparency on their calculation and are sometimes modified due to political interference. Yet PEF values are defined and used in building energy performance calculations. This is not the case in Lebanon where readily available PEFs values do not exist.

State of electricity supply in Lebanon

Lebanon's electricity generation depends on a mix of public power plants and private generators. Since the national electricity company, Electricité du Liban (EdL), which is state-owned, produces

1 848 MW of the roughly 2 500 MW needed, there is approximately a shortage of 700 MW of capacity [82]. A significant part of this shortage is currently covered by private generators (80 kW to 240 kW on average) that are installed in neighbourhoods. The power distribution lines installed by private generator owners are generally of poor quality and are rarely correctly dimensioned. This leads to significant voltage drop along the lines as well as high losses which can be roughly estimated at 20% These generators, as well as the dominant majority of the large power plants, are operated on oil-based products. Even some gas turbine power plants are currently operated on diesel. According to the Lebanese Ministry of Energy and Water [82], 95.5% of EdL's electricity production is based on oil products with the rest provided by hydroelectric plants. Based on the shortage of supply by EdL's plants, electricity is supplied 18h per day by EdL (75%) and 6h per day by private generators (25%) [82]. This means that the calculation of the PEF for electricity in Lebanon needs to take into account EdL's oil-based generation, EdL's hydroelectric generation and private generators.

Determining the primary energy conversion factor for electricity in Lebanon

In this work the primary energy conversion factor for electricity (PEF_{el}) is calculated for the Lebanese case, based on EN 15603 [81]. The factor comprises generation losses, distribution losses as well as upstream losses in terms of electricity requirements for electricity generation.

The first step in determining the PEF_{el} is to evaluate the PEF for oil-based plants ($PEF_{el,oil,EdL}$) of state-run Electricité du Liban (EdL). $PEF_{el,oil,EdL}$ is calculated using the average power plant efficiency, average distribution losses and average upstream losses in terms of electricity requirements. The calculation is formalised into Equation B.1.

$$PEF_{el,oil,EdL} = \frac{1}{\underbrace{\frac{1}{FI_{oil,EdL} \times \frac{SE_{oil,EdL}}{3.6} \times 10^{-6}}}_{Generation\ efficiency} \times \underbrace{\left(1 - L_{dist,EdL}\right)}_{Distribution\ efficiency} \times \underbrace{\left(1 - L_{up,elec,EdL}\right)}_{Upstream\ efficiency}} \tag{B.1}$$

Where:

$PEF_{el,oil,EdL}$ = Primary energy conversion factor for electricity from oil-based power plants of state-run Electricité du Liban (EdL); $FI_{oil,EdL}$ = Average fuel intensity of EdL's oil-based power plants in g/kWh_{output}; $SE_{oil,EdL}$ = Average specific energy of fuels used in oil-based plants of EdL in kJ/kg; $L_{dist,EdL}$ = Average distribution losses on EdL's grid; and $L_{up,elec,EdL}$= Average electricity requirements for electricity generation in EdL's oil-based plants.

Once $PEF_{el,oil,EdL}$ is determined, it has to be combined with $PEF_{el,hydro,EdL}$ which represents the primary energy conversion factor for hydroelectricity in Lebanon. However, since hydroelectricity represents only 4.5% of Lebanon's electricity mix [82], and since very little data is available about the plant efficiency and the upstream losses of hydroelectric plants in Lebanon, an estimated value of 1.5 for $PEF_{el,hydro,EdL}$ has been used and is based on average hydroelectric plants in Europe from EN 15603 [81]. The choice of this value has a very limited influence on the overall PEFel.

Both $PEF_{el,oil,EdL}$ and $PEF_{el,hydro,EdL}$ are combined based on the energy mix as per Equation B.2 to provide $PEF_{el,EdL}$.

$$PEF_{el,EdL} = PEF_{el,oil,EdL} \times S_{oil,EdL} + PEF_{el,hydro,EdL} \times S_{hydro,EdL} \quad \text{(B.2)}$$

Where:

$PEF_{el,EdL}$ = Primary energy conversion factor for electricity of state-run Electricité du Liban (EdL); $PEF_{el,oil,EdL}$ = Primary energy conversion factor for electricity from oil-based power plants of EdL; $S_{oil,EdL}$= Share of oil-based electricity in EdL's electricity mix; $PEF_{el,hydro,EdL}$ = Primary energy conversion factor for hydroelectric plants of EdL; and $S_{hydro,EdL}$= Share of hydroelectricity for EdL's electricity mix.

The $PEF_{el,EdL}$ has to be combined with the PEF_{el} of private generators in Lebanon ($PEF_{el,gen}$). The latter is calculated as per Equation B.1. but without considering upstream losses (in terms of electricity needed to run the generator) since the latter is assumed to be negligible. Indeed, only current from the starter battery is required to start the generator. Figures for fuel intensity, specific energy of the fuel used and distribution losses are adapted to the private generators situation based on average manufacturers' specifications, AIE [83] and an estimation, respectively.

The final PEF_{el} for Lebanon is estimated at 3.8 based on Equation B.3 by combining $PEF_{el,EdL}$ and $PEF_{el,gen}$ using a 75% and 25% contribution, respectively.

$$PEF_{el} = PEF_{el,EdL} \times S_{EdL} + PEF_{el,gen} \times S_{gen} \quad \text{(B.3)}$$

Where:

PEF_{el} = Primary energy conversion factor for electricity in Lebanon; $PEF_{el,EdL}$ = Primary energy conversion factor for electricity of state-run Electricité du Liban (EdL); S_{EdL}= Share of EdL electricity in Lebanon's electricity mix; $PEF_{el,gen}$ = Primary energy conversion factor for private diesel generator; and S_{gen} = Share of private generators in Lebanon's electricity mix.

The values of all equations terms (including intermediate results) which are required for the calculations, as well as all associated sources, are provided in Table B.1. These were obtained from a report by Kampet et al. [28] as well as a policy paper by the Lebanese Ministry of Energy and Water [82].

Table B.1: List of terms, values and sources used in the determination of the primary energy conversion factor for electricity in Lebanon.

Term	Value	Source
Average fuel intensity of EdL's oil-based plants ($FI_{oil,EdL}$)	276.8 g/kWh	Based on figures for two representative power plants from Kampet et al. [28]
Average specific energy of fuels used in oil-based plants of EdL ($SE_{oil,EdL}$)	46 500 kJ/kg	Based on Kampet et al. [28]
Average distribution losses on EdL's grid ($L_{dist,EdL}$)	16.5%	Based on MEW [82]
Average electricity requirements for electricity generation in EdL's oil-based plants ($L_{up,elec}$)	6.5% of electricity production	Based on Kampet et al. [28]
Primary energy conversion factor for electricity from oil-based power plants of EdL ($PEF_{el,oil,EdL}$)	3.99	Based on Equation B.1
Primary energy conversion factor for hydroelectric plants of EdL ($PEF_{el,hydro,EdL}$)	1.5	Based on EN 15603 [81]
Share of oil-based electricity in EdL's electricity mix ($S_{oil,EdL}$)	95.5%	Based on MEW [82]

Term	Value	Source
Share of hydroelectricity for EdL's electricity mix ($S_{hydro,EdL}$)	4.5%	Based on MEW [82]
Primary energy conversion factor for EdL's electricity ($PEF_{el,EdL}$)	3.89	Based on Equation B.2
Average fuel intensity of private generators (FI_{gen})	210 g/kWh	Based on specifications from manufacturers for generators of 80-220 kW
Average specific energy of diesel used in private generators ($SE_{dies,gen}$)	46 000 kJ/kg	Based on AIE [83]
Average distribution losses on private generators grid ($L_{dist,gen}$)	20%	Estimated
Primary energy conversion factor for private generators electricity ($PEF_{el,gen}$)	3.35	Based on Equation B.1 with relevant terms substituted with generators data.
Share of EdL electricity in Lebanon's electricity mix (S_{EdL})	75%	Based on MEW [82]
Share of private generators in Lebanon's electricity mix (S_{gen})	25%	Based on MEW [82]
Primary energy conversion factor for electricity in Lebanon (PEF_{el})	3.8	Based on Equation B.3

Note: Intermediate and final results are underlined. EdL = Electricité du Liban.

Considering upstream losses in the determination of primary energy coefficients

Upstream losses and requirements can significantly affect the value of the primary energy conversion factor (PEF). These requirements include but are not limited to: transport of fuel, fuel refining and fuel extraction. These can be further extended by taking into account energy requirements for building and maintaining the power plants. Trying to quantify the energy requirements of each of these processes to determine upstream losses and calculate a comprehensive PEF is an extremely demanding work that requires large amount of data which are often hard to obtain. This is further complicated by the fact that in most countries, these processes occur in another country and therefore, data specific to the supplier and related country is required. To further complicate matters, each of the upstream processes relies in turn on a number of other processes that in turn rely on a series of others and so on, resulting in a quasi infinite number of upstream stages. This is probably one of the reasons behind the lack of consideration of upstream losses in the calculation of PEF in many European countries. The only currently available method to take into account all these inputs across global supply chains is multi-regional input-output analysis (MRIOA) [70, 84, 85]. Future calculations of PEFs should ideally rely on MRIOA to ensure that all inputs upstream in the global supply chain are taken into account.

To estimate the potential influence of taking into account upstream losses, fuel transport requirements are estimated for Lebanon. Most fuels are delivered to Lebanon from the Persian Gulf and come from countries such as KSA or the UAE. An estimated one-way trip length from KSA to Lebanon through the Suez channel is 6 500 km based on Google Earth. Assuming a coastal shipping energy intensity (including direct and indirect requirements) of 0.4 MJ/ntkm based on Lenzen [48] (ntkm stands for net tonne-kilometre), each kg of heavy fuel oil that arrives to Lebanon requires 2 600kJ of energy for a one-way shipment. If this energy requirement is taken into account in the calculations (for both state-run power plants and private generators), the resulting PEFel for Lebanon would be 4 instead of 3.8. This very rough estimation reveals that upstream losses can be significant (+5% for transportation only) and should ideally be taken into consideration.

Primary energy conversion factor for gas

The primary energy conversion factor for gas is estimated at 1.1, as in some European countries. This means that upstream losses, associated with gas extraction and transportation, are estimated at 10%. Losses in the installed boilers are taken into consideration when converting final energy requirements to delivered energy (with an efficiency of 95% based on the manufacturers' details as indicated in Table 1).

While the 1.1 PEF for gas is an approximation that is due to the unavailability of relevant data, it is still more realistic than considering a unitary PEF for gas and other fuels as in Belgium [86] or Sweden [47] where upstream losses are ignored. The 1.1 value is similar to the PEF for gas used in the UK (1.06), Poland (1.1) and Spain (1.08) [47] or Germany (1.1) (based on the Passive House Planning Package). Most importantly, only heating and cooking are operated on gas in the studied building. These two operational energy demands represent together less than 6% of the total life cycle energy demand. The potential error in the PEF of gas does not therefore affect the findings of this paper.