This is a preprint version of the paper. Significant changes have been made during the peer-review process, notably justifying the use of Australian data for embodied energy, updating the calculation of thermal requirements and detailing the quantification of the primary energy conversion factor for electricity in Lebanon. For more accurate and reliable results please refer to the final version.

The final version of the paper has been published in the Journal of Energy and is available at: http://www.sciencedirect.com/science/article/pii/S0360544214008500

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

André Stephan[a,b,1], Laurent Stephan[c]

[a]Research Fellow at the Belgian National Fund for Scientific Research (F.R.S. – FNRS), 5 Rue D'Egmont, Brussels 1000, Belgium
[b]Building, Architecture and Town Planning, Université Libre de Bruxelles (ULB), 50 Av.F.-D. Roosevelt, Brussels 1050, Belgium
[c]Technical Enterprises Co., 1 Rue Lycée de Ville, Adonis Zouk-Mosbeh, Lebanon

[1]Corresponding Author: André Stephan
Tel: +32 485 443 248
Fax: +32 2 650 27 89

Building, Architecture and Town Planning
Université Libre de Bruxelles (ULB)
50 Av.F.-D. Roosevelt,
Brussels 1050
Belgium
e-mail: andre.stephan@ulb.ac.be

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Abstract

Buildings require a substantive amounts 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 consumption 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 (55%) followed by operational (24%) and embodied (21%) requirements. The main ways to reduce this life cycle energy demand comprise relocating jobs outside of the capital, put in place an adequate public transport network, improve the town planning to favour pedestrians and rely on gas or renewable energy sources instead of electricity when possible, especially for domestic hot water.

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

1 Introduction:

In the last 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 [1]. 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 160m² (based on the average apartment size in recent buildings), this equates to 140 000 apartment units, approximately, far more 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.

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The construction and operation of buildings require significant amounts of energy and are responsible for huge environmental impacts [2]. It is therefore crucial to determine the overall energy consumption of recent residential buildings in Lebanon to establish their energy use profile and to identify means of reducing their energy demand.

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) [3]. 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 [4].

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 consumption for transport which needs to be taken into account to provide an overall picture of the energy demand [5].

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 [6] and Ruble and El Khoury [7]. The embodied energy is seldom mentioned [8], and rarely quantified. The transport energy demand of building occupants is never taken into account at the same time with embodied and operational requirements. There is therefore a need for a comprehensive energy assessment of the 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.

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1.2 **Scope**

This work focuses solely on energy, as Junilla [9] has 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.

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2 Method

2.1 **A multi-scale life cycle energy analysis framework**

Buildings are the constituting brick of the built environment. They can be seen as 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 [10]. In Lebanon, Mourtada [11] has estimated this figure at 35% (including commercial buildings). 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 [12], 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. This work relies on the framework and software tool developed by Stephan et al. [13] 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 [14] and Winistorfer et al. [15] 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 embodied energy of the infrastructures that are essential to the functioning of the building is taken into account. The determination of each of the embodied, operational and user transport energy requirements are explained below.

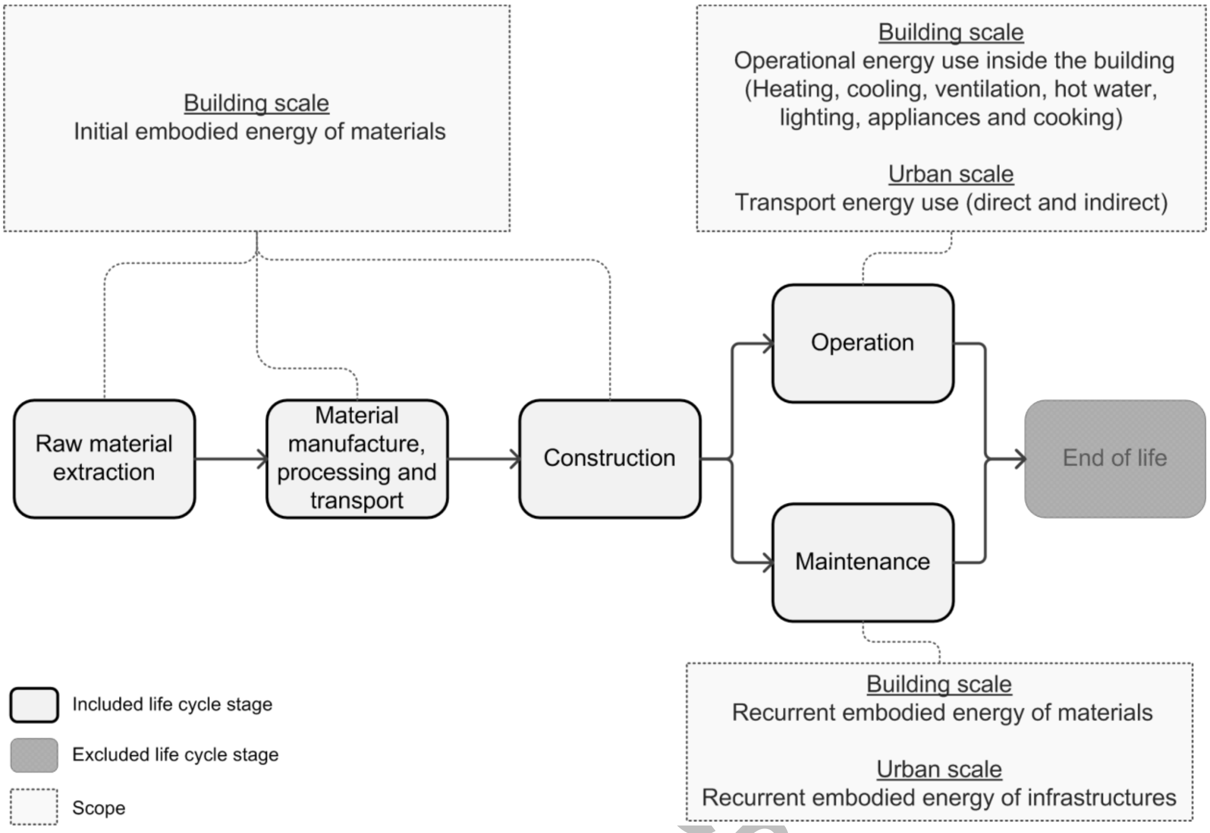

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Figure 1 System boundaries of the life cycle energy analysis framework

2.1.1 Embodied energy calculations

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, etc.

In this work, embodied energy is quantified using the comprehensive input-output-based hybrid analysis technique developed by Treloar [16]. This technique relies on the so-called ‘input-output analysis’ to cover all material and non-material inputs across the whole supply chain. At the same time, it 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 embodied energy quantification techniques can be found in Crawford [2], Finnveden et al. [17] and Suh et al. [18].

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 are added afterwards since the coefficient comprises only material-related inputs. 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.

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 infrastructure in terms of roads, power and water distribution and sewage already exist in the area.

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

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.

While input-output-based hybrid analysis is the most comprehensive technique currently available to determine embodied energy, it is rarely used. The only readily available database of construction materials has been developed for Australia by Treloar and Crawford [19]. Yet, even if using Australian figures can result in errors, they are still recommended compared to using the widely available process data. Indeed, in their study of a Passive House in Belgium, Stephan et al. [20] have demonstrated that process data produces embodied energy figures four times lower than those obtained with hybrid analysis. In this work, since there is no embodied energy database for Lebanon as it might exist in other countries, Australian data is used and the resulting errors are taken into account (see Section 2.1.5). The Lebanese construction cost is converted to Australian figures using the average purchasing power parity coefficient from 2008 to 2012, based on World Bank [21].

The use of the comprehensive Australian data is further justified in this case as the Lebanese construction sector relies on a large variety of suppliers that are scattered across the globe. Indeed, while concrete and some stone products are produced locally, Lebanon imports most manufactured goods since it does not have the required raw materials. Recently, Chinese products are being widely used. These range from ceramic tiles to building systems such as boilers. Also, European products, such as French roof tiles or German taps are commonly used. The resulting supply chain is incredibly complex and encompasses many economies. The only way to combine process data with input-output data from multiple economies requires using multi-regional input-output analysis [22]. Yet even this approach requires the development of reliable input-output data for Lebanon to be integrated with other databases. Since Australia and China both have an energy mix dominated by coal [23], the average energy intensity of their economies are likely to be comparable. With most building construction materials imported from China to Lebanon, the use of an Australian input-output-based analysis technique is unlikely to induce extremely large errors.

2.1.2 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 provide 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,

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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 Austin in Texas, USA. It was further developed by the department of energy and building design of the faculty of architecture at Lund's University in Sweden. The program is a dynamic building energy simulation software for the calculation of heating and cooling demands, peak loads, indoor temperature, lighting levels, etc. It comprises very detailed windows and solar radiation models and is therefore very well suited for a country with high solar radiation levels such as Lebanon. The details regarding the actual modelling can be found in Appendix B.

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. Ruble and El Khoury [7] have previously used this approach to determine the daily electricity consumption of a Lebanese household. The list of appliances and their average power and operating hours are presented in Table B.4, Appendix B.

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$$DE_u = 365 \times 3.6 \times P_s \times OT_s \times N_s \tag{2}$$

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 consumption per capita of 50 L. This figure is derived from the 200 L per household per day used by Ruble and El Khoury [7] and the average household size of Lebanon: 4.07 [24]. The average water distribution temperature is assumed at 20ºC (293.13 K) [7]. The annual hot water final energy demand is determined as per Equation 3.

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

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 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, similar to the factor in Germany for the certification of Passive Houses. The primary energy conversion factor for electricity is calculated for Lebanon's unique situation in Appendix A and has a value of 3.2.

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 (assuming that energy use and the energy mix remain the same).

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

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.

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2.1.3 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 [25] and Jonson [26] 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 transport modes used, including direct and indirect requirements, should be multiplied by the average travel distance using 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. 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 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 details is beyond the scope of this paper.

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

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.

2.1.4 Life cycle energy calculations

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

$$LCE_b = LCEE_b + LCEE_{\text{inf}} + LCOPE_b + LCTE_b \tag{6}$$

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.

2.1.5 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 [2]. This often results in an overall 40% uncertainty for hybrid data. The variability level on operational energy is estimated at ±20%, based on Pettersen [27] 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. [28]. 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.

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2.2 **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, 20 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 1860 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 B. Table 1 summarises the building characteristics.

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

Source: Technical Enterprises Co. [29]

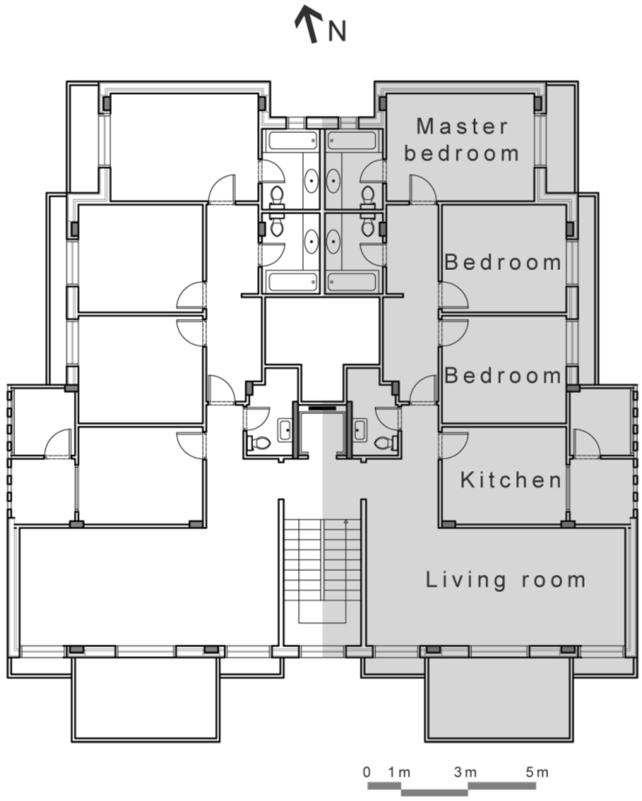

Figure 3: Plan view of a typical floor of the case study apartment building in Sehaileh, Lebanon

Source: Technical Enterprises Co. [29]

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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
Operational energy sources	Gas heating (eff. 95%) and cooking (eff. 90%); Electrical cooling with a heat pump (eff. 250%); Electric domestic hot water system (eff. 100%)
Primary energy conversion factors	Electricity: 3.2 , Gas: 1.1
Average car travel distance per year (km) (no public transportation)	40 000 (two cars and based on interview of inhabitants, see Appendix B)
Average occupancy rate of cars	1.6 (assumed)
Total energy intensity of cars [MJ/pkm]	4.13 (See appendix B)

2.3 Other variations

2.3.1 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 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. 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.

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2.3.2 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 name 50%_EMPTY_X where X is the number of years during which the building is 50% empty.

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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, respectively. 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 and 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 25 143 GJ (28 GJ/m²) and is divided into its initial (16 977 GJ, 67.5%) and recurrent (8 166 GJ, 32.5%) parts. This embodied energy is equivalent to the direct energy required to drive around the equator 163 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 (48%) is lower than in other studies relying on hybrid analysis for the quantification of embodied energy such as Crawford [30] (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 buildings.

Figure 4 shows the life cycle embodied energy requirements over 50 years, by material. The largest single contributing material is concrete (20.4%), followed by steel (15.4%), paint (12.5%), and ceramics (12.1%). The remaining materials, such as glass, aluminium timber, plastics and others represent less than 5% 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 (22.5%) 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 will 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 42.6%. 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 [17, 18, 31-33].

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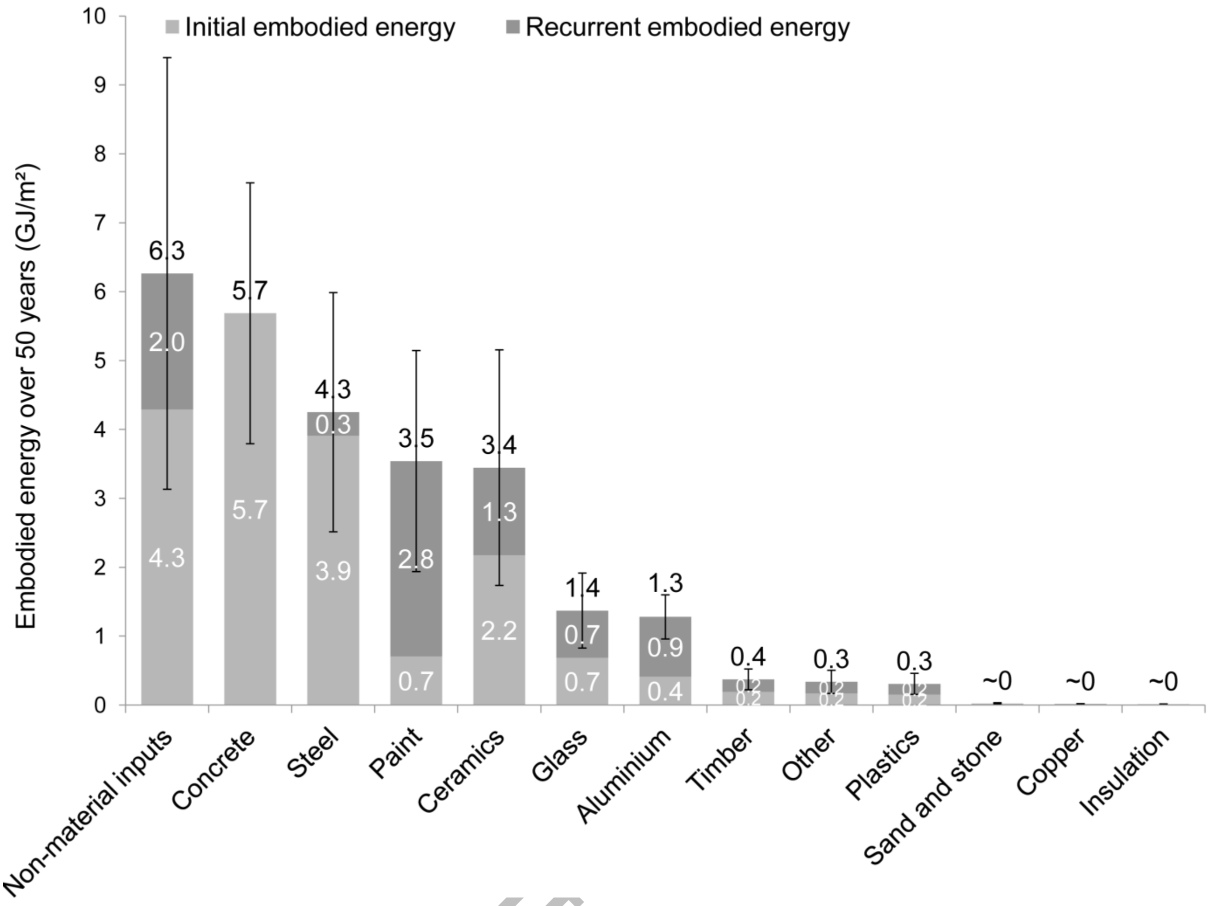

Figure 4: Initial and recurrent embodied energy requirements of the case study apartment building in Sehaileh, Lebanon over 50 years, per square meter of usable floor area, by material. Note: Figures may not sum due to rounding

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 [34-36]. 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 [37], which is considered among the low figures, globally).

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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 B.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 B.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

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The life cycle primary operational energy demand of the assessed case study apartment building is 28 292 GJ (31.3 GJ/m²). As shown in Figure 5 this primary energy demand is dominated by domestic hot water (48.4%) followed by appliances (27.4%), cooling (7.5%), cooking (6.8%), heating (5.7%) and finally lighting (4.3%). However, the breakdown of the delivered energy demand is more even with 39.1%, 22.1%, 6%, 16%, 13.3% and 3.5% 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 and appliances. Relying on electricity for end-uses that can be operated with other energy sources, such as solar or gas, should be encouraged.

Another observation is the low contribution of space heating towards the operational energy demand. 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 very low annual space heating final energy demand (28.8 MJ/m².a or 8 kWh/m².a). This figure is nearly half the requirement for passive houses in Europe, one of the most stringent facultative certifications regarding building energy efficiency. Lebanon’s Mediterranean climate requires very 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 the same performance. The use of less materials for such systems also reduces embodied energy.

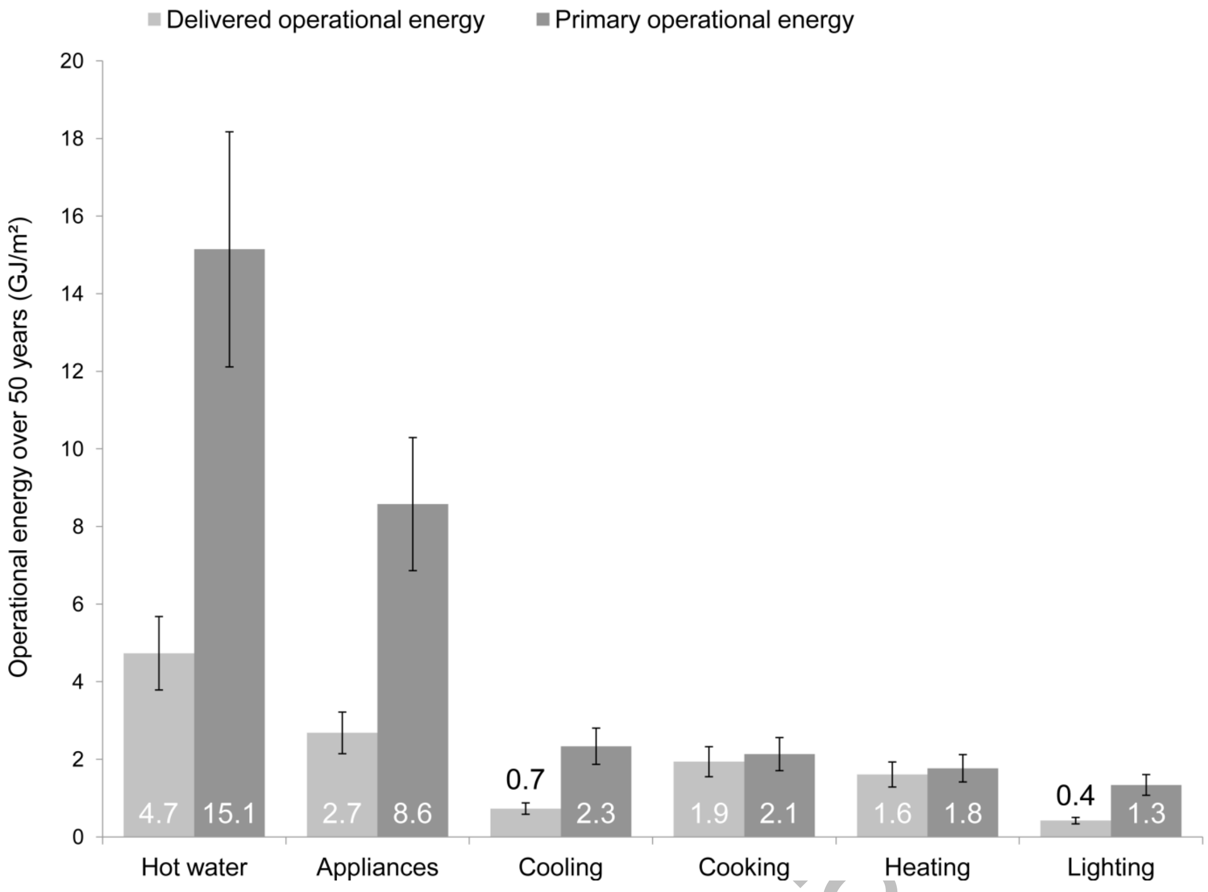

Figure 5 Final and primary life cycle operational energy requirements of the case study apartment building in Sehaileh, Lebanon over 50 years, per square meter of usable floor area, by use. Note: Figures may not sum due to rounding.

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 [7]. 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 energy demand can be reduced by 43.8%. This reduction requires a very small net increase in the embodied energy (20 GJ). This result joins the conclusions of Crawford and Treloar [38] that demonstrated that solar hot water systems have a marginal embodied energy that it 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.

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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 job locations is needed to reduce the transport energy demand and also improve living conditions.

3.4 Life cycle energy requirements

The total life cycle energy requirements of the case study building represents 119 475 GJ (3 734 GJ/capita). This amount of energy is equivalent to the average solar irradiation on the roof of the building over approximately 63 years (based on an annual irradiation of 6 210 MJ/m².a). This life cycle energy demand is divided into its embodied (21%), operational (24%) and transport (55%) 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

47% while operational energy represents 53%. Therefore at the building scale, embodied and operational energy have similar contributions. This distribution is in line with other studies relying on the input-output-based hybrid analysis [2, 39-41].

As depicted in Figure 6, results suffer from a significant level of uncertainty and variability. Indeed, embodied, operational and transport energy requirements fluctuate between 451-1 121 GJ/capita, 707-1 061 GJ/capita and 1 651-2 476 GJ/capita, respectively. The associated contributions towards total energy use fluctuate between 11-32%, 16-34% and 43-68% 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.

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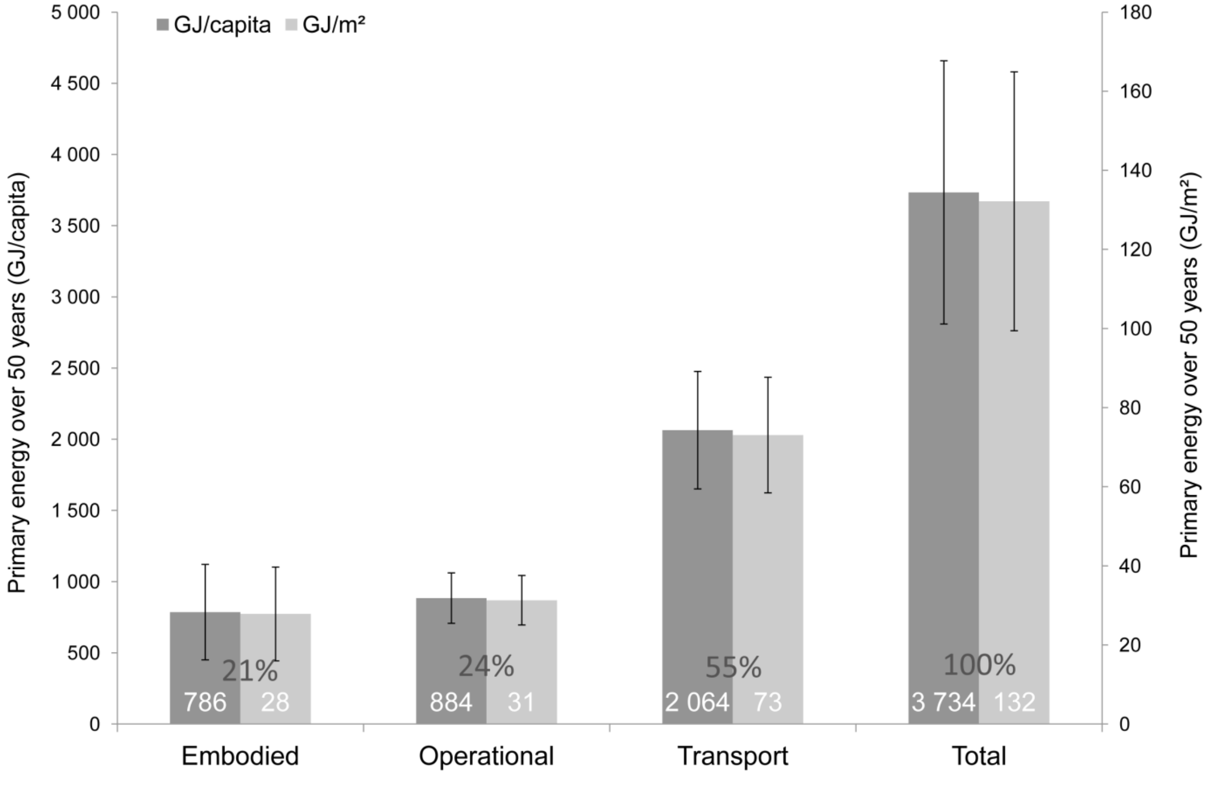

Figure 6: Life cycle energy demand of the case study apartment building in Sehaileh, Lebanon over 50 years, per capita and per square meter of usable floor area, by use.

Figure 7 shows the life cycle energy demand breakdown, by use. Direct and indirect transport energy requirements represent the highest contributions with 29% and 27% respectively. They are followed by domestic hot water (11%), appliances (7%) and then multiple embodied energy categories such as finishings and shared areas (5%), structure (5%), non-material inputs (5%) and envelope (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. [13] 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 sceptic 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 unlikely to occur 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.

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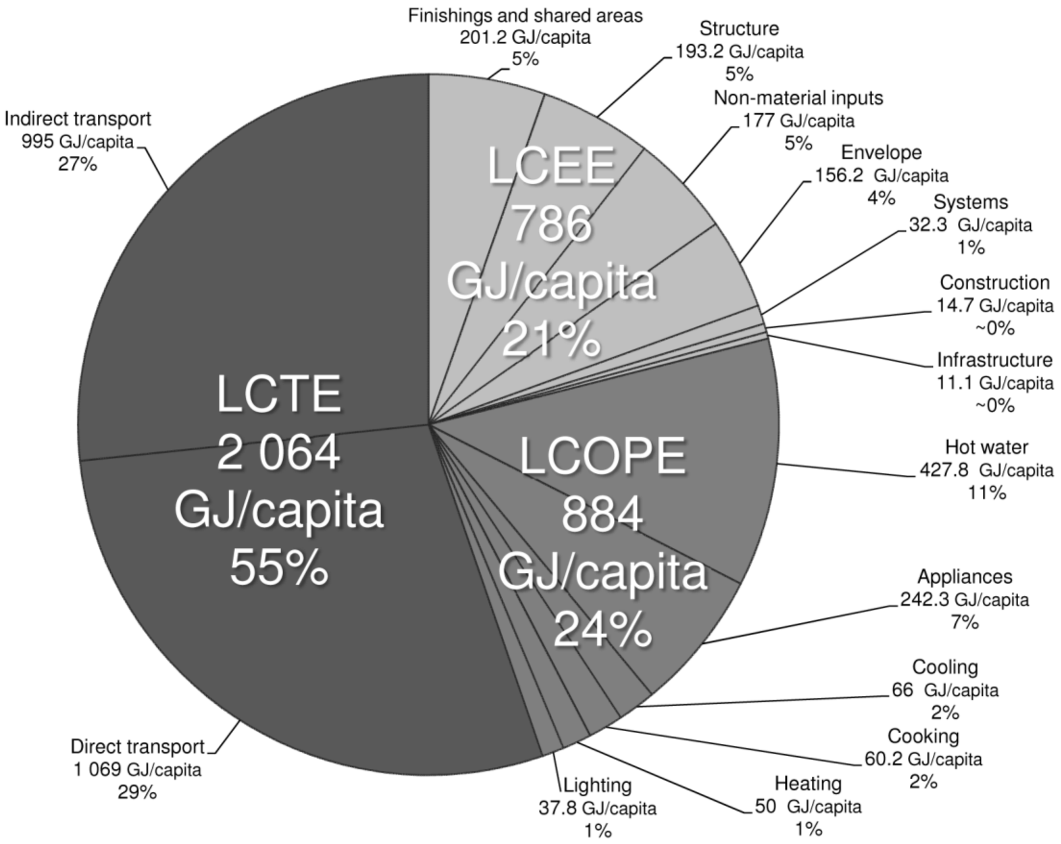

Figure 7: Detailed life cycle energy demand of the case study apartment building in Sehaileh, Lebanon over 50 years, per capita and per square meter of usable floor area, by use. Note: figures may not sum due to rounding; LCEE = Life cycle embodied energy; LCOPE = Life cycle operational energy; LCTE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

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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. 1.6. 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 22% 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 22%

results in a reduction of the total energy demand over 50 years by 5%. This is due to the small relative contribution of operational energy that is run on electricity.

This scenario shows that while it is crucial for Lebanon and EDL 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. [42] 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 job locations.

3.5.2 Empty apartments

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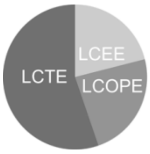
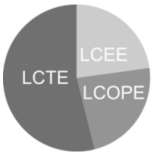
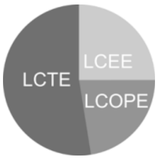
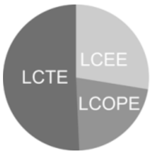
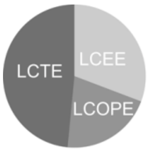
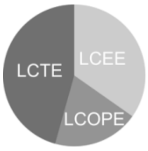
As described in Sections 1 and 2.3.2, a significant number of apartments in recently constructed buildings remain empty since they are bought by Lebanese expatriates and other foreigners who visit only occasionally. This aspect is modelled as five scenarios in which the 50% of the apartments are empty 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 39% 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 job 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	25 143 (21%)	28 292 (24%)	66 040 (55%)	119 475 (100%)	
50%_EMPTY_10	25 143 (23%)	25 643 (23 %)	59 436 (54%)	110 222 (100%)	
50%_EMPTY_20	25 143 (25%)	22 634 (22%)	52 832 (53%)	100 609 (100%)	
50%_EMPTY_30	25 143 (28%)	19 805 (22%)	46 228 (51 %)	91 176 (100%)	
50%_EMPTY_40	25 143 (31%)	16 975 (21%)	39 624 (49%)	81 742 (100%)	
50%_EMPTY_50	25 143 (35%)	14 146 (20%)	33 020 (46%)	72 309 (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

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 (55%), followed by operational 884 GJ/capita (24%) and embodied 786 GJ/capita (21%) requirements. This repartition may be very similar to other Mediterranean regions with a similar urban context of such as parts of Greece, Spain, Morocco, Egypt and Turkey. Yet, this energy breakdown is different from the average of seventy case study variations in Belgium and Australia found by Stephan [12]. 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

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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 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 is dominated by domestic hot water (48.4%) which is operated on electricity. The improved thermal performance of the case study building, coupled with Lebanon’s mild Mediterranean climate result in a very low contribution of heating and cooling energy requirements. The primary energy factor for electricity in Lebanon has been estimated for the first in this paper, allowing the measurement of the total raw energy requirements, unlike in previous studies [6, 7].

Embodied energy is dominated by concrete and steel (31%), the two structural materials. Non-material inputs represent around 16% of the embodied energy. This supports the use of the input-output-based hybrid analysis technique developed by Treloar [16] as it provides more comprehensive embodied energy figures compared to any other method [31].

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 on electricity, especially for domestic hot water, can significantly reduce primary energy use since electricity in Lebanon is generated with a mix of old 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 in the Lebanese energy mix for electricity generation been modelled through a reduction of the primary energy conversion factor for electricity. This evolution resulted in a 22% reduction of the operational energy demand and 5% reduction of the total energy requirements since embodied and transport energy were not affected.

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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 that evident. Indeed, even if accurate figures regarding the use of electricity for embodied and indirect transport requirements were available for Lebanon, most building materials 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 on a particular sector of relying on renewable energy sources.

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 and the operational and transport energy requirements, 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.

However, this study suffers from a number of limitations. The absence of embodied energy databases or input-output tables for Lebanon imposes the use of foreign data such as the Australian data used in this case. This results in a large uncertainty in embodied energy figures as shown in Sections 3.1 and 3.4. Although the use of Australian data could be judged as acceptable for the case of Lebanon (see Section 2.1.1), relying on proper figures will result in much more reliable energy use numbers. Also, since input-output matrices are required to determine indirect transport energy intensities, their absence in the Lebanese context renders the used Australian figures approximate. The case study building is located in a the Mount-Lebanon region which has accommodated most of the recent construction activity. Yet, other studies taken into account the other climatic conditions of Lebanon (e.g. Alpine in the mountains or dry in the North-East) should be performed. 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

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previous studies relying on the same technique [13, 20, 36]. 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 very 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 job location, their age and gender can all significantly affect the energy demand beyond the imposed 20% variability.

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5 Conclusion

This paper has established that most of the energy spent by occupants of recent low-rise apartment buildings in Lebanon is used for mobility, followed by operational and embodied requirements. It has shown a reduction of the total energy requirements is beyond the scope of any one actor of the construction industry and includes planning, regional management, 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 use of solar energy with an auxiliary gas boiler for domestic hot water.
- Favour the use of small cars instead of SUVs.

Long term strategies:

- Develop public transport infrastructures between the capital Beirut and other coastal cities.
- 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.

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 consumption of buildings and assessing other buildings in other locations to verify the results.

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Acknowledgments

This research is funded by the Belgian National Fund for Scientific Research (F.R.S.-FNRS). The authors would also like to thank Dr. Robert Crawford from the University of Melbourne for allowing them to use the embodied energy database and for his contribution at previous stages of this research.

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Appendix A : Primary energy conversion factor for electricity

This appendix explains how the primary energy conversion factor for electricity is derived for Lebanon. It provides a brief explanation of the difference between final, delivered and primary energy figures before providing the details of the calculation.

There are three different classifications for energy consumption: final, delivered and primary energy. Consider a heating system operated by a heat pump. Final energy represents the energy consumption at the end-point, i.e. the heating energy demand. Delivered energy represents the energy consumption at the delivery point to the customer, by taking into account the efficiency of the systems used, e.g. the electricity consumption to operate the heat pump (the final energy divided by the coefficient of performance of the heat pump). The conversion of final to delivered energy therefore depends on the system type and its efficiency. Primary energy represents the total energy consumption at the source of production; that is the delivered energy augmented by the distribution losses and the efficiency of the power plant. The conversion of delivered to primary energy depends on the energy source, e.g. 1.4 for gas in Australia compared to 3.4 for electricity in Victoria, Australia [43].

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 1848 MW of the roughly 2500 MW needed, there is approximately a shortage of 700 MW of capacity [44]. A significant part of this shortage is currently covered by private generators that are installed in neighbourhoods. These generators, as well as most of the large power plants, are operated on oil-based products, such as gas, diesel and residual oil. According to ALMEE [45], 87% of EDL's electricity production is based on oil products with the rest provided by hydraulic power plants. Based on the shortage of supply by EDL's plants, the electricity supply can be estimated at 18h per day from EDL and 6h per day from private generators. Assuming that the average efficiency of Lebanon's aging thermal plants is 35% and considering average losses on the grid of 15% [45], the primary energy conversion factor for EDL's thermal plants is 3.4. The primary energy conversion factor for the remaining 13% of hydraulic plants can be estimated at 1.5 based on figures from Molenbroek *et al.* [46]. The average primary energy conversion factor for EDL electricity in Lebanon can therefore be estimated at 3.15.

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The average neighbourhood generator power ranges between 80 kW and 240 kW. Based on specifications from manufacturers, the average diesel intensity is 210 g per kWh of output electricity. Based on a primary energy density of 46 MJ/kg (12.8 kWh/kg) for diesel, the average efficiency of such generators is 37%. 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%. The overall primary energy conversion factor for generator electricity is therefore 3.4. Based on a 75%/25% ratio of electricity provided by EDL and private generators, the total average primary energy conversion factor for electricity in Lebanon is 3.2. Over the last three years, electricity supply from the state owned EDL has been progressively deteriorating leading to an increase in the share of electricity produced by private generators. However, given the close values obtained for the primary energy conversation factors of EDL and the private generators, a shift in the ratio of electricity supply is unlikely to affect the total average primary energy conversion factor for electricity in Lebanon.

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Appendix B : 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.

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 B.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 B.1.

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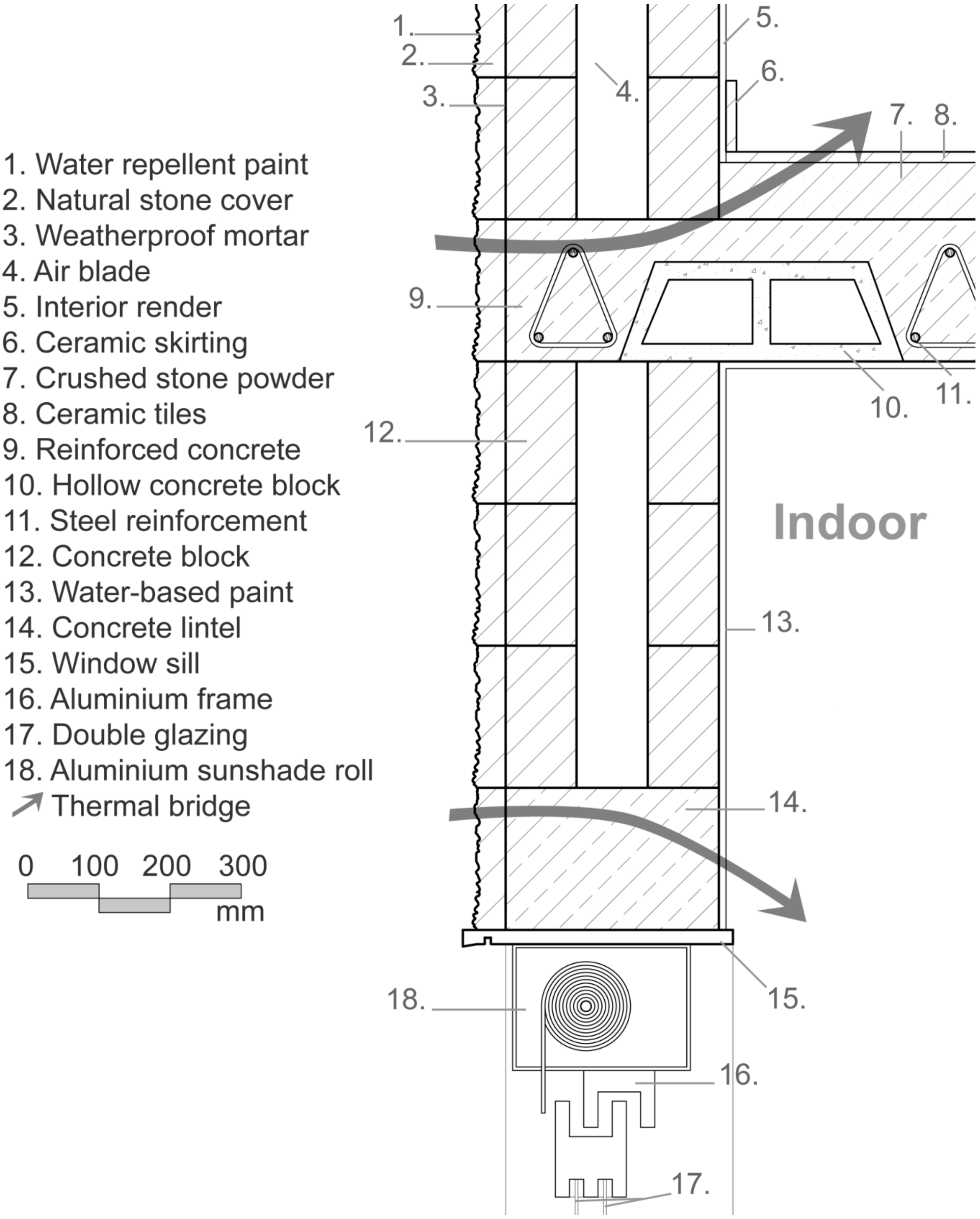

Figure B.1: Wall-slab junction detail of the case study apartment building in Sehaileh, Lebanon

Table B.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 finishing is 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 [12]. The quantities of the main construction materials are given in Table B.2 along with the average useful life of these materials, based on NAHB [47] and Ding [48]. 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 [49], on CSIRO [50] and on Crawford [51].

Table B.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 m³	1.3	110.6 m³	UL_b[a]
Concrete blocks 15 MPa	240.5 m³	1.1	264.6 m³	UL_b
Concrete 25 MPa	510.1 m³	1.1	561.1 m³	UL_b

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Material	Delivered quantity	Wastage coefficient	Total quantity	Average useful life (years)
Steel	38.6 t	1.05	40.4 t	UL_b
Ceramic tiles (10 mm thick)	1 507.2 m²	1.05	1 582.6 m²	UL_b
Roof tiles	327.8 m²	1.1	360.5 m²	UL_b
Natural stone	21.5 m³	1.3	28 m³	UL_b
Aluminium frames	522.2 m	1.05	548.4 m	40
Glass	348.2 m²	1.03	358.6 m²	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

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 B.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 B.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.

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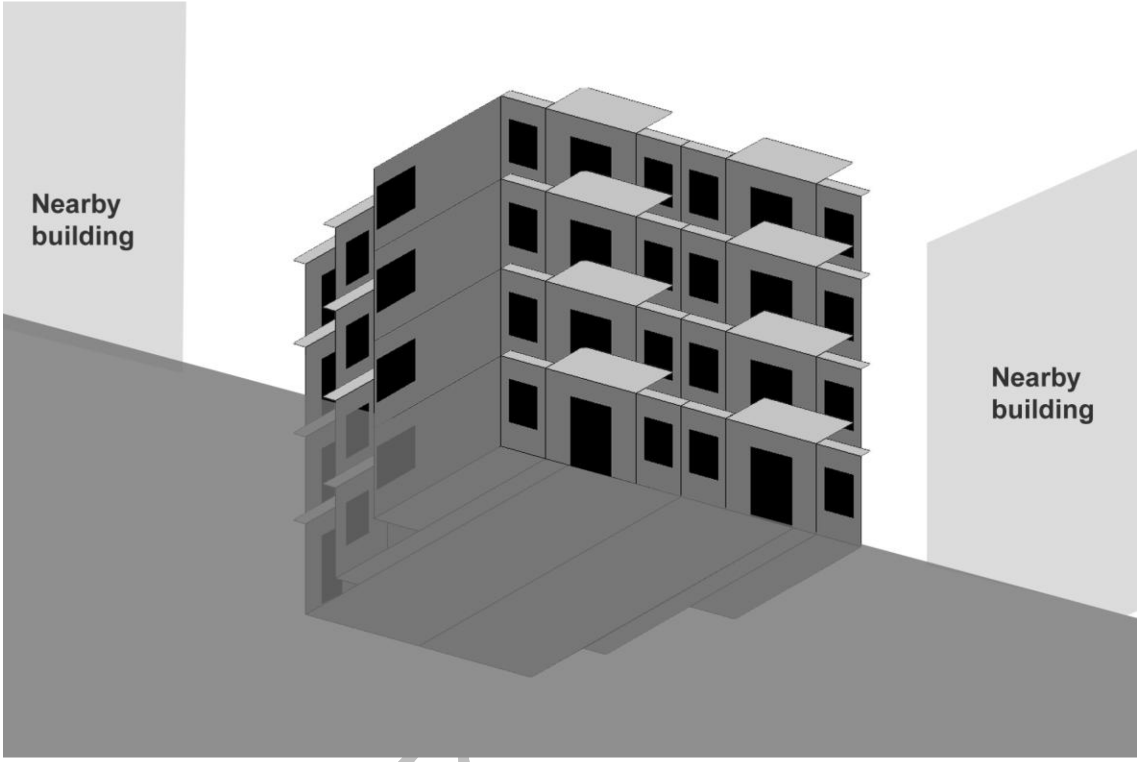

Figure B.2: South façade of the DEROB-LTH model of the case study apartment building in Sehaileh, Lebanon

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The parameters used in this model are given in Table B.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 95% 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 B.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 m^2	Excludes wall thickness, balconies and common areas such as the staircase
Number of occupants	4	

Parameter	Value	Comment
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
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	

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Parameter	Value	Comment
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 operational energy demands are based on figures from Ruble and El Khoury [7] which have been augmented to consider other requirements, such as electronic appliances. The power ratings of the latter are based on Blomsterberg and Avasoo [52]. The number of appliances in the household is based on a survey by Ipsos [53]. The data used for non-thermal operational energy demands is provided in Table B.4.

Table B.4: Estimated annual delivered energy consumption 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 consumption (MJ)
CFL lights	12	6	10	946
Fridge/freezer	300	6	1	2365
Washing machine (7 kg)	1800	0.65	1	1537
LCD television	200	2	2	1051

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Router	5	24	1	158
Laptop	30	2	2	158
Other	100	6	1	788
Gas stove	3000 (based on manufacturer)	1	1	3942

Source: Adapted from Ruble and El Khoury [7], Power ratings based on Blomsterberg and Avasoo [52] unless specified otherwise. Number of appliances adjusted from Ruble and El Khoury [7] based on Ipsos [53].

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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) [54]. 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 [25] 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 [34] 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).