Multi-scale life cycle energy analysis of a low-density suburban neighbourhood in Melbourne, Australia.

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Abstract

There is an increasing pressure on cities worldwide to accommodate the increasing population. Most cities are likely to expand in the coming decades and this expansion will probably take place as low-density neighbourhoods. It is therefore crucial to assess the energy demand and related greenhouse gas emissions of such development from a comprehensive perspective.

This paper uses a representative low density case study neighbourhood near Melbourne, Australia, to assess its energy consumption and greenhouse gas emissions over 100 years. Different housing typologies, such as row houses and low-rise apartment buildings, are tested. Results show that the energy required to produce and replace building materials and infrastructures constitutes nearly 26.9% of the total energy consumption while operational and transport requirements represented 39.4% and 33.7% respectively. Variations to the housing types reveal that apartment buildings reduce the energy consumption per capita by 19.6% compared to the one-storey single family detached house typical pattern. Regardless of the uncertainty in the data, the main conclusion is that each of the embodied, operational and transport energy demand and associated greenhouse gas emissions should be lowered in order effectively reduce the environmental impacts of new urban neighbourhoods.

Keywords: Urban form – Energy consumption – Life cycle energy analysis – Greenhouse gas emissions- Urban sprawl – Suburban neighbourhood – Embodied energy – Operational energy – Transport energy

1 Introduction

The world population is expected to increase to 9.3 billion people by 2050 (from the current 7 billion) with all the increase expected to be absorbed by urban areas [1]. This, in addition to the fact that cities accommodate more than 50% of the world's population since 2009 [2], puts an increasing pressure on urban centres. In order to accommodate the increasing population in cities, notably in Asia, new housing units have to be built. Many studies (e.g. [3]) have shown that most cities are likely to expand. This expansion is generally characterised by low-density urban sprawl in major urbanising centres such as China [4, 5]. This outward expansion of cities is typically copied on American or Australian cities.

A significant body of literature treats of the energy intensity of low-density suburban neighbourhoods. While most studies deal with transport energy requirements, e.g. [6-8], other works such as Halleux [9], highlight higher space and infrastructure requirements compared to denser alternatives. However, very few studies assess the total energy demand and associated greenhouse gas emissions related to a whole neighbourhood. In his review of studies assessing urban forms and energy, Rickwood [10] underlines the lack of comprehensive energy assessment of different urban forms (notably suburban) which take into account embodied, operational and transport energy and greenhouse gas emissions.

The aim of this paper is to undertake a complete life cycle energy assessment of a new suburban neighbourhood and to analyse variations pertaining to house size, car technology and housing type. This comprehensive assessment will provide an insight into the energy demand breakdown and the greenhouse gas emissions intensity of suburban neighbourhoods and the associated urban form. In this regard, a case study neighbourhood near Melbourne, Australia, typical of low density urban sprawl layouts, is used.

2 Analysing the total energy consumption and greenhouse gas emissions of a suburban neighbourhood

2.1 A multi-scale life cycle energy analysis

A comprehensive life cycle energy and greenhouse gas emissions assessment requires that the neighbourhood be evaluated regarding its embodied, operational and transport requirements. In this work, the neighbourhood is modelled as the sum of various buildings. The total energy demand of the neighbourhood is therefore the sum of the energy demand of its constituting buildings and households. The details of the calculation method used for each building is given in Stephan *et al.* [11]. A summary of the approach is given below.

Embodied energy represents the total energy associated with the production and construction of the buildings and the infrastructure, across the supply chain. Recurrent embodied energy accounts for the replacement of building materials or infrastructures across the useful life of buildings. The embodied energy assessment relies on the input-output-based hybrid analysis technique developed by Treloar [12]. The related database of embodied energy coefficients for Australia [13] is used in this paper. The infrastructures taken into account are: roads, power lines, water and distribution systems and sewage.

Operational requirements comprise the energy and greenhouse gas emissions associated with the operation of buildings. This includes the space heating and cooling demand, ventilation, domestic hot water, lighting, cooking and appliances. Thermal energy requirements are based on static heat transfer equations while non-thermal requirements (e.g. appliances, cooking, etc.) are sourced from average regional data.

Transport energy accounts for all the energy consumption associated with the mobility of the population. The yearly travel distances are sourced from regional averages while the energy intensity of the transport modes is based on input-output analysis data from Lenzen [14].

Uncertainty and variability in the data are taken into consideration though interval analysis. This technique provides a certain range around the nominal value in which the actual figure may lie [15]. The uncertainty on the embodied energy data is set to ±20% for process analysis data and ±50% for the input-output analysis data based on Crawford [16]. The variability in operational energy figures is set to ±20% based on Pettersen [17] and assumed to be the same for transport energy.

2.2 Converting energy demand to greenhouse gas emissions

Greenhouse gas emissions are directly derived from the primary energy consumption, based on the fuel source used for operational and transport requirements and on an fixed average figure for embodied energy. The conversion of primary energy to greenhouse gas emissions is performed as per Eq. 1.

$$LCGHG_u = LCPE_u \times EF\ \ S_u \tag{1}$$

Where: $LCGHG_u$ = Life cycle greenhouse gas emissions of the use u, in kg of CO_2-e; $LCPE_u$ = Life cycle primary energy consumption associated with the use u, in GJ; EF = Emissions factor, in kg of CO_2-e/GJ; and S_u = energy source of the use u.

The emissions factors for the different energy demands and associated energy sources are provided in Table 1.

Table 1: Emissions factors for the different energy demands and associated energy sources

Energy use	Energy source	Emissions factor(kg of CO_2-e/GJ)	Based on
Embodied energy	Various	60.00	Treloar [18]
Operational energy	Electricity (Brown coal in Victoria, Australia)	93.11	DCCEE [19]
Operational energy	Liquefied Petroleum Gas	51.33	DCCEE [19]
Transport energy	Gasoline	67.10	DCCEE [19]

2.3 Case study neighbourhood

A typical residential suburban neighbourhood, comprising single family detached houses in a low density setup, is used to evaluate the total life cycle energy demand and associated greenhouse gas emissions of such developments. The assessed suburb is a representation of most suburban districts around Melbourne, Australia. In order to obtain a realistic configuration, the area of Wyndham (Latitude 37.89°S, Longitude 144.66°E), 28 km west of Melbourne central business district (located in the outer sector), is used as a basis.

Wyndham, like many other suburbs, has witnessed a dramatic increase in population in the last years. On average, suburbs in the so-called outer-sector (area around the city) accommodated 58% of the population growth of Melbourne with between 2001 and 2010 [20]. Most of the new developments were single family detached houses. This increase in the outer-sector population is small scale representation of what is likely to happen in cities around the world in order to accommodate the increasing population [1].

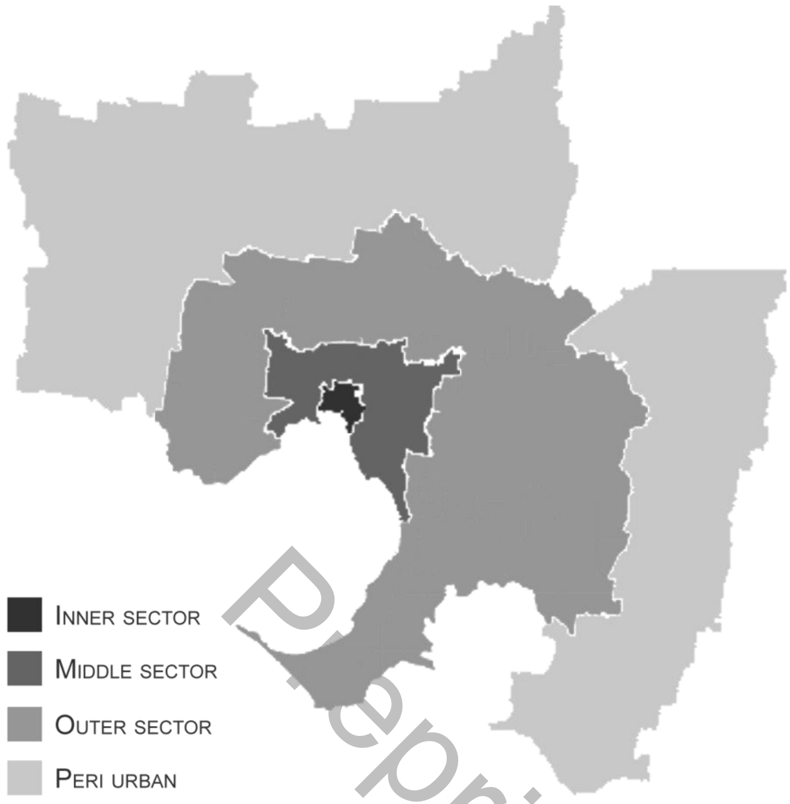

Figure 1: Urban sector classification of Melbourne, Australia

Source: Adapted from BITRE [20]

A population density of 500 inhabitants/km² is chosen for the assessed area. The Bureau of infrastructure, transport and regional economics [20] has shown that the average population density of the suburban areas of Melbourne (middle, outer and peri urban, see Figure 1), is 230 inhabitant/km². According to the same source, the average population density of Wyndham ranges between 500 and 1 500 inhabitants/km². The lower boundary of Wyndham's population density is chosen to reflect the average density of the outer sector.

The base case neighbourhood (BC) is assessed over 100 years, and is modelled with a surface area of 1.5 km² of which 44 000 m² are attributed to the residential buildings. The infrastructures land coverage are not included this built area. Two houses with different sizes, each representing 50% of the built stock, are used to model the neighbourhood. The first house (BC4) is 230 m² in area and is assumed to host 4 users. The second house (BC3) is 180 m² and accommodates 3 users. With 107 buildings of each type, the obtained density for the district is 499 inhabitants/km².The number of people per household is based on the number of bedrooms in each house. The floor area of the houses is determined according to the current market trend. The main characteristics of the houses are provided in Table 2.

Both houses have individual reinforced concrete (RC) footings on which an RC concrete slab is cast. Timber framing constitutes the structural skeleton of the buildings. Timber trusses support the concrete tiled tilted roof which comprises 160 mm of fibreglass insulation.

Brick veneer walls are used for the houses façades. The outer walls comprise 80 mm of fibreglass insulation. Painted plasterboards are used on the inner faces of the outer walls and for the internal walls of the houses. Double glazed aluminium windows, with a *U*-value of 2.8 W/(m²K) are installed.

A ducted, gas fired, heating system, with a 70% efficiency, is installed in the buildings. The same system is used to cool the houses. Cooling is operated by an electrical heat pump with a coefficient of performance (COP) of 2.5. Solar panels for hot water are installed on all buildings and provide 75% of the domestic hot water demand.

The infrastructure for both houses is assumed to be built at the same time as part of a new residential area, typical of urban sprawl expansion. The initial embodied energy of infrastructures is hence accounted for in the life cycle energy demand.

Both houses are assumed to own two gasoline cars which are driven in total 28 000 km and 24 000 km per year, for BC4 and BC3 respectively, based on averaged figures from Department of Transport [21]. While a train connection is available in Wyndham, only private cars are generally available in such suburbs. Indeed, 84.2% of trips are made by car and only 4% by public transport while walking and biking represent the remaining shares [21].

Table 2: Main characteristics of the studied passive house

Characteristics	BC4	BC3
Period of analysis (years)	100 years	
Building useful life (years)	100 years	
Number of houses in the district	107	107
Gross floor area (m²)	230	180
Number of occupants	4	3
Structure	Timber-framed	
Façade	Brick veneer wall – 80 mm of fiberglass insulation - Double glazed aluminum framed windows	
Roof	Concrete tiles – 160 mm of fiberglass insulation	
Finishings	Medium finishing standing	
Average *U*-value (W/m²K)	0.60	
Operational energy sources	Gas heating (eff. 0.7) and cooking (eff. 0.9); Electrical cooling (eff. 2.5); Solar domestic hot water (solar fraction 0.75) with gas	

	auxiliary system (eff. 0.9).	
Primary energy conversion factors	Electricity: 3.4[a] Gas: 1.4[a]	
Cars	2 gasoline	
Average car travel distance per year (km)	28 000[b]	24 000[b]
Average occupancy rate of cars	1.6[c]	
Total energy intensity of gasoline cars (MJ/pkm)	4.41[d]	

Note: eff. represents the efficiency of the end-use system. The solar fraction represents the fraction of hot water energy demand supplied by the solar system. Delivered energy figures are used for lighting and appliances because no information is available about the efficiency of the devices used. All average figures for operational energy consumption are derived from [22]. Sources: [a] from [23], [b] based on [21], [c] from [24] and [d] based on [14]

2.4 Size and transport variations

Since Australian dwellings dramatically increased in size in the last decades [25], it is important to evaluate the impact of reducing the dwelling size on the life cycle energy demand and each of the embodied and operational requirements. While Fuller and Crawford [26] advocate the importance of reducing dwelling size in regard to embodied energy, no study has yet investigated the effect of house size on the energy consumption of a whole district.

Two scenarios, involving reducing the base case house floor areas by 10% (SK10) and 20% (SK20) are tested. The height between floors and the number of units built on the plot are kept constant for the sake of comparison.

A switch to 100% electric cars is tested on the base case to investigate its effect on the life cycle energy demand. Electric cars are being marketed as a so-called “green” alternative to traditional combustion engine vehicles and have a much lower direct energy demand compared to standard vehicles [27]. However, the high primary energy conversion factor for electricity in Victoria, Australia (3.4), the indirect requirements of electric cars and the high emissions factor for electricity in Victoria, are expected to lessen their advantage over combustion engines. A variation, testing the effect of using of electric cars on the life cycle energy requirements is modelled. The total energy intensity of electric vehicles used in this paper is 2.63 MJ/pkm.

2.5 Alternative housing typologies

Urban form has been identified as an important factor to achieve a more environmentally friendly built environment [28]. However, a universal sustainable urban model does not exist [29]. The complexity of each case should be included and local measures undertaken to lower the environmental impact. Yet, dense and compact cities have often been associated with a reduced environmental impact, although planners often have too high expectations on the car use reduction aspect [30]. Also, from a life cycle energy consumption perspective, developing denser districts will save significant amounts of materials per capita and allow the implementation of more efficient systems such as district heating/cooling. Moreover, if densification entails intensification and improved accessibility, the average travel distances are likely to drop. This will decrease the transport energy requirements. For all of the above reasons, denser configurations of the assessed suburb are assessed through variations of the dwelling typology.

The constituting bricks of any urban structure are its buildings and infrastructure. Hence, higher density urban structures have to rely on specific building typologies which accommodate more people per square meter. When it comes to residential buildings, row houses and apartment buildings can provide higher density districts compared to detached houses. The introduction of these two housing typologies, and its repercussion on the life cycle energy demand, is investigated in this case study. Half of the built area of the base case (BC), i.e. 22 000 m^2, is attributed, in turn, to these two types of construction.

Row houses share a party wall on each side and have two façades, except for the houses at the edges, which have three. These houses are expected to save embodied energy compared to normal houses with the same area. Indeed, the shared party wall is typically less energy intensive than an outer wall comprising insulation, glazing and weatherproof materials. Moreover, the space heating energy demand of row houses is also lower because of their lower heat transfer area: the party walls are in contact with a heated space.

In this paper, two types of row houses are introduced: single and double storey houses. The latter are modelled to test the influence of increasing the density, through an additional floor, on the life cycle energy consumption. Row houses are grouped in blocks of four houses with smaller houses in the middle and larger edge houses with three façades, called semi-detached houses (see Figure 2). A depth of 12 m is chosen for all houses with less than four façades to allow natural daylight inside the house. This figure is based on the passive zone concept used by Ratti *et al.* [31].

The 168 m² row houses (RH3) and the 216 m² semi-detached houses (SDH4) respectively accomodate 3 and 4 users. The one-storey scenario lodges 57 houses of each type (RH3 and SDH4) with double the number (114) in the two-storeys scenario. In the latter case, the population density rises from 500 to 785 inhabitant/km². The row houses use the same assemblies as the base case houses except in the two-storeys scenario where the additional upper floor is timber framed. Otherwise, only the geometry is modified. The travel distances per household are the same as in the BC.

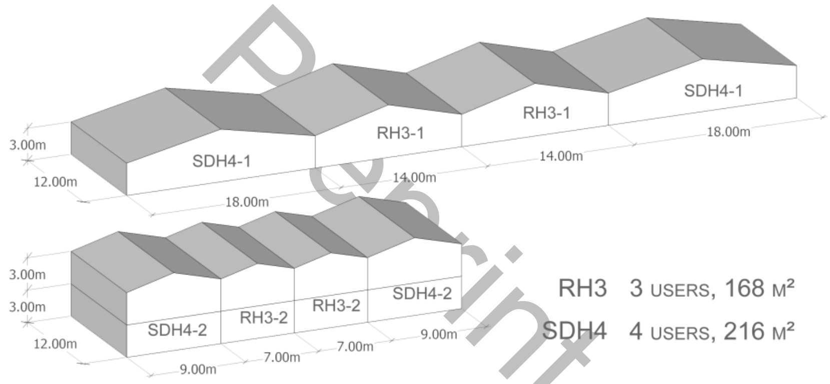

Figure 2: Basic geometric and volumetric layout of modelled row and semi-detached houses

Besides row houses, low-rise apartment buildings are used to test the effect of changing the housing type on the life cycle energy demand of the assessed neighbourhood. It is assumed that a radical change of housing type, such as medium rise apartment buildings with 10 stories, will not be accepted in traditionally low-density areas.

The low-rise buildings are modelled with four-storeys in this work. Continuous footing reinforced concrete (RC) foundations support the ground floor slab. Precast RC bearing walls are used to support the upper storeys and constitute the external walls and part of the internal partition of the building.

A steel frame, lodging 80 mm of fibreglass insulation bats, is attached to the interior face of the external walls. Painted plasterboards are fixed to the steel frame on external walls, and to steel joists on internal walls. Double glazed windows with aluminium frames cover 70% of the external walls area. The roof comprises 160 mm of fibre glass insulation. The *U*-values of envelope elements are the same as those used in the base case houses and the row houses variation.

Ceramic tiles are installed in the living rooms, the kitchen and the toilets while nylon carpets constitute the flooring of the bedrooms. Other finishings are considered with a medium standing.

As depicted in Figure 3, each modelled building comprises 12 two-façades flats of 120 m² each and 8 three-façades flats of 168 m². Three and four users live respectively in each of the small (AP3) and large apartments (AP4). The depth of 12 m is based on the passive zone concept [31] as in the row houses variation. The height between floors is lowered to 2.8 m in this case. In total, 31 apartment buildings are constructed leading to an average neighbourhood density of 1680 inhabitant/km².

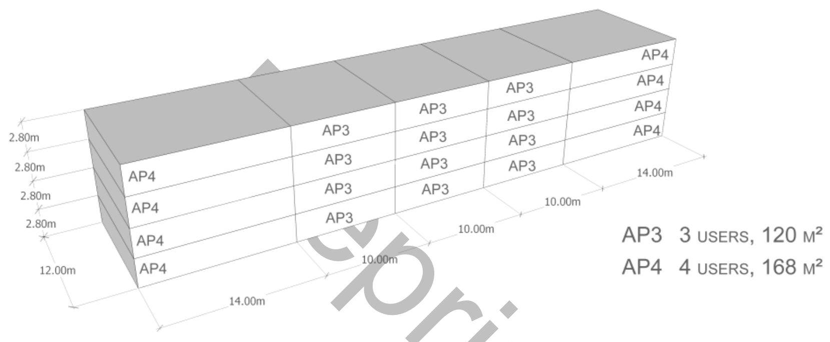

Figure 3: Basic geometric and volumetric layout of modelled low rise apartment buildings

While, no changes are made regarding the travel distances of the households compared to the base case, the modal split is modelled as evolving in time. Indeed, the construction of the low rise apartment buildings will greatly increase the density of the district. It is hence assumed that in time, the population density is enough to support the development of a reliable train connection to the city. The modal split is hence modified through time. Table 3 shows the assumed modal split evolution for car and train transport, for the low rise apartment building case. The yearly values are interpolated using a cubic function.

Table 3: Modal split evolution for the low rise apartment building variation

Year	Gasoline car share	Train travel share
0	100%	0%
33	75%	25%
66	50%	50%
99	25%	75%

3 Results

3.1 Life cycle energy demand and greenhouse gas emissions

The life cycle requirements of the assessed suburban neighbourhood are presented in this section. The breakdown of the energy demands and associated greenhouse gas emissions is first given before analysing each of the embodied, operational and transport requirements in more detail.

Figure 4 shows the life cycle energy demand (LCE) and greenhouse gas emissions (LCGHG) breakdown of the base case neighbourhood (BC). The LCE and LCGHG of the whole neighbourhood respectively represent 7 300 TJ and 543 kt of CO_2-e. This energy consumption is equivalent to the amount of solar energy hitting 75% of the ground surface of the district during one year and the greenhouse gas emissions represents 64% of the annual transport emissions of Iceland [32]. The operational energy represents the largest share of the LCE (with 39.4% of the total) as well as the largest contribution to the LCGHG with 42.4%. The transport requirements rank second with respectively 33.6% and 36.0% of the LCE and LCGHG. Embodied energy and related emissions represent 26.9% and 21.6% of the respective totals. Embodied and transport energy and emissions requirements, which are often overlooked, represent more than half of the LCE and LCGHG over 100 years.

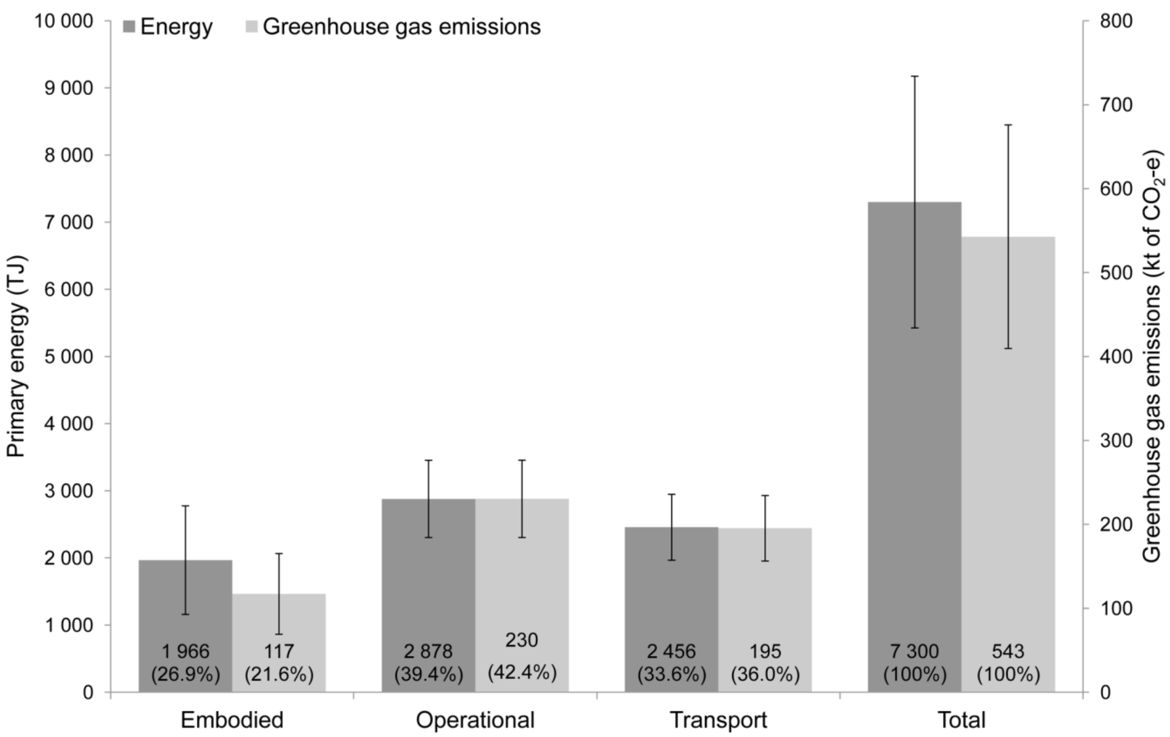

Figure 4: Life cycle energy and greenhouse gas emissions of the suburban neighborhood base case, by use. Note: Figures may not add up due to rounding.

Operational energy is the most emitting of all flows with 80.4 kg of CO_2-e/GJ followed closely by transport with 79.5 kg of CO_2-e/GJ. Embodied energy has an average emissions factor of 60.0 kg of CO_2-e/GJ which explains its lower contribution to LCGHG compared to LCE. It is hence important to lower greenhouse gas emissions from transport, electricity generation and other operational energy fuels such as gas.

If only the operational and embodied energy demands are considered, embodied energy represents 40.6% of the consumption. If the district is assessed over 50 years (period of analysis), this figure rises to 46.0%. The share of embodied energy is hence decreasing in time. Indeed, on average, embodied energy increases by 11 462 GJ/year while operational energy increases by 28 270 GJ/year over 100 years. However, if the buildings' design life is shortened to 50 years (resulting in the replacement of all buildings at year 50), the embodied energy demand increases to 2 455 TJ, representing 31.5% of the total LCE over 100 years, or 46.0% if only operational and embodied requirements are considered. Embodied energy and related greenhouse gas emissions are hence significant in all cases.

The embodied energy demand of the district is presented, by category including the total for all houses, in Figure 5. The categories include: envelope (building shells), finishings, infrastructure, remainder, structure, systems and the direct energy required for construction. The maximum contribution from a single category is 26.2% (envelope). Thus, the embodied energy demand cannot be significantly lowered if the requirements of only one category of assemblies are reduced. All categories should be tackled together, through the reduction of house sizes for example.

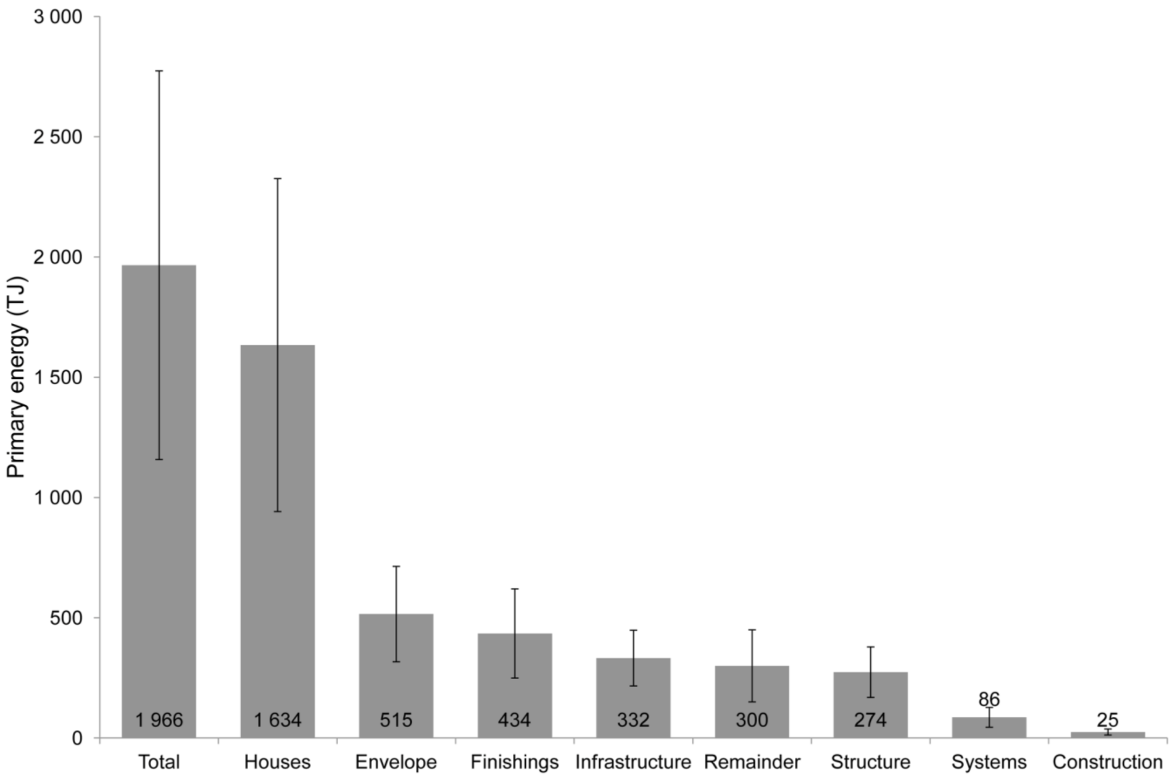

Figure 5: Life cycle embodied energy demand breakdown of the suburban neighborhood base case, by category.

An important result to underline is the important contribution of infrastructures (16.9%, 3rd rank). Roads are critical contributors since they are the second most energy intensive assembly, after roofs, over 100 years. Power lines, supported by timber poles every 20 m are more energy intensive over 100 years than the combined concrete and steel in all foundations of the buildings. Hence, energy requirements for infrastructures should be taken into account.

The remainder category represents the energy requirements, across the supply chains of used construction materials, which are associated with non-material services such as insurance and advertising. The remainder's energy demand which is omitted in other embodied energy assessment techniques represents an important share of the total (15.3%, 4th rank).

The greenhouse gas emissions associated with embodied energy are calculated by multiplying the former by a scalar coefficient of 60.0 kg of CO_2-eq/GJ as explained in Section 2.2. Therefore the same rankings and contributions are obtained for embodied emissions.

The life cycle operational energy demand (LCOPE) and greenhouse gas emissions (LCOPGHG) are dominated by appliances. As can be seen in Figure 6, appliances represent 47.7% of the LCOPE and 55.5% of the LCOPGHG. Since the thermal performance of the envelope follows new regulations, the heating demand is lower than the average building stock. The systematic installation of solar panels, providing 75% of the domestic hot water demand, dramatically reduces the primary energy consumption of the latter and the related greenhouse gas emissions.

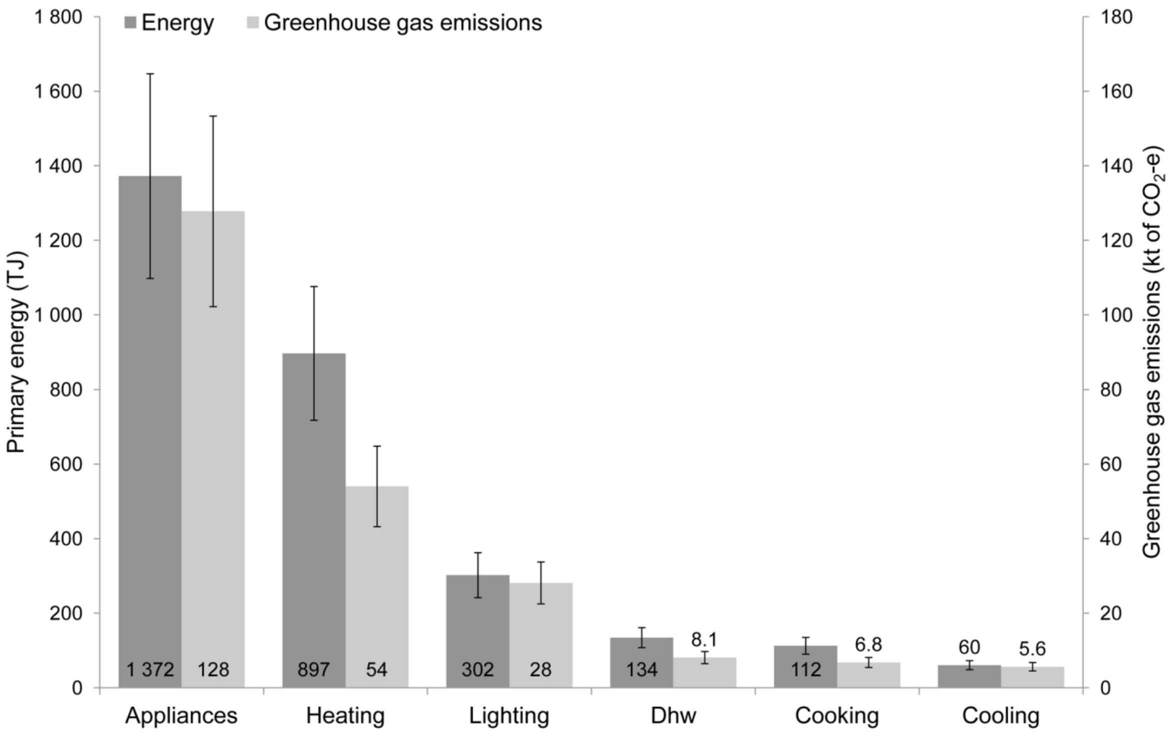

Figure 6: Life cycle operational energy demand and greenhouse gas emissions breakdown of the suburban neighborhood base case, by use.

A clear trend is visible regarding the energy source and the associated greenhouse gas emissions: end-uses running on electricity (appliances, lighting and cooling) have a higher contribution to the LCOPGHG than those operating on gas (heating, auxiliary domestic hot water and cooking). The higher emissions factor for electricity in Victoria, Australia is responsible for this shift (see Table 1). The overall contribution of the cooling demand to the LCOPE and LCGHG is insignificant.

The life cycle transport energy consumption (LCTE) of the district is 2 456 TJ over 100 years and is associated with the emission of 195 kt of CO_2-e (LCTGHG). The totality of the transport requirements are associated with private car use since it is the sole transport mode utilised.

Direct energy consumption represents 54.8% and 48.0% of the LCTE and LCTGHG respectively. Indirect energy requirements and emissions represent 1 109 TJ (45.2%) and 102 kt of CO_2-e (52.0%) respectively. In this case, the indirect transport energy represents 123.7% of the heating primary energy demand. These ratios underscore the importance of integrating indirect transport requirements in a more comprehensive assessment.

3.2 Size and transport variations

The reduction of the house size by 10% (SH10) and 20% (SH20) reduces the life cycle energy demand (LCE) by 3.1% and 6.2% and the life cycle emissions (LCGHG) by 2.7% and 5.4% respectively (see Table 4). The greater reduction of the energy demand compared to emissions is due to the fact that transport energy, which is more emitting than embodied energy, is not affected.

Table 4: Effect of house size and transport variations on the life cycle energy and emissions breakdown of the suburban neighborhood base case

Use	SH10		SH20		ELEC CAR	
	Value	Relative difference with BC	Value	Relative difference with BC	Value	Relative difference with BC
LCEE	1 832 TJ	-6.8%	1 699 TJ	-13.6%	1 966 TJ	0.0%
LCOPE	2 784 TJ	-3.3%	2 691 TJ	-6.5%	2 878 TJ	0.0%
LCTE	2 456 TJ	0.0%	2 456 TJ	0.0%	1 466 TJ	-40.3%
LCE	**7 072 TJ**	**-3.1%**	**6 845 TJ**	**-6.2%**	**6 310 TJ**	**-13.6%**
LCEGHG	109 kt of CO_2-e	-6.8%	101 kt of CO_2-e	-13.5%	117 kt of CO_2-e	0.0%
LCOPGHG	224 kt of CO_2-e	-3.0%	217 kt of CO_2-e	-5.9%	230 kt of CO_2-e	0.0%
LCTGHG	195 kt of CO_2-e	0.0%	195 kt of CO_2-e	0.0%	140 kt of CO_2-e	-28.4%
LCGHG	**528 kt of CO_2-e**	**-2.7%**	**513 kt of CO_2-e**	**-5.4%**	**487 kt of CO_2-e**	**-10.2%**

Note: Figures may not add up due to rounding. SH10:10% house size reduction, SH20: 20% house size reduction, ELEC CAR: replace all gasoline cars by electric cars, BC: Base case, LC: Life cycle, EE: embodied energy demand, OPE: operational energy demand, TE: transport energy demand, LCE: life cycle energy demand, EGHG: embodied greenhouse gas emissions, OPGHG: operational greenhouse gas emissions, TGHG: transport greenhouse gas emissions, LCGHG: life cycle greenhouse gas emissions.

The highest reduction occurs for the embodied requirements (-6.8% for SH10 and -13.6% for SH20). It is logical that a reduced house size will imply less material usage and hence a lower embodied energy and associated emissions. However, the different categories within embodied energy and emissions are not affected in a similar way by the floor area reduction. For instance, in the SH20 case, structural requirements (foundations and slab) are reduced by 16.8%, finishings requirements are reduced by 15.9%, envelope by 15.0% and systems by 12.5%. In all cases, a notable decrease is observed.

Operational requirements are also reduced but to a lesser extent. Indeed, the affected operational energy demands are heating, cooling and lighting while cooking and appliances depend only on the number of users. For example, the heating demand of SH20 is reduced by 13.3% because of the lower heat loss area and heated volume while the appliances demand (which is the most energy-intensive) remains constant. The operational end-uses which depend solely on the number of users in the calculations tend to flatten the impact of a reduced house size.

The reduction of the house sizes should not realistically affect the travel patterns of the inhabitants, especially since the overall density of the district is kept constant. Hence, transport requirements tend to even up the results. This implies that only reducing the house size will have a limited overall impact since transportation is not affected.

Relying on purely electric cars instead of gasoline results in significant reductions in the life cycle transport and total requirements. The life cycle transport energy (LCTE) is reduced by 40.3% compared to the base case and the resulting emissions by 28.4%. The difference between energy and emissions is due to the very high greenhouse gas emissions from electricity generation in Victoria, Australia (93.11 kg of CO_2-eq/GJ). The life cycle energy demand is reduced by 13.6% and the associated emissions by 10.2%. The use of electric cars has a notable impact on the life cycle requirements.

The high primary energy conversion factor for electricity and the high emissions factor for electricity generation intuitively suggest that electric cars might not be an interesting alternative to combustion engine vehicles. However, using electric cars imply a significant reduction of energy and emissions requirement. This is due to the much higher efficiency of the electric motor. Indeed, the so-called “tank-to-wheel” efficiency (engine/motor efficiency) of electric vehicles is much higher than for combustion engines [27, 33].

Using, electric cars can therefore lower the total energy expenditures and, to a lesser extent, the resulting greenhouse gas emissions, according to the current energy mix in Victoria, Australia.

However, even if electric cars are more efficient, they support low-density urban sprawl and hence indirectly affect the embodied and operational energy demands

3.3 Alternative housing typologies

The variations in housing typology, as described in Section 2.5, are grouped for the presentation of the results. The scenario including row houses and single detached houses with one and two-storeys are referred to as RH_SDH_1 and RH_SDH_2 respectively. The variation including low-rise apartment buildings is denominated AP. The base case scenario is referred to as BC, as above.

Figures 7 and 8 show a clear trend with correlates lower energy consumption and greenhouse gas emissions with higher density housing and more compact buildings. The AP scenario has the lowest life cycle energy demand per capita, i.e. 7 886 GJ, representing a 19.6% decrease compared to the BC. In parallel, its total emissions are 14.7% lower. RH_SDH_1 and 2 present lower reductions in energy requirements (-3.8% and -7.3% respectively) and greenhouse gas emissions (-3.2% and -6.0% respectively). Various aspects pertaining to embodied, operational and transport requirements are behind the observed difference in total requirements.

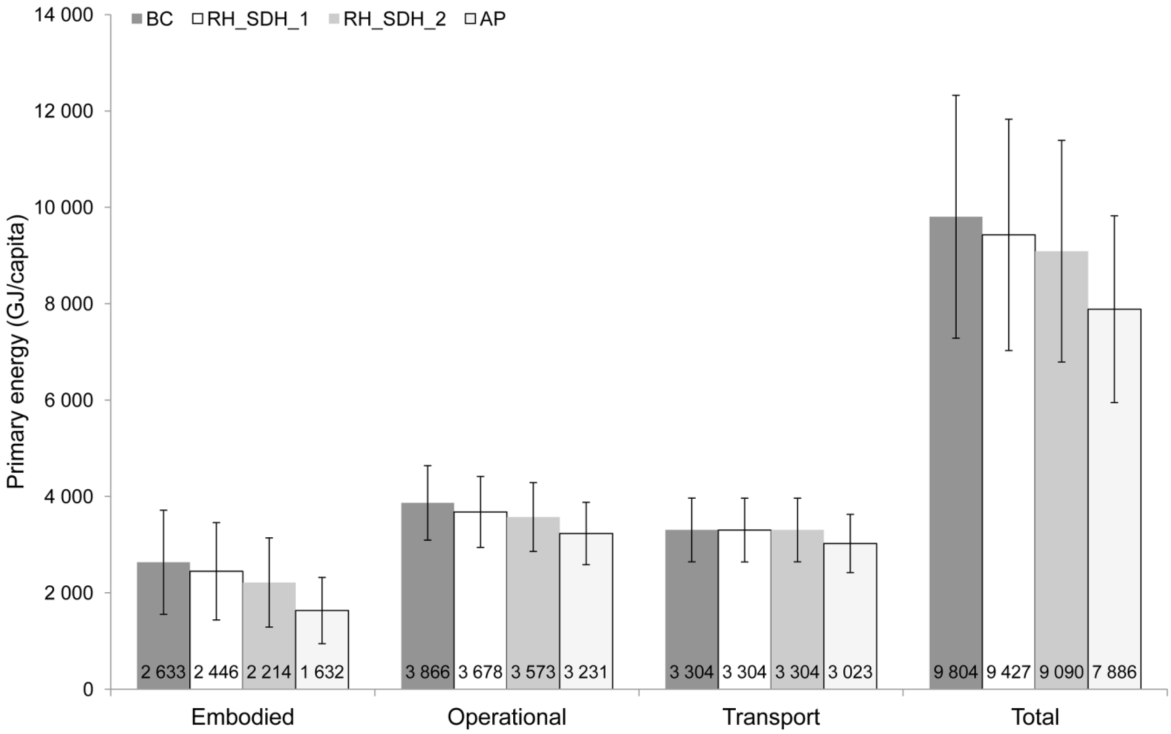

Figure 7: Life cycle energy demand breakdown of the housing typologies variations of the suburban neighborhood. Note: Figures may not add up due to rounding.

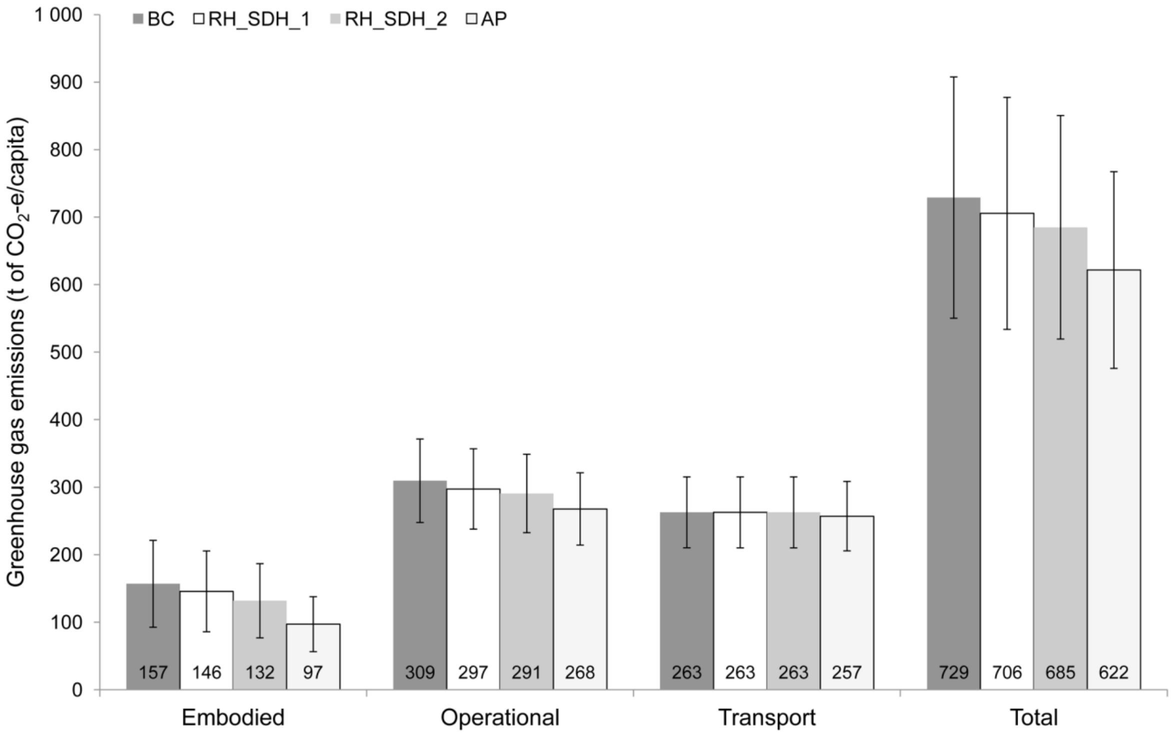

Figure 8: Life cycle greenhouse gas emissions breakdown of the housing typologies variations of the suburban neighborhood. Note: Figures may not add up due to rounding

The embodied energy demand and associated emissions of the RH_SDH_1 are 7.1% lower than the BC. This is due to sharing party walls among houses and the slightly lower living area per capita. The RH_SDH_2 variation reduces the embodied energy demand to 2 214 GJ/capita or -15.9% compared to the BC, by sharing the infrastructures among more people (higher density) and slightly less energy intensive houses (-2.1% for RH3-2 compared to RH3-1 and -1.5% for SDH4-2 compared to SDH4-1). The most important reduction of embodied requirements occurs for the AP scenario (-38.0% for energy and -38.2% for emissions compared to the BC). The lower living area per capita (-26.2% compared to the BC) and the greatly increased density (+236.4%) which implies sharing the infrastructures, are responsible for this decrease.

Operational energy requirements decrease by 4.9%, 7.6% and 16.4% for the RH_SDH_1, RH_SDH_2, and AP variations respectively. The decrease in operational energy is due to end-uses related to the building geometry (i.e. heating, cooling and lighting). The reduced heat loss areas and floor areas imply lower demands. The highest contribution to reduction comes from the heating demand which is gas powered. This explains why the reductions in emissions are less important. Indeed, greenhouse gas emissions resulting from gas combustion are lower than for electricity generation in Victoria, Australia.

Transport requirements are the same for the BC, RH_SDH_1 and RH_SDH_2. This explains the lower reduction of total energy and emissions requirements compared to the AP scenario which has lower transport requirements due to the gradual shift to train transportation. If no train shift is modelled, the reduction in total energy and emissions requirements for AP would be 16.5% and 13.7% respectively. However, the train shift does not affect the transport requirements as importantly as expected. Indeed, the transport energy is reduced by 8.5% and the associated emissions by 2.2% only. This is due to the high primary energy coefficient and emissions factor for electricity due to the use of wet brown coal. For instance, if these two parameters are reduced to 20% of their current values in 100 years, the transport energy and emissions for the AP scenario drop by 17.9% and 17.1% respectively (compared to the BC). Hence, relying solely on a train shift, without ensuring that the fuel source is efficient and non-polluting, cannot provide significant reductions.

Another interesting observation is the importance of the functional unit used to express the results. Indeed, when expressing the energy demand (or emissions) on a per km² basis (see Figure 9), the denser scenarios are the most energy intensive. However, the opposite trend is visible when using a per capita unit. While intensification implies a higher concentration and higher energy usage per surface area, it also (in the modelled cases) result in more efficient consumption per capita.

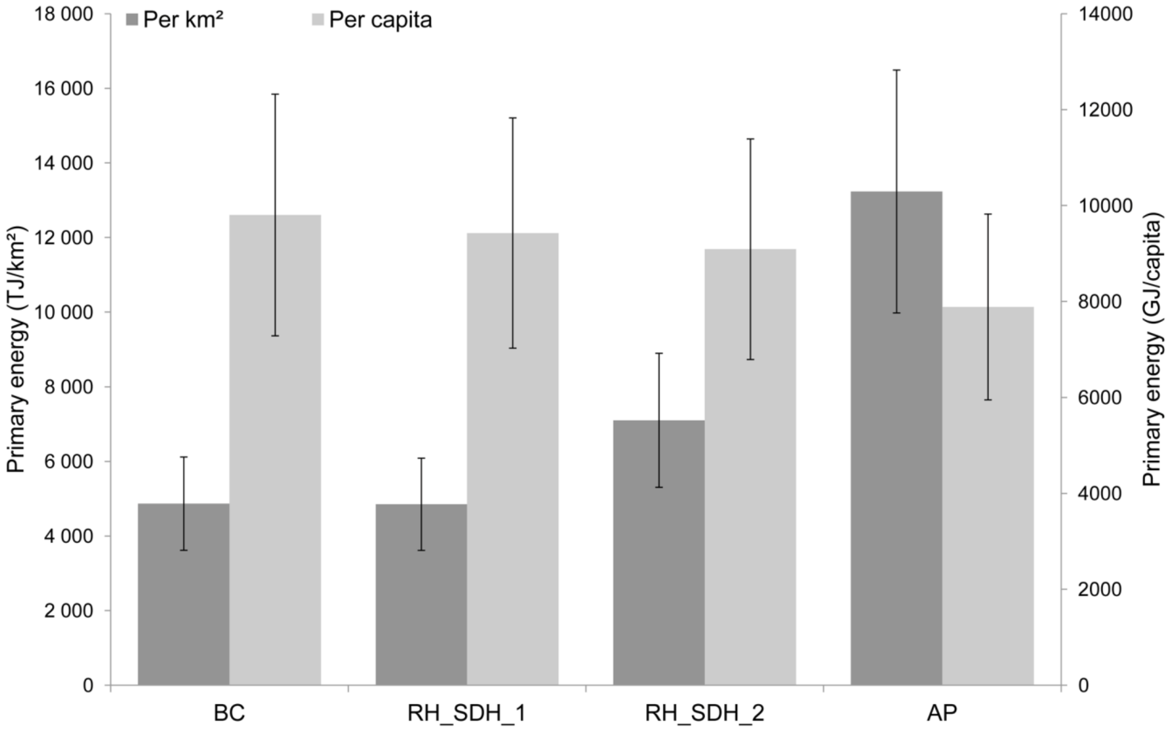

Figure 9: Life cycle energy demand and greenhouse gas emissions of the housing typologies variations of the suburban neighborhood, per km² and per capita

4 Discussion

This paper has analysed the life cycle energy demand and greenhouse gas emissions of a low density suburban neighbourhood near Melbourne, Australia using a comprehensive assessment technique developed by Stephan *et al.* [11]. The life cycle requirements breakdown reveals that when considering wide system boundaries, each of the embodied, operational and transport requirements are significant and none can be omitted from the assessment.

Results show that an increased density tends to reduce the total energy demands and associated greenhouse gas emissions per capita. Indeed, the sharing of infrastructure by more inhabitants reduces the associated embodied requirements as found by Carruthers and Ulfarsson [34]. Moreover, the reduced house sizes (lower living area per capita) results in less material usage, less land usage, and a reduced space heating and cooling energy demand per capita. Yet, intensifying these neighbourhoods also increases their energy demand per km² and thus their hinterland [35]. This could hinder their overall performance.

Also, this paper shows that each of the embodied, operational and transport requirements are individual levers that can be used to reduce the energy demand and greenhouse gas emissions of neighbourhood. All three levers have to be used simultaneously to ensure that net energy savings and greenhouse gas abatements do occur.

While this study has assessed the life cycle requirements of a suburban neighbourhood in with an unprecedented scope, the assessment suffers from uncertainty in the data. Indeed, the average uncertainty on the total life cycle energy demand is ±25%. The uncertainty on embodied requirements is the highest with an average of ±40%. More research is needed to compile robust embodied energy databases. This uncertainty in embodied figures and variability in operational and transport requirements could alter the results. The shares of embodied, operational and transport energy demands therefore lie within, 15.3%-39.4%, 28.7%-52.5%, and 23.9%-46.0% respectively. The most relevant strategies to reduce the energy demand can therefore change depending on the actual contribution of each use. Nevertheless, even by considering uncertainty, the main finding still holds: an effective reduction of energy consumption and associated greenhouse gas emissions requires measures for each of the embodied, operational and transport requirements.

This paper focuses on the energy demand and greenhouse gas emissions of suburban neighbourhoods using an Australian case study. While results give an indication about effective measures to deploy in order to reduce these requirements, more environmental impacts, such as water demand, toxicity, and others should be investigated. Moreover, other case studies, in different contexts should be assessed in order to verify the findings.

5 Conclusion

The increase in world population in the coming decades will take place in cities which will undoubtedly expand, most likely in the form of low density suburban neighbourhoods. This paper shows that such developments are energy and greenhouse gas intensive in terms of embodied, operational and transport energy. By intensifying such neighbourhoods, using alternative housing types, relying on public transport and renewable energy generation, the total requirements can be curved and cities might be able to grow with a lower environmental impact.

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