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

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Abstract

Many cities are likely to expand in the coming decades and this expansion will probably include low-density neighbourhoods. There is indeed an increasing pressure on cities worldwide to accommodate an increasing population. It is therefore crucial to assess the energy demand and related greenhouse gas emissions implications of such development.

This paper uses a representative low density case study neighbourhood in Melbourne, Australia, to assess its energy consumption and greenhouse gas emissions over 100 years and investigate various scenarios related to house size, transport technology and housing typology.

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. One of the analysed scenarios reveals that replacing half of the built area of the suburb with apartment buildings reduces the total energy consumption per capita by 19.6%, compared to a typical single storey detached house layout.

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 can be considerably reduced in order to improve the overall environmental performance 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's 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 have accommodated 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 because of this, 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 mirrors what has occurred in American or Australian cities over the last century.

A significant body of literature has analysed 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], and Fuller and Crawford [10], 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 [11] 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.

In their comparison of various housing types, Fuller and Crawford [10] have taken into account embodied, operational, and transport energy requirements. However, their study remains at the building level and does not integrate the embodied energy of nearby infrastructures such as the water and gas distribution systems, roads, power lines and sewage. Other studies, such as Säynäjoki *et al.*

[12] investigate multiple energy efficiency levels for different housing types for a new development in Finland. Yet, their study does not integrate transport energy and uses a pure input-output analysis, which is not always reliable [13], for the quantification of embodied energy. Other studies such as Glaeser and Kahn [14] compare different cities regarding the energy consumption associated with the operation of buildings and the transportation of their users but do not integrate embodied energy. Finally, some studies such as Heinonen and Junnila [15, 16] have quantified the total energy and greenhouse gas emissions associated with cities in Finland. The scope covers the built environment but also other sources of energy consumption such as food, leisure travel, etc.. While these studies rely on very comprehensive boundaries, they do not provide a detailed assessment of the energy demand and greenhouse gas emissions of a neighbourhood but rather focus on a city or metropolitan area. Therefore, while some studies have assessed the life cycle energy demand and associated greenhouse gas emissions of dwellings and cities, none have investigated a neighbourhood by integrating embodied, operational and transport requirements.

The aim of this paper is to undertake a comprehensive life cycle energy analysis of a new suburban neighbourhood in Melbourne, Australia and to analyse variations pertaining to house size, car technology and housing type. The influence of the evolution of key parameters in time is also investigated. This comprehensive assessment of the built environment will provide an insight into the energy demand and greenhouse gas emissions intensity of suburban neighbourhoods and their associated urban form.

Section 2 briefly describes the life cycle energy analysis framework, the case study neighbourhood, and proposes scenarios which are used to investigate the effect of various parameters on the total energy demand, and associated greenhouse gas emissions. Section 3 provides the results of the life cycle energy analysis of the base case neighbourhood and compares the latter to the other scenarios. These results, their implications, and the limitations of this study are discussed in Section 4 before concluding in Section 5.

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

2.1 Goal and scope definition

This paper aims to provide a detailed life cycle energy assessment of a new suburban neighbourhood that complies with standard building code and energy efficiency regulations. Therefore, this study does not consider low energy buildings, zero energy buildings or so-called 'green neighbourhoods' as most urban development globally does not comply with stringent energy efficiency codes.

This paper focuses on the built environment and does not take into consideration energy requirements associated with other expenditures such as food, clothing, leisure travel, and other items. While these expenditures can significantly contribute to the energy demand and associated greenhouse gas emissions of a city as described in [15, 16], they are not taken in consideration in this paper which focuses on the built environment. This is further discussed in Section 4.

This study takes into consideration the initial embodied energy of buildings and infrastructures, the energy associated with the replacement of building and infrastructure materials across the period of analysis (recurrent embodied energy), the operational energy of buildings (including, space heating, cooling, ventilation, domestic hot water, lighting, appliances and cooking) and the transport energy requirements of the building occupants (both direct and indirect). All greenhouse gas emissions associated with these energy requirements are taken into account. The system boundaries of this study are presented in Figure 1. Although it might result in considerable amounts of waste, the end of life stage of the life cycle is not taken into account as it often represents less than 1% of the total energy requirements over a building's life cycle [17, 18].

Yet, this low figure for the end of life stage is associated solely with the demolition and disposal of building materials and does not consider the fate of these materials. For example, recycled materials often have a significantly lower embodied energy compare to newly manufactured ones. Therefore recycling some of the building materials might result in a recovery of the initial embodied energy. Also, other the incineration of some materials, such as wood, at the end of their service life can recover a significant part of their embodied energy. The allocation of the recycling or incineration energy value is a controversial issue [19] since there is no common agreement consent about how it should be dealt with. Two main schools of thought exist in this regard. The first argues that the energy content of recycling or incineration should be deducted from the initial embodied energy. The second point of view stresses that the ultimate fate of the material is unknown, especially when it has a long service life, and therefore the benefit should be attributed to the recycled material in the future and not to the present one [20]. While the first perspective can favour the use of recyclable materials the second position seems more realistic and pragmatic and is adopted in this work.

Regarding the greenhouse gas emissions aspect, building materials can result in significant emissions after the end of their service lives, notably in the case of wood in landfill. In their study on wood products Sathre and O'Connor [21] have shown that decaying wood products in landfill can emit methane (CH_4) a greenhouse gas with a global warming potential 25 times that of carbon dioxide [22]. While this methane can be recovered to produce energy, it can also be directly emitted into the atmosphere. Hence the uncertainty regarding the greenhouse gas emissions of a range of building materials at their end of life stage is as significant as for their recycling or incineration fate. Greenhouse gas emissions associated with the end of life stage are therefore not taken into consideration in this work.

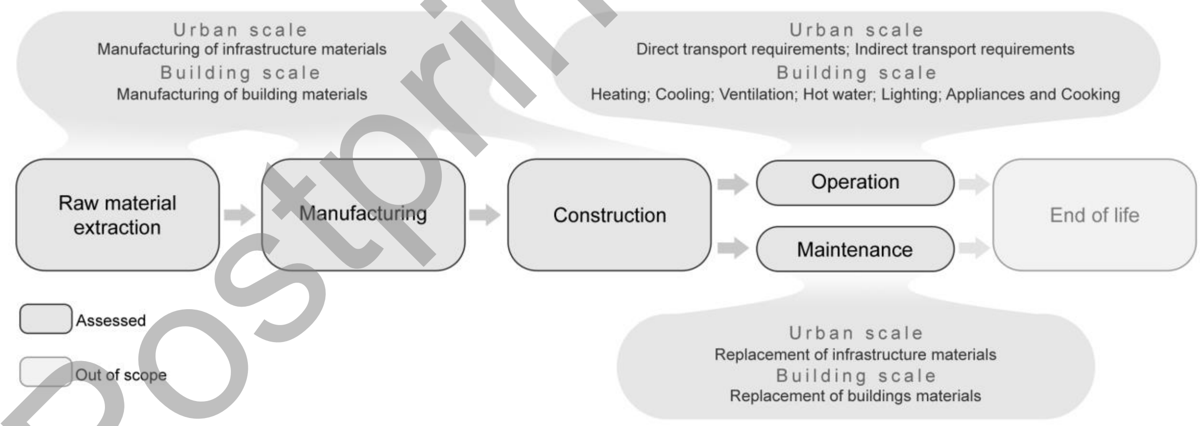

Figure 1: System boundaries of the multi-scale life cycle energy analysis of the Australian suburban neighbourhood

The functional units used in this paper are TJ, TJ/km² and GJ/capita for energy consumption and ktCO_2-e, and tCO_2-e/capita for greenhouse gas emissions. The use of absolute, spatial and per capita functional units allows a better comparability with other studies. The use of a per capita functional unit captures social differences such as the house size [23].

2.2 A multi-scale life cycle energy analysis

The life cycle energy analysis is based on the framework developed by Stephan *et al.* [24]. This framework, which is summarised in this section, is formalised into a software tool which automates all calculations and conducts a rapid life cycle energy assessment by relying on multiple databases. This software tool allows the evaluation of multiple scenarios and variations including building materials, annual travel distances and modal splits, building geometry, building systems and more than 300 parameters. This tool can provide a broad energy analysis of individual buildings and suburbs and is used in this paper to model the Australian neighbourhood.

A comprehensive life cycle energy and greenhouse gas emissions assessment requires that the neighbourhood be evaluated in terms of its embodied, operational and transport energy requirements. In this work, the neighbourhood is modelled as the sum of a mixture of buildings. The total energy demand of the neighbourhood is therefore the sum of the energy demand of its constituent buildings and households.

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 across the useful life of buildings and over the period of analysis for infrastructures. The infrastructures taken into account are: roads, power lines, water and gas distribution systems, and sewage.

The embodied energy assessment relies on the input-output-based hybrid analysis technique developed by Treloar [25]. This technique which is systemically complete provides the most comprehensive figures for embodied energy compared to the traditional process analysis or input-output analysis [26, 27]. The related database of embodied energy coefficients for Australia [28] is used in this paper. The embodied energy calculations for buildings are performed as per Eq. (1). The embodied energy of infrastructures is calculated using a similar algorithm but with less comprehensive system boundaries (process-based hybrid analysis), i.e. the energy demand associated with non-material processes is not taken into account. This might result in a slight underestimation of the infrastructure embodied energy.

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

Where: $LCEE_n$ = Life cycle embodied energy of neighbourhood n; Q_m = Quantity of material *m* in the building, EC_m = Hybrid energy coefficient of material *m*; TER_n = Total energy requirements of the building construction-related input-output sector *n,* in GJ/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*; UL_m = Useful life of the material *m*; $TER_{i \neq m}$ = 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.

Operational requirements comprise the energy and greenhouse gas emissions associated with the operation of buildings. This includes the space heating and cooling demands, ventilation, domestic hot water, lighting, cooking and appliances. Thermal energy requirements are based on static heat transfer equations that multiply the average heat transfer coefficient of the building (*U*-value) by its heat loss area and the heating or cooling degree hours. Ventilation losses and gains are taken into consideration by multiplying the average ventilation rate per send by the volume thermal capacity of air and the heating/cooling degree hours. It is assumed that the buildings are naturally ventilated. Non-thermal requirements (e.g. appliances, cooking, etc.) are sourced from average regional data based on DEWHA [29]. These final energy demands are converted to primary energy terms based on the energy source as per Eq. (2) and summed over the period of analysis.

$$LCOPE_n = POA \times \sum_{b=1}^{B} \sum_{e=1}^{E} \left(1 - SF_e \right) \times \frac{PEF_e \times OPE_e}{\eta_e} \quad (2)$$

Where: $LCOPE_n$ = Life cycle primary operational energy of the neighborhood *n* in GJ; *POA* = Period of analysis of the neighborhood *n*; SF_e = Solar fraction for the end-use *e* in building *b*; PEF_e =

Primary energy conversion factor for the energy source of the end-use *e* in building *b*; OPE_e = Yearly operational final energy demand of the end-use *e* in building *b* in GJ; and η_e = Average efficiency of the end-use *e* in building *b*.

Transport energy accounts for all the energy consumption associated with the mobility of the population over the period of analysis. The yearly travel distances are sourced from regional averages [30] while the energy intensity of the transport modes is based on input-output analysis data from Lenzen [31]. The energy intensity calculated by Lenzen comprises both direct and indirect requirements for a range of private and public transport modes in Australia. Direct transport requirements account for the energy consumption associated with the propulsion of the vehicles, such as burning fuel in an engine, or propelling a train using an electric motor. Indirect transport requirements are associated with services that support the transport process, such as manufacturing the vehicle, building roads, insurance, registration, and others.

Uncertainty and variability in the data are taken into account though interval analysis. This technique provides a certain range around the nominal value in which the actual figure may lie [32]. The uncertainty on the embodied energy data is set to ±20% and ±50% for the process data and input-output data components, respectively, based on Crawford [13]. The difference between the uncertainty ranges is due to the more accurate nature of process data compared to input-output data. Indeed, input-output analysis relies on sectorial economic transactions which are converted to energy intensities. This conversion, along with the use of the price of the material to determine its embodied energy, result in significant potential errors. On the other hand, process data is often collected from the product manufacturers and therefore is more accurate. The variability in operational energy figures is set to ±20% based on Pettersen [33] and assumed to be the same for transport energy.

The uncertainty boundaries are assumed to be symmetrical to simplify the assessment. For instance, the uncertainty ranges for process data (regarding embodied energy and greenhouse gas emissions) is often shifted upwards. This means that in most cases process data tends to underestimate the real value rather than overestimate it. Yet, since the input-output-based hybrid analyses is used and since input-output data has the largest contribution towards embodied energy, the use of a symmetric interval is justified.

Stephan *et al.* [24] provide all the equations for the quantification of energy requirements only. The conversion to associated greenhouse gas emissions is described in the following section.

2.3 Converting energy demand to greenhouse gas emissions

Greenhouse gas emissions are derived directly from the primary energy consumption, based on the fuel source used for operational and direct 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. (3).

$$LCGHG_u = LCPE_u \times EF_{S_u} \quad (3)$$

Where: $LCGHG_u$ = Life cycle greenhouse gas emissions of the use u, in $kgCO_2$-e; $LCPE_u$ = Life cycle primary energy consumption associated with the use u, in GJ; EF = Emissions factor, in $kgCO_2$-e; and S_u = energy source of the use u, e.g. natural gas, gasoline, etc..

The emissions factors for the different energy demands and associated energy sources are provided in Table 1 and are sourced from Treloar [20], Crawford [13] and DCCEE [34]. Indirect transport greenhouse gas emissions intensities are based on Lenzen [31] and are determined using input-output analysis. These factors are used to determine the greenhouse gas emissions of the case study neighbourhood which is described in Section 2.3.

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

Energy use	Energy source	Emissions factor ($kgCO_2$-e)	Source
Embodied energy	Various	60.00	Treloar [28] and Crawford [13]
Operational energy (cooling, appliances, etc..)	Electricity (Brown coal in Victoria, Australia)	93.11	DCCEE [29]
Operational energy (Heating, hot water, cooking)	Natural Gas	51.33	DCCEE [29]

Direct transport energy (Electric cars and trains)	Electricity (Brown coal in Victoria, Australia)	93.11	DCCEE [29]
Direct Transport energy (Gasoline cars)	Gasoline	67.10	DCCEE [29]

2.4 Case study neighbourhood

A typical residential suburban neighbourhood, comprising single family detached houses, is used to evaluate the total life cycle energy demand and greenhouse gas emissions associated with a large urban area. The assessed neighbourhood is a representation of suburban areas in Australia and many other regions of the world. This neighbourhood is based on the area of Wyndham (Latitude 37.89°S, Longitude 144.66°E), 28 km west of Melbourne's central business district.

Wyndham, like many other suburbs, has witnessed a dramatic increase in population in the last ten years (an average of 25% increase per year [35]) . On average, suburbs in the so-called 'outer-sector' (see Figure 2) accommodated 58% of the population growth of Melbourne between 2001 and 2010 [35]. Most of the new developments were single family detached houses. This increase in the outer-sector population is a small scale representation of what might happen in cities around the world in order to accommodate an increasing population [1].

Figure 2: Urban sector classification of Melbourne, Australia

Source: Adapted from BITRE [35]

A population density of 500 inhabitants/km² is chosen for the case study neighbourhood. The Bureau of infrastructure, Transport and Regional Economics [35] has shown that the average population density of the suburban areas of Melbourne (middle, outer and peri urban), is 230 inhabitant/km². According to the same source, the average population density of Wyndham ranges from 500 to 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 square kilometres of which 43 850 m² is attributed to the floor area of the residential buildings. The remaining area accounts for the large gardens, footpaths, roads, and other infrastructures. Two houses of 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 accommodate 4 occupants. The second house (BC3) is 180 m² and accommodates 3 occupants. 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 and is in line with the average floor area of new residential buildings in Australia (270 m²) [36]. The main characteristics of the houses are provided in Table 2.

Table 2: Main characteristics of the case study houses

Characteristics	BC4	BC3
Period of analysis (years)	100 years	
Building useful life (years)	100 years	
Number of houses in the neighbourhood	107	107
Gross floor area (m²)	230	180
Number of occupants	4	3
Structure	Timber-framed	
Façade	Brick veneer wall – 80 mm of fibreglass insulation - Double glazed aluminium framed windows	
Roof	Concrete tiles – 160 mm of fibreglass insulation	
Finishings	Medium standard finishes	
Average *U*-value (W/(m²K))	0.60	
Average air renewal rate (ach^{-1})	0.5	
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] (Use of wet brown coal in Victoria, Australia) 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 (converted to primary energy terms) 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 [29]. Sources: [a] from [37], [b] based on figures for Melbourne suburbs from [30], [c] from [38] and [d] based on [31].

Both houses have individual reinforced concrete (RC) footings on which a RC slab is cast. Timber framing constitutes the structure of the buildings. Timber trusses support the concrete tiled roof which comprises 160 mm of fibreglass insulation (R4). Brick veneer walls are used for the houses façades. The outer walls comprise 80 mm of fibreglass insulation (R2). Painted plasterboard is 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. The thermal performance of these buildings complies with the requirements of the 6-Star standard [39].

A ducted, gas fired, heating system, with 70% efficiency, is installed in the buildings. The same ducts are 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 households 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 for Melbourne suburbs from the Department of Transport [30]. While a train connection is available in Wyndham, 84.2% of trips are made by car and only 4% by public transport while walking and biking represent the remaining shares [30].

Multiple scenarios are used to evaluate the effect of certain parameters on the life cycle energy demand and greenhouse gas emissions. These scenarios are divided into two categories and are described in the following sections.

2.5 Dwelling size and private mobility scenarios

Since Australian dwellings have dramatically increased in size over the past 60 years [36], it is important to evaluate the influence that reducing the dwelling size has on the life cycle energy demand of the case study neighbourhoods. While Fuller and Crawford [10] 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.

The first scenario comprises two size variations and involves reducing the base case house floor areas by 10% (S10) and 20% (S20). The number of units built on the plot and the population density are kept constant for the sake of comparison.

The second scenario (ELEC_CAR) tests a switch to 100% electric cars 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 [40]. 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. The energy intensity of electric vehicles used in this paper is 2.63 MJ/pkm and comprises both direct and indirect requirements. Direct requirements (1.22 MJ/pkm) are based on their average energy efficiency [40] converted to primary energy terms. Indirect requirements (1.41 MJ/pkm) are assumed to be the same as for gasoline cars based on Lenzen [31], but excluding fuel production requirements.

These two scenarios investigate variations which do not modify the housing typology nor the population density of the neighbourhood. These two factors are investigated in the following scenarios which evaluate alternative housing typologies.

2.6 Alternative housing typologies scenarios

Urban form has been identified as an important factor in achieving a more environmentally friendly built environment [41]. However, a universal sustainable urban model does not exist [42]. The complexity of each case should be included and local measures undertaken to lower the environmental impact of urban areas.

Dense and compact cities have often been associated with a reduced environmental impact, notably because of lower transport energy requirements [7, 14], although actual transport figures show that this benefit is often exaggerated [43]. Also, from a life cycle energy consumption perspective, developing denser neighbourhoods will save significant amounts of materials per capita because of shared infrastructures, more compact housing, party-walls, and other factors. This will also allow the implementation of more efficient systems such as district heating and cooling. If operated on renewable energy sources, district heating and cooling and combined heat and power production can significantly reduce the primary operational energy demand [44]. Moreover, if densification entails intensification and improved accessibility, the average travel distances are likely to drop. This will ultimately decrease the transport energy requirements. For all of the above reasons, denser configurations of the assessed case study neighbourhood are assessed through variations to the dwelling typology. As specified in Section 2.1, this study does not consider extremely energy efficient buildings as these are not representative of most urban growth globally.

Higher density urban structures have to rely on specific building typologies which accommodate more people per square meter. However, high-rise apartment buildings might require a significant amount of additional materials for fire safety, common areas, lifts, and other systems but also more energy for operating the common areas in terms of lighting, lifts, etc.. For this reason, and following Rickwood's [45] conclusions on the least energy-intensive housing form, only semi-detached houses and low-rise buildings are assessed in this paper.

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 three different scenarios. One half of the built area of the base case (BC), i.e. approximately 22 000 m², is attributed to row houses or apartment buildings in each of the three housing typologies scenarios. The other half is kept as in the BC.

The first scenario, RH_SDH_1, replaces half of the built floor area with row houses and semi-detached houses. Row houses share a party wall on each side and have two façades, except for the houses at the edges (semi-detached houses), which have three. These houses are expected to save embodied energy compared to normal houses with the same area because of their more efficient use of materials. Beside this aspect, row and semi-detached houses are also typically smaller than detached houses and therefore use less materials in absolute terms.

In the RH_SDH_1 scenario, houses are grouped in blocks of four houses with 168 m² row houses in the middle (RH3-1) and 216 m² houses with three façades, called semi-detached houses (SDH4-1), on the edge (see Figure 3). A depth of 12 m is chosen for all houses with less than four façades to allow natural daylight deep inside the house. This figure is based on the passive zone concept used by Ratti *et al.* [46]. The row houses and semi-detached houses use the same assemblies as in the base case neighbourhood houses (see Table 2). The travel distances per household are also assumed to be the same as in the base case, based on the number of occupants.

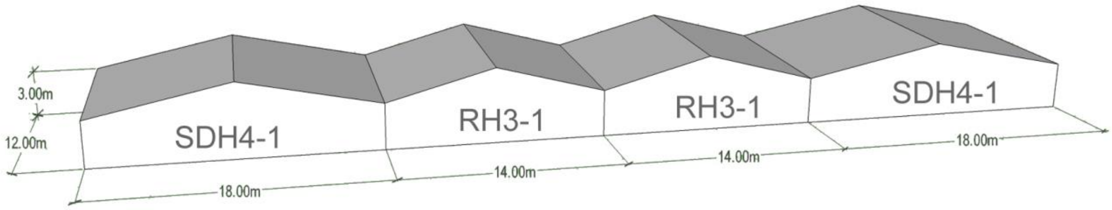

Figure 3: Basic geometric and volumetric layout of modelled row and semi detached houses in the RH_SDH_1 scenario

The second scenario, RH_SDH_2, is similar to the first but uses double storey row houses (RH3-2, 168 m²) and semi-detached houses (SDH4-2, 216 m²) (see Figure 4). The width of row and semi detached houses is divided by two compared to the RH_SDH_1 scenario. This results in an increased population density because more houses can be built on the same surface area.

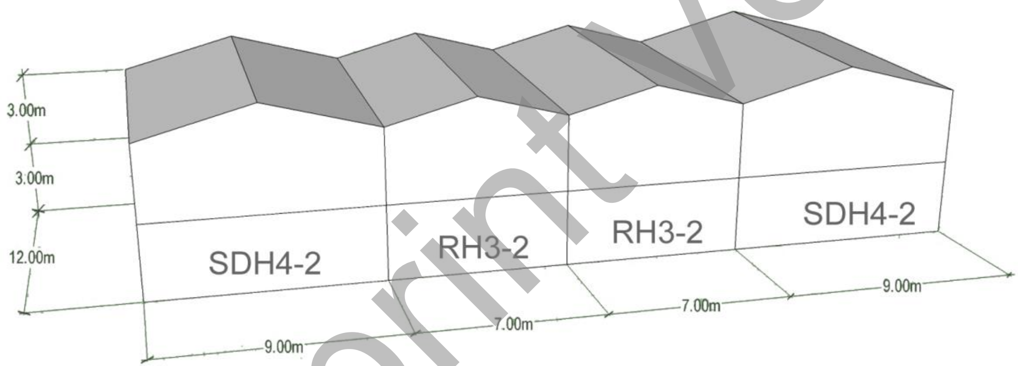

Figure 4: Basic geometric and volumetric layout of modelled row and semi detached houses in the RH_SDH_1 scenario

The third scenario, APB, consists of replacing half of the built area in the BC with four-storey apartment buildings. 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.

As depicted in Figure 5, each modelled building comprises 12 double-façade flats of 120 m² each and 8 triple-façade flats of 168 m². Three and four users live in each of the small (AP3) and large apartments (AP4), respectively. The depth of 12 m is based on the passive zone concept [46] as in the row houses scenarios. 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 1653 inhabitants/km², keeping the same neighbourhood area.

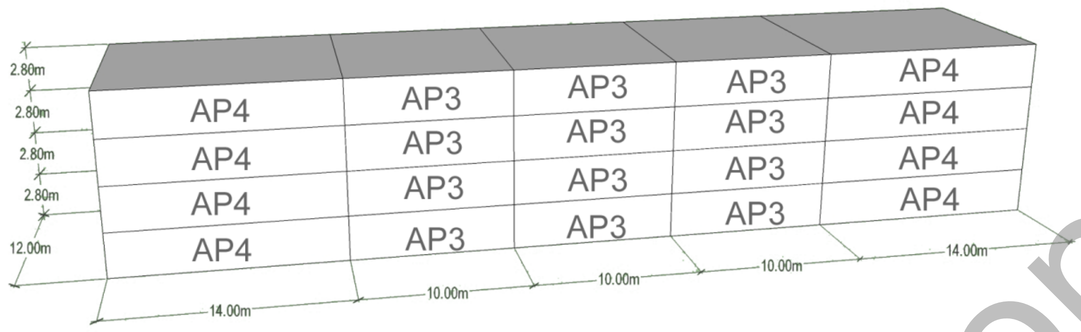

Figure 5: Basic geometric and volumetric layout of modelled low rise apartment buildings in the APB scenario

Continuous reinforced concrete (RC) footings 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, containing 80 mm of fibreglass insulation bats (R2), is attached to the interior face of the external walls. Painted plasterboard is fixed to the steel frame of the external walls, and to the steel framed internal walls. Double glazed windows with aluminium frames cover 70% of the external wall area. The roof comprises 160 mm of fibre glass insulation (R4). The *U*-values of envelope elements are the same as those used in the base case neighbourhood and the row houses scenarios. Ceramic tiles are installed in the living rooms, the kitchen and the bathrooms while nylon carpets constitute the flooring of the bedrooms. Other finishings are considered to be of a medium standard.

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 sufficient to support the development of a reliable train connection to the city. The share of train trips is linearly increased from 0% at year 0 to 75% of all trips in 100 years. At the same time, the share of car trips is decreased from 100% at year 0 to 25% in 100 years. Also, the energy intensity for private transport is kept constant in all housing typologies scenarios since most of the driving is expected to occur on the same roads, notably the highway to Melbourne.

The main characteristics of each of the three housing typology scenarios: RH_SDH_1, RH_SDH_2, and APB are provided in Table 3.

Table 3: Main characteristics of the three housing typologies scenarios

Characteristics	RH_SDH_1	RH_SDH_2	APB
Number of houses in the neighbourhood, by dwelling type	BC4: 53 BC3: 53 RH3-1: 57 SDH4-1: 57	BC4: 53 BC3: 53 RH3-2: 114 SDH4-2: 114	BC4: 53 BC3: 53 AP3: 372 AP4: 248
Gross floor area, by dwelling type (m²)	BC4: 240 BC3: 180 RH3-1: 168 SDH4-1: 216	BC4: 240 BC3: 180 RH3-2: 168 SDH4-2: 216	BC4: 240 BC3: 180 AP3: 120 AP4: 168
Number of occupants, by dwelling type	BC4: 4 BC3: 3 RH3-1: 3 SDH4-1: 4	BC4: 4 BC3: 3 RH3-2: 3 SDH4-2: 4	BC4: 4 BC3: 3 AP3: 3 AP4: 4
Total neighbourhood area (km²)	1.5	1.5	1.5
Population density (inhabitants/km²)	513	779	1653

2.7 Evolution of parameters over time

Many key factors such as the energy source for electricity, the efficiency of appliances or the energy intensity of transport modes are subject to significant change over the chosen period of analysis, i.e. 100 years. There is great uncertainty about potential technological breakthroughs and the penetration of renewable energy on the market. In order to investigate how potential changes in the energy production or efficiency of systems might affect the life cycle energy demand and associated greenhouse gas emissions, a number of key parameters are changed over time. The effect of the parameter evolution is tested on all scenarios.

The key parameters which are modified over 100 years are:

- The primary energy conversion factor for electricity (PEF_{el});
- The greenhouse gas emissions factor for electricity production (GHG_{el});
- The appliances energy demand (APP); and
- The energy efficiency of cars (EEF_{c}).

The reduction of the primary energy conversion factor for electricity and the greenhouse gas emissions factor for electricity production over 100 years represents the potential installation of renewable energy sources. These renewable energy sources result in a net reduction of the primary energy requirement since they rely on solar, wind or tidal/wave energy. The burning process and its inefficiencies are removed from the energy supply chain when compared to fossil fuels plants. The greenhouse gas emissions associated with this combustion is also removed. It is important to highlight that the primary energy conversion factor does not take into account indirect requirements of the energy supply chain such as the embodied energy of the plant. Two evolutions are investigated for the appliances energy demand: an increase by 50% over 100 years and a decrease by 50% over 100 years. The evolution that increases the appliances energy demand is modelled to project the current trend of constant increase into the future [29, 47] while the other evolution attempts to model a dramatic increase in the energy efficiency of appliances that results in a decrease in the associated energy demand. Finally, even if it has been nearly constant for the last 100 years [48], the energy efficiency of cars (petrol and electric) is gradually improved to 150% of its current values over 100 years. These parameters are modified using a cubic interpolation between the values specified in Table 4.

Table 4: Evolution of key parameters over time

Year	PEF_{el} [a]	GHG_{el} [a]	APP+ [b]	APP- [b]	EEF_c [b]
0	100%	100%	100%	100%	100%
33	60%	60%	125%	80%	125%
66	40%	40%	140%	60%	140%
99	20%	20%	150	50%	150%

Source: [a] inspired from the 450 scenario of the IEA [49] for the first 22 years and assumed for the remaining period of time; [b] assumed.

The evolution of these parameters is assumed to occur simultaneously, resulting in two major evolution scenarios, the first: ALL+ including PEF_{el}, GHG_{el}, APP+ and EEF_c and the other ALL- including PEF_{el}, GHG_{el}, APP- and EEF_c. These two evolution scenarios are compared with the original variations and base case: NO_EVOL. The recurrent embodied energy and the indirect transport energy demands and associated emissions are not affected by these evolutions in this study. Indeed, the databases used do not comprise sufficient details to be able to model the influence of the change of electricity production on embodied energy or indirect transport energy.

3 Results

The results of the life cycle energy and greenhouse gas emissions analyses are presented for the base case, the dwelling size and private mobility scenario, and the alternative housing typologies, respectively.

3.1 Life cycle energy demand and greenhouse gas emissions of the base case neighbourhood

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

Figure 6 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 represent 7 300 TJ and 543 ktCO_2-e, respectively. This energy consumption is equivalent to the amount of solar energy hitting 75% of the ground surface of the suburb during one year, or nearly 30% of the annual final energy consumption for residential lighting in Australia [29]. 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 (42.4%). The transport requirements rank second with 33.6% and 36.0% of the LCE and LCGHG, respectively. 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.

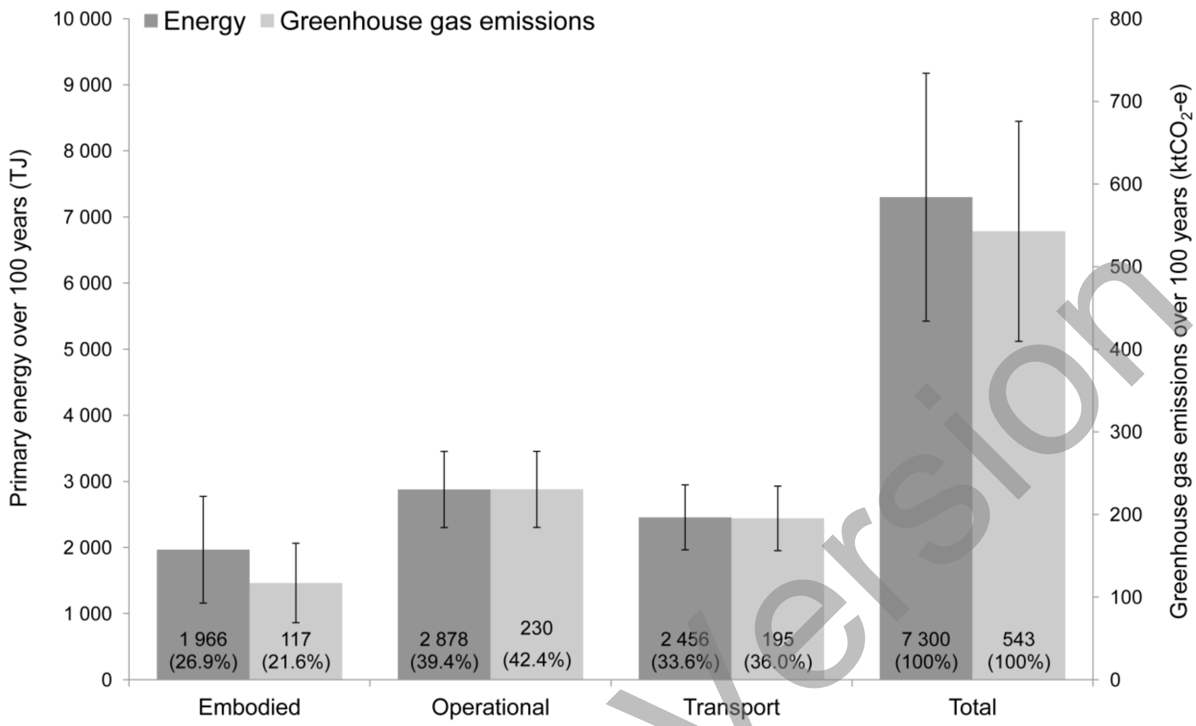

Figure 6: Life cycle energy and greenhouse gas emissions of the suburban neighbourhood base case, by use, over 100 years. Note: Figures may not sum due to rounding.

Operational energy is the greatest contributor to greenhouse gas emissions with 80.4 $kgCO_2$-e emitted per GJ followed closely by transport with 79.5 $kgCO_2$-e emitted per GJ. Embodied energy has an average emissions factor of 60 $kgCO_2$-e emitted per GJ which explains its lower contribution to LCGHG compared to LCE. It is therefore important to first reduce greenhouse gas emissions from transport, electricity generation and other operational energy fuels such as gas.

3.1.1 Embodied energy and greenhouse gas emissions

The embodied energy demand of the neighbourhood is presented by element in Figure 7. The elements include: envelope (building shells), finishings, infrastructure, structure, systems, the direct energy required for construction and other items. The maximum contribution from a single element is 26.2% (envelope). Thus, the embodied energy demand cannot be significantly lowered if the requirements of only one element are reduced. All elements should be tackled together, through the reduction of house size for example.

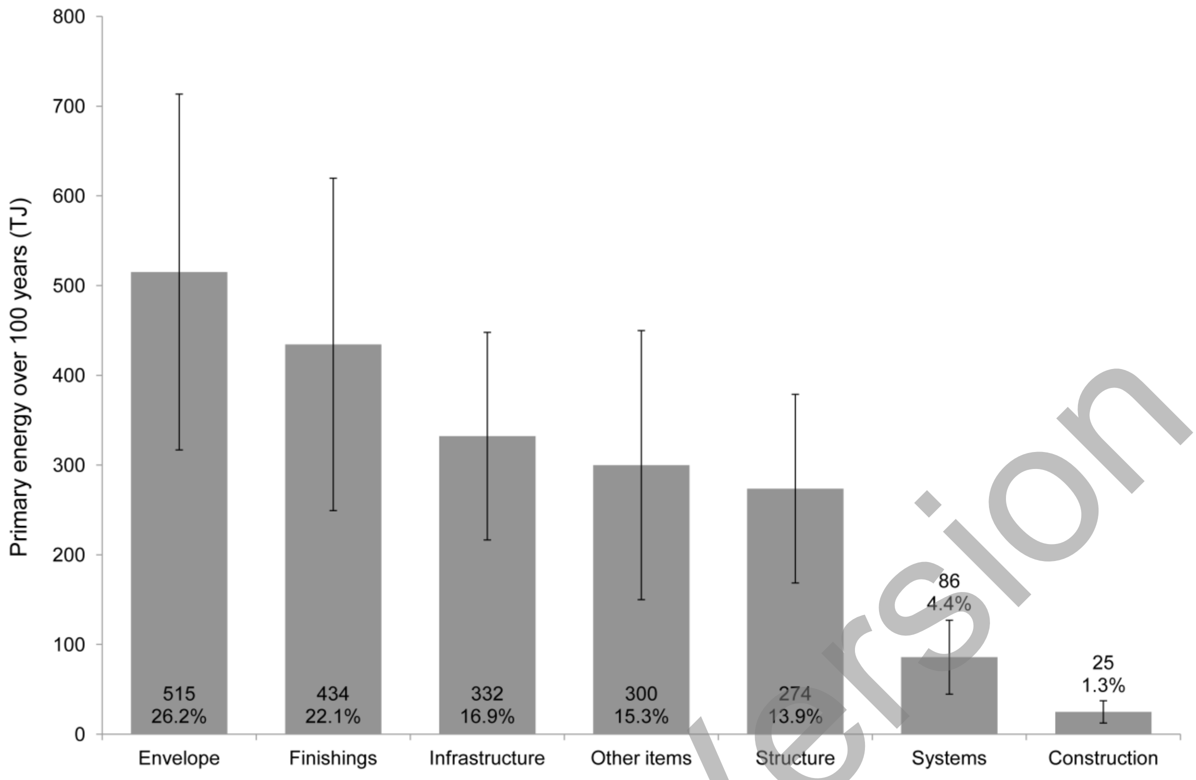

Figure 7: Life cycle embodied energy demand of the suburban neighbourhood base case, by element.

An important finding to underline is the important contribution of infrastructures to the neighbourhood life cycle embodied energy (16.9%). While roads are the most critical contributors, power lines, supported by timber poles every 20 m are more energy intensive over 100 years than the combined concrete and steel in all footings of the buildings. Hence, it is critical that the requirements for infrastructures are taken into account in building life cycle energy analysis studies.

The ‘other items’ element represents the energy requirements associated with non-material inputs, such as insurance and advertising services, that support the building infrastructure and construction processes. The other items’ energy demand, which is omitted in other embodied energy assessment techniques, represents 15.3% of the total.

The greenhouse gas emissions associated with embodied energy are calculated by multiplying the former by an emissions factor of 60 kgCO_2-eq/GJ as explained in Section 2.2. Therefore the same rankings and contributions are obtained for embodied emissions, as for embodied energy.

3.1.2 Operational energy and related greenhouse gas emissions

The life cycle operational energy demand (LCOPE) and related greenhouse gas emissions (LCOPGHG) are dominated by appliances. As can be seen in Figure 8, appliances represent 47.7%

of the LCOPE and 55.5% of the LCOPGHG. Since the thermal performance of the envelope is in line with stringent energy efficiency regulations, the heating demand is lower than the average building stock. The installation of solar panels, providing 75% of the domestic hot water demand, dramatically reduces the primary energy consumption and related greenhouse gas emissions of the latter.

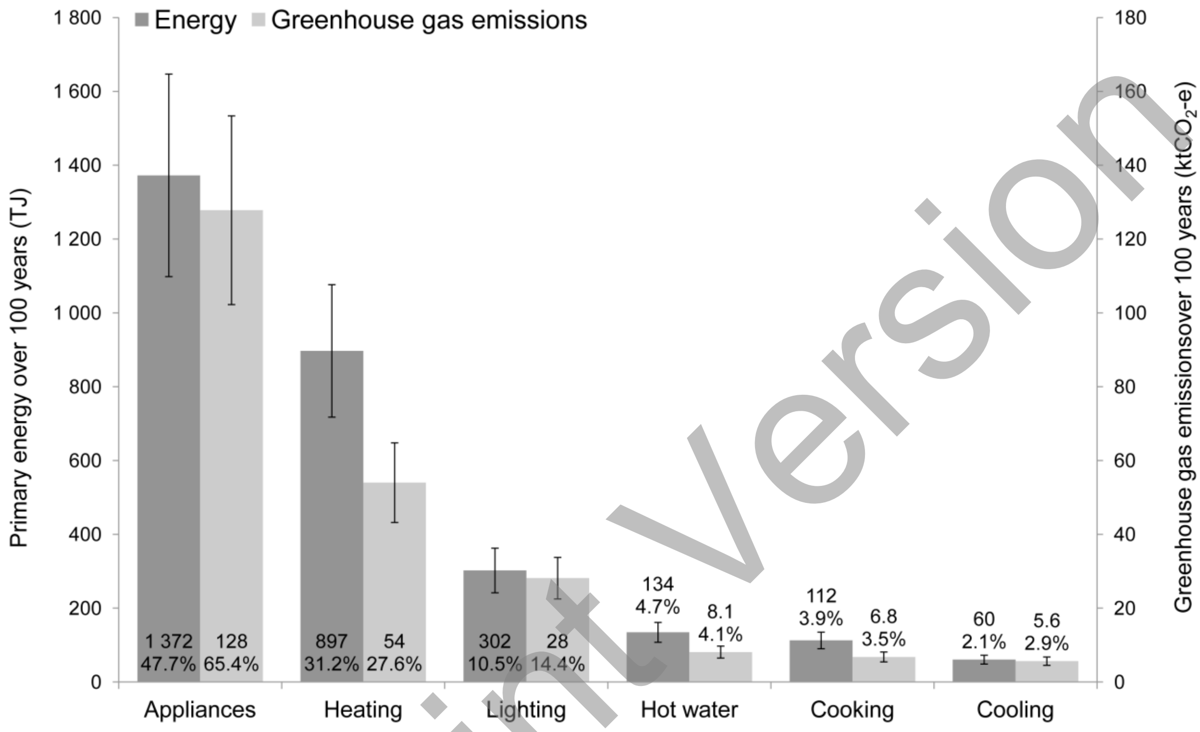

Figure 8: Life cycle operational energy demand and greenhouse gas emissions of the suburban neighbourhood base case, by use.

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 partly responsible for this shift (see Table 1). The overall contribution of the cooling demand to the LCOPE and LCGHG is insignificant due to the temperate climate.

3.1.3 Transport energy and related greenhouse gas emissions

The life cycle transport energy consumption (LCTE) of the neighbourhood is 2 456 TJ over 100 years and is associated with the emission of 195 ktCO_2-e (LCTGHG). The totality of the transport requirements are associated with private car use since it is the sole transport mode utilised in the base case.

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 ktCO_2-e (52.0%) respectively. In this case, the indirect transport energy represents 123.7% of the heating primary energy demand of the houses. This ratio highlights the importance of integrating indirect transport requirements in the analysis of household energy requirements.

3.2 Dwelling size and private mobility scenarios

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 5). The greater reduction of the energy demand compared to emissions is due to the fact that transport energy, which has a higher emissions factor than embodied energy, is not affected by changes to the size of the houses.

Table 5: Effect of house size and transport variations on the life cycle energy and emissions breakdown of the suburban neighbourhood base case

Use	SH10		SH20		ELEC_CAR	
	Value	Relative difference with BC	Value	Relative difference with BC	Value	Relative difference with BC
LCEE (TJ)	1 832	-6.8%	1 699	-13.6%	1 966	0.0%
LCOPE (TJ)	2 784	-3.3%	2 691	-6.5%	2 878	0.0%
LCTE (TJ)	2 456	0.0%	2 456	0.0%	1 466	-40.3%
LCE (TJ)	**7 072**	**-3.1%**	**6 845**	**-6.2%**	**6 310**	**-13.6%**
LCEGHG (ktCO_2-e)	109	-6.8%	101	-13.5%	117	0.0%
LCOPGHG (ktCO_2-e)	224	-3.0%	217	-5.9%	230	0.0%
LCTGHG (ktCO_2-e)	195	0.0%	195	0.0%	140	-28.4%
LCGHG (ktCO_2-e)	**528**	**-2.7%**	**513**	**-5.4%**	**487**	**-10.2%**

Note: Figures may not sum 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 in energy 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 embodied energy and greenhouse gas emissions of the different elements are not equally affected by the floor area reduction. For instance, in the SH20 case, the embodied energy associated with the structure (footings and slab) is reduced by 16.8%, finishings by 15.9%, envelope by 15.0% and systems by 12.5%. In all cases, a notable decrease in embodied energy and emissions is observed.

Operational energy 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 reduction in house size should not realistically affect the travel patterns of the users, especially since the overall density of the district is kept constant. This implies that only reducing the house size will not lead to dramatic energy savings since transportation is not affected. This aspect is investigated in the second scenario which replaces all gasoline cars with electric cars.

Relying purely on electric cars instead of gasoline results in a significant reduction in the life cycle transport and total energy requirements. The life cycle transport energy (LCTE) is reduced by 40.3% compared to the base case and the associated emissions by 28.4%. The life cycle energy demand of the entire neighbourhood is reduced by 13.6% and the associated emissions by 10.2%. The difference between energy and emissions reductions is due to the high emissions intensity from electricity generation in Victoria, Australia (93.11 kgCO_2-eq/GJ). The use of electric cars has a notable impact on the life cycle requirements. Using electric cars can therefore lower the total energy 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. Also, the high primary energy conversion factor for electricity and the high emissions factor for electricity generation intuitively suggest that electric cars might not be a viable alternative to combustion engine vehicles from an energy and greenhouse gas emissions abatement perspective. Yet, using electric cars also implies a significant reduction in energy requirements and emissions. 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 (74% on average) is much higher than for combustion engines (maximum 40%) [40, 50].

These two scenarios, relating to the reduction of dwelling size and the use of electric cars, show that an important reduction of energy consumption and associated greenhouse gas emissions can be achieved. The following section describes how alternative housing typologies scenarios affect the life cycle energy demand and greenhouse gas emissions.

3.3 Alternative housing typologies scenarios

The three scenarios, RH_SDH_1, RH_SDH_2, and APB, which replace half of the built area of the district (approximately 22 000 m²) with single-storey row and semi detached houses, double-storey row and semi detached houses, and apartment buildings (see Section 2.5), respectively, are grouped for the presentation of the results.

Figures 9 and 10 show a clear trend which correlates lower energy consumption and greenhouse gas emissions with higher density housing and more compact buildings. The APB scenario has the lowest life cycle energy demand per capita, i.e. 7 886 GJ, representing a 19.6% decrease compared to the BC. It also results in a 14.7% reduction in the life cycle greenhouse gas emissions. Scenario RH_SDH_1 and scenario RH_SDH_2 present lower reductions in energy requirements (3.8% and 7.3%, respectively) and greenhouse gas emissions (3.2% and 6.0%, respectively).

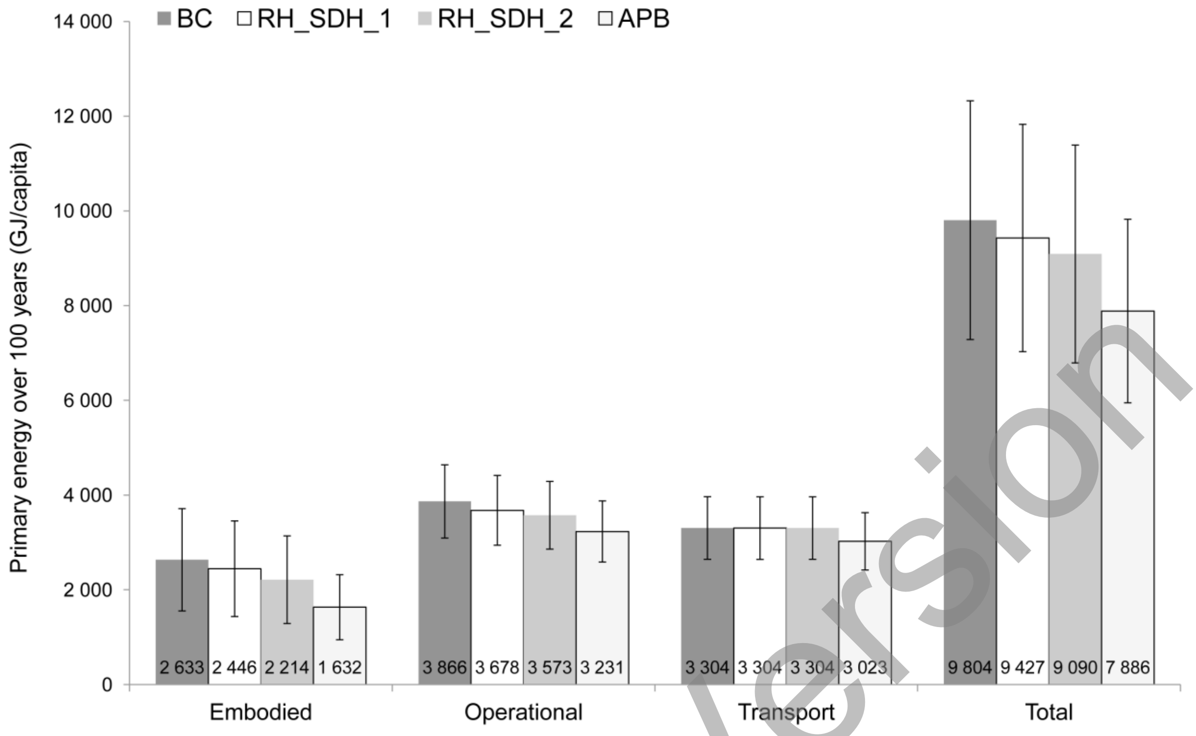

Figure 9: Life cycle energy demand of the alternative housing scenarios for the case study suburban neighbourhood. Note: Figures may not sum due to rounding.

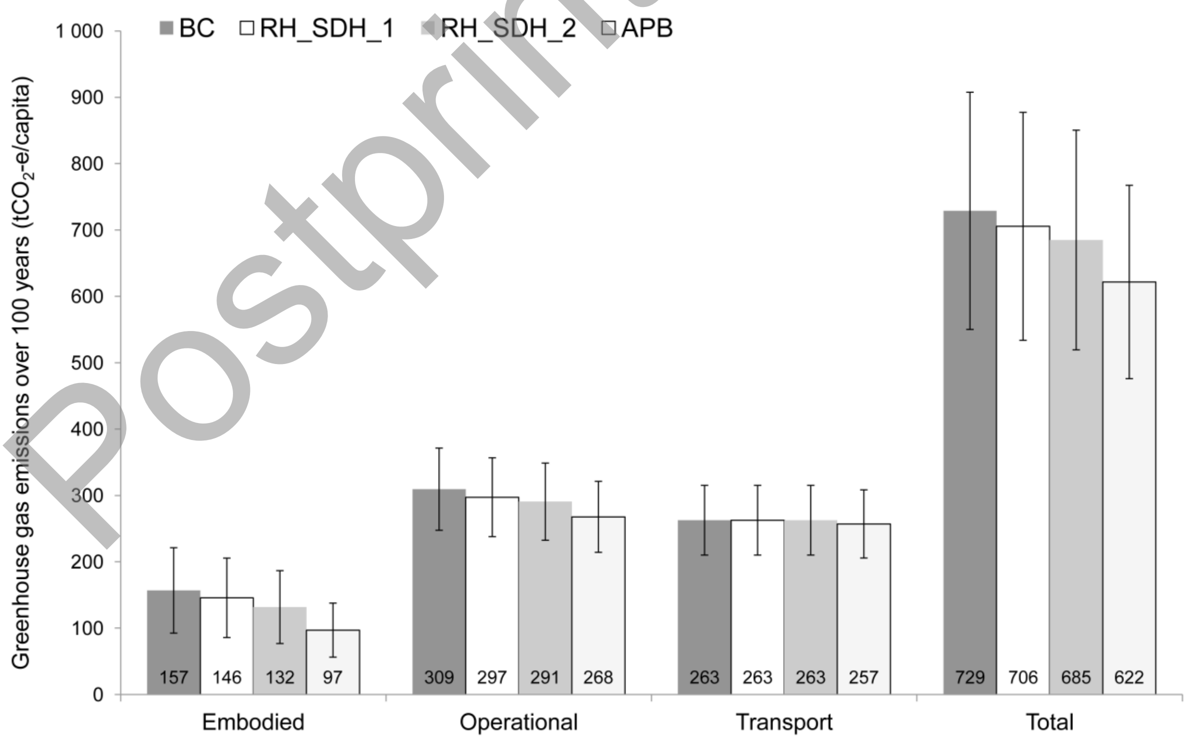

Figure 10: Life cycle greenhouse gas emissions of the alternative housing scenarios for the case study suburban neighbourhood. Note: Figures may not sum due to rounding

Various aspects are behind the observed difference in total requirements. These are related to embodied, operational and transport requirements and are described in this order hereafter.

The embodied energy demand and associated emissions of the RH_SDH_1 scenario are 7.1% lower than the BC. This is due to sharing party walls among houses and the slightly smaller living area per capita. The RH_SDH_2 scenario variation reduces the embodied energy demand to 2 214 GJ/capita or by 15.9% compared to the BC, by sharing the infrastructures among more people (higher density) and slightly less energy intensive houses (-2.1% for the RH3-2 house compared to the RH3-1 house, and -1.5% for the SDH4-2 house compared to the SDH4-1 house). The most significant reduction in embodied requirements occurs for the APB scenario (-38% for energy and -38.2% for emissions compared to the BC). The smaller living area per capita (26.2% smaller compared to the BC) and the greatly increased density (+231.3%) resulting in a greater sharing of the surrounding infrastructure, are responsible for this reduction.

Operational energy requirements decrease by 4.9%, 7.6% and 16.4% for the RH_SDH_1, RH_SDH_2, and APB scenarios respectively. The decrease in operational energy is due to end-uses related to the building geometry (i.e. heating, cooling and lighting). The highest contribution to the reduction in operational energy demand comes from the heating demand which is gas powered. The reduction in the heat loss area, due to party walls and smaller house size per capita, is responsible for the lower space heating energy. This explains why the reduction in emissions is less significant, primarily due to the greenhouse gas emissions resulting from gas combustion being lower than for electricity generation in Victoria, Australia (see Table 1).

Transport energy requirements and associated greenhouse gas emissions are the same for the BC, RH_SDH_1 and RH_SDH_2 scenarios. This explains the lower reduction of total energy and emissions requirements compared to the APB 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 the APB scenario would be 16.5% and 13.7% respectively (compared to 19.6% and 14.7% with the shift to train usage included). If the share of train travel is assumed to be 75% from year 0 for the APB scenario, the total energy demand and associated greenhouse gas emissions would be 22.8% and 15.9% lower than for the BC, respectively. Hence, imposing an immediate use of trains for 75% of the annual travel distance further reduces the energy consumption by 3.2% and the greenhouse emissions by 1.2% compared to a gradual shift over 100 years. This shows that the immediate use of trains does not affect the transport requirements as significantly as expected. 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 APB scenario drop by 17.9% and 17.1% instead of 8.5% and 2.2%, 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 in emissions.

Another interesting observation is the importance of the functional unit used to express the results. When expressing the energy demand (or emissions) on a per km^2 basis (see Figure 11), the denser scenarios are the most energy intensive. However, the opposite trend is visible when using a per capita functional unit. While intensification implies a higher concentration and higher energy usage per surface area, it also (in the modelled cases) results in more efficient consumption per capita. This finding highlights the importance of the choice of functional unit. Using a spatial unit, such as TJ/km^2 measures the intensity of energy use and gives an idea of the broader implications of such intensity since energy is rarely produced inside a neighbourhood or a city. Since this paper also takes into consideration embodied energy, it also gives an indication of the material stock and its energy intensity. The per capita unit allows the assessment of the efficiency of use and of the energy intensity of the population. This can be an interesting metric to compare different neighbourhoods with different population sizes or in different countries.

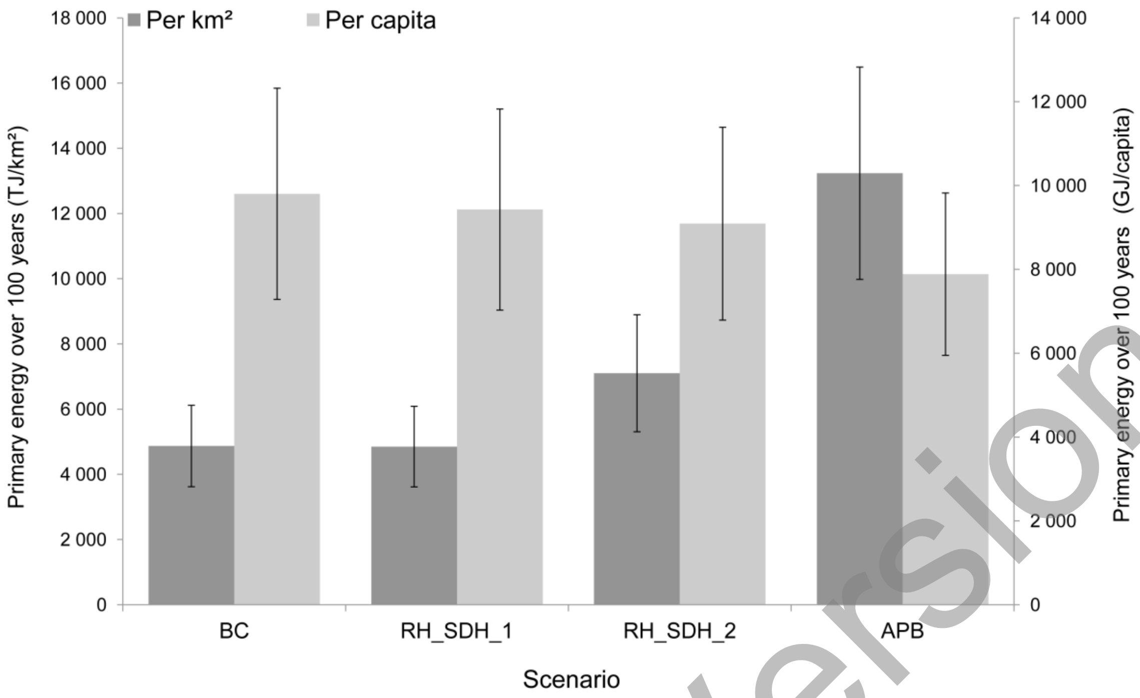

Figure 11: Life cycle energy demand and greenhouse gas emissions of the alternative housing scenarios for the case study suburban neighbourhood, per km² and per capita

3.4 Evolution of parameters over time

Table 6 presents the relative difference of the life cycle energy demand and related greenhouse gas emissions of the suburban neighbourhood base case, for each evolution scenario. The percentage compare to the NO_EVOL scenario. The evolution of the primary energy conversion factor for electricity and the greenhouse gas intensity of electricity production are coupled since they are both the result of installing renewable sources for electricity generation.

Table 6: Relative difference of the life cycle energy demand and associated greenhouse gas emissions of the suburban neighborhood base case, for each evolution scenario, compared to the original case without any temporal evolution of parameters.

Evolution scenario	Relative difference with NO_EVOL	
	Life cycle energy demand	Life cycle greenhouse gas emissions
PEF_{el} & GHG_{el}	-11.3%	-20.3%
APP+	+5.8%	+7.1%
APP-	-5.4%	-6.9%
EEF_c	-4.1%	-4.0%

ALL+	-12.9%	-22.5%
ALL-	-17.6%	-25.3%

Note: all scenario acronyms refer to Table 4 and Section 2.7.

Results show that the single most effective measure to reduce the total energy demand is to install additional renewable sources for electricity production (-11.3%), followed by the reduction of the appliances energy demand (-5.4%) and the improvement of the car fuel efficiency (-4.1%). Doubling the current appliances energy demand over 100 years results in a 5.8% increase in the total energy demand. Testing the influence of each evolution scenarios alone can inform which is the most effective measure to implement and what impacts it will have. Also, when combining all parameters together, the overall reduction is lower than the sum of the individual components. This is due to the coupling of some scenarios in the model, such as PEF_{el} & GHG_{el} and APP+ and APP-. Since, it is likely that all parameters will evolve simultaneously and that some of these parameters are coupled, it is crucial to study the influence of their simultaneous evolution.

Figure 12 shows the influence of the evolution of key parameters over 100 years on the life cycle energy demand and greenhouse gas emissions of all assessed scenarios. Results show that on average the ALL+ and ALL- scenarios result in a reduction of 14.2% and 19.3% of the life cycle energy demand and 24.8% and 27.8% of the greenhouse gas emissions, respectively. Greenhouse gas emissions a more affected by the evolution of parameters due to the combination of reducing the primary energy conversion factor for electricity and its associated greenhouse gas emissions factor. This can be noticed in Figure 12 by a more pronounced shift of the evolution scenarios along the abscissa (greenhouse gas emissions) compared to ordinates (energy demand). The expected improvement of energy production and energy efficiency over 100 years have a significant impact on both energy consumption and the associated energy emissions.

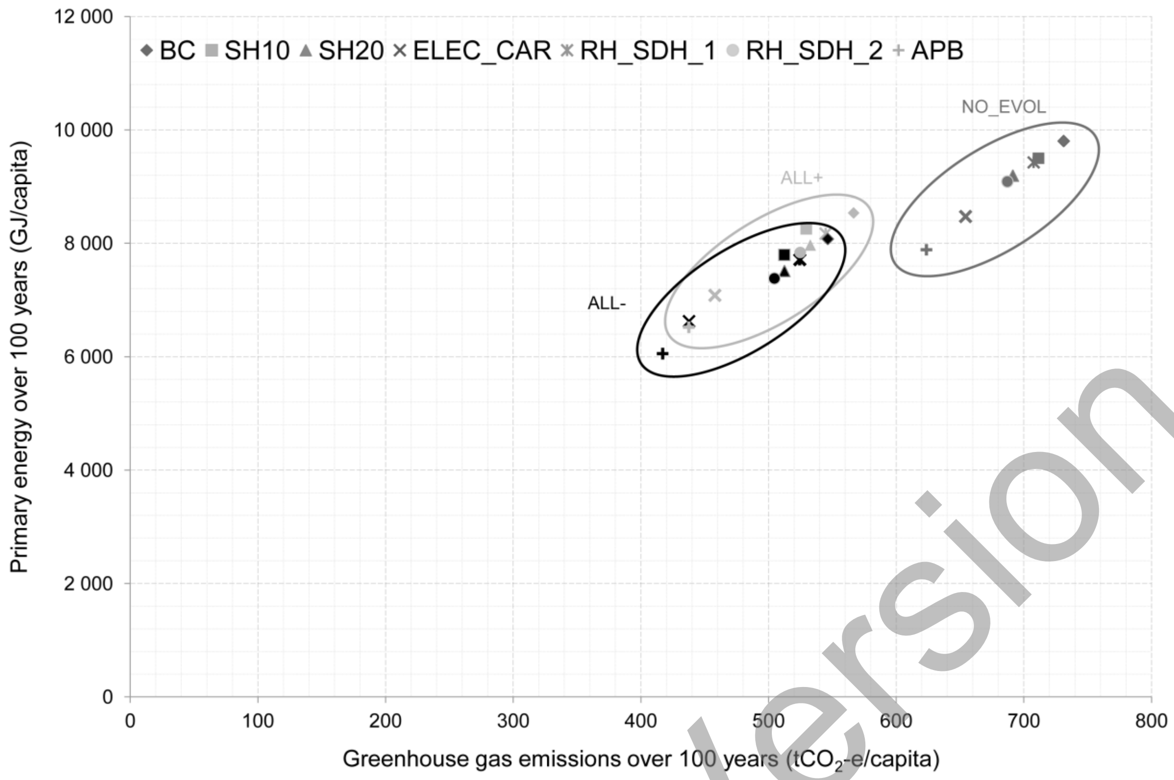

Figure 12: Life cycle energy demand and greenhouse gas emissions of the case study suburban neighborhood using evolution scenarios for key parameters, by scenario and per capita.

Also, the evolution of parameters over 100 years shows that if energy is produced from renewable sources at a neighbourhood level, a low density neighbourhood (e.g. SH10_ALL-), can have lower energy consumption (7 512 GJ/capita) and greenhouse emissions (512 tCO_2-e/capita) compared to a high density neighbourhood relying on conventional energy production (e.g. APB_NO_EVOL, 7 886 GJ/capita, 622 tCO_2-e/capita).

Finally, by analysing the evolution of parameters through time and the improvement of energy production, energy efficiency, transport modes and household appliances, the importance of the temporal allocation of greenhouse gas emissions emerges. As demonstrated by Kendal *et al.* [51] and Schwietzke *et al.* [52], greenhouse gases emitted in the coming decades have a more significant global warming potential compared to emissions in the future. When assessing all scenarios in a non-linear manner using ALL-, 40.5% of greenhouse gases (or 200 tCO_2-e/capita) will have been emitted within 30 years. Of these 200 tCO_2-e/capita, 29.5% are attributed to initial embodied emissions in building materials on average. Therefore the potential future improvements in energy production and efficiency might not be enough to abate greenhouse gas emissions and reduce the associated global warming since a significant amount of greenhouse gases will be emitted in the first 30 years. The selection of building materials with low embodied energy and greenhouse gas emissions, and the installation of on-site renewable energy production should be urgently supported to effectively reduce the environmental impacts resulting from energy consumption and greenhouse gas emissions. An example of using low embodied energy materials resulting in lower life cycle greenhouse gas emissions is the substitution of ceramic or steel building materials with wood-based products [21].

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 for residential buildings developed by Stephan *et al.* [24]. The analysis reveals that when considering wider system boundaries than in previous studies at the neighbourhood level, each of the embodied, operational and transport requirements are significant and none can be omitted from the assessment.

Results show that increasing population density while maintaining low-rise building typology 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 per capita as found by Carruthers and Ulfarsson [53]. 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. This finding is in line with the conclusions of Fuller and Crawford [10], Norman *et al.* [54] and Glaeser and Kahn [14].

Additionally, in the three housing typology scenarios only half of the built area was replaced with row and semi-detached houses or apartment buildings. If all the built area of the neighbourhood is replaced with apartment buildings, the total life cycle energy demand is reduced by 22.9% (compared to 19.6% if half of the built area is replaced). Therefore, the link between density and energy savings is not linear. It is likely that from a certain density, other measures should be investigated to reduce energy consumption and greenhouse gas emissions.

The modelling of the evolution of key parameters over time revealed the significant role of the energy source and energy efficiency of systems. A low density suburban neighbourhood that will increasingly rely on renewable energy sources and use energy efficient systems can have a lower energy demand and associated greenhouse gas emissions compared to a denser configuration that operates on traditional energy sources. This highlights the importance of relying on renewable energy source for energy production and the use of more efficient systems.

Also, the non-linear evolution of parameters in time highlighted the importance of the temporal allocation of greenhouse gases. As demonstrated by [51, 52], greenhouse gas emissions occurring in the near future have a greater global warming potential compared to those occurring in 50 years or more. The initial embodied emissions in building materials, which represent 29.5% on average of the total emissions at 30 years for the ALL- evolution scenario, should be reduced as they have a huge environmental impact.

This paper shows that each of the embodied, operational and transport requirements are individual levers that can be used to reduce the total energy demand and greenhouse gas emissions of neighbourhood. Individual measures, such as reducing the house size or relying on electric cars can only yield a limited reduction in total energy requirements and related emissions. All three levers have to be used simultaneously to ensure that net energy savings and greenhouse gas abatements actually occur, and are not simply shifted between categories of energy consumption.

New suburban neighbourhoods, built to accommodate the growth in city populations can have a reduced life cycle energy demand and result in less greenhouse gas emissions compared to typical low density developments. By relying on more compact housing that maintains architectural quality while reducing the living area per capita, building designers can reduce both the embodied and operational energy requirements. Also, by selecting low embodied energy and greenhouse gas emissions materials, such as recycled materials, renewable materials (e.g. bamboo), building designers can further reduce the environmental impact of the suburban neighbourhood. Denser configurations that support public transport while maintaining a low-rise typology can combine the benefits of a more efficient use of infrastructures and materials while being socially acceptable in the suburbs. The use of energy efficient transport modes such as electric cars can significantly reduce the overall energy demand, especially if electricity is locally produced by renewable energy sources such as solar energy. However, even then, the necessity for roads, parking spaces and other infrastructures, makes public transport more efficient. It is important to combine all of the measures above to effectively reduce energy consumption and greenhouse gas emissions at a neighbourhood level.

However, intensifying neighbourhoods also increases their energy demand per km² and thus their hinterland [55], which is the amount of land required to sustain the suburb in terms of food, energy, water and other primary needs. Since a very small part of these needs is produced in the neighbourhood, most of them have to be routed to the suburb. In their study of Denver, Colorado in the USA, Ramaswami *et al.* [56] have showed that these requirements can contribute significantly to the overall greenhouse emissions of a city. The increased complexity of the related supply chains of a denser neighbourhood could hinder its overall performance. Further research is required to determine the overall implications of intensification and to ensure that it does not push energy consumption and related environmental impacts outside the system boundaries used in this paper. An example of such research has been undertaken by Heinonen and Junnila [15, 16] for cities and metropolitan areas in Finland. They find that density is not correlated with a lower energy consumption per capita when all energy requirements are taken into account.

While this study has assessed the life cycle energy requirements of a suburban neighbourhood with a broad scope, it assumes that all buildings are always occupied. This assumption results in higher operational and transport energy requirements and associated greenhouse gas emissions. In a real case, it is very likely that not all buildings are occupied. This might affect the calculated density and other quantities and might influence the results. Also, while average figures have been used for operational energy (appliances, lighting, domestic hot water and cooking), and transport energy, a great variation can occur among different households. This has not been taken into consideration since this paper assesses the overall consumption of a neighbourhood. Relying on average figures is therefore suitable for this purpose.

The assessment suffers from considerable 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 energy figures and variability in operational and transport requirements could alter the findings. When comparing scenarios, the uncertainty in the results can be higher than the difference in figures. However, this paper very likely exaggerates the uncertainty in the data when comparing scenarios. Indeed, most parameters between two scenarios are similar, e.g. type of building materials, average operational energy demand for appliances, lighting, hot water, energy intensity of transport modes, etc.. Therefore, if one parameter deviates from the assumed value in one scenario, it does in the other, and the associated uncertainty should be removed when comparing both. Also, this paper uses interval analysis to take uncertainty into account. While being simple to implement, interval analysis attributes a flat distribution for the possible values of parameters. This tends to overestimate the uncertainty since many parameters will have a normal distribution, such as the indoor comfort temperature [33] used to determine heating and cooling degree hours. This means that the likelihood of one parameter having a value at the border of the interval is very low. In other terms, the probability of the uncertainty being near the boundaries is very low and likely the real value is situated around the nominal value. Unfortunately, there is currently no sufficient information to produce a probabilistic uncertainty model for the all the parameters taken into consideration in this work.

According to the simple approach used in this work to tackle uncertainty, the shares of embodied, operational and transport energy demands lie within, 15.3%-39.4%, 28.7%-52.5%, and 23.9%-46.0%, respectively. The most appropriate strategies for reducing the energy demand can therefore change depending on the actual contribution of each category of energy consumption. The long lifespan of buildings also makes the forecasting of energy consumption in the future very hard and subject to uncertainty. Nevertheless, even by considering uncertainty (which is very likely overestimated), the main finding still holds: an effective reduction in 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. While results give an indication of the most effective measures to implement in order to reduce these requirements, other environmental impacts, such as water demand, toxicity, and others should also be investigated.

Moreover, since this paper uses an Australian neighbourhood, other case studies, in different contexts should be assessed in order to verify the findings. Culture, infrastructure, technology, climate, and other aspects might influence 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. Using a case study near Melbourne, Australia, this paper shows that such developments are energy and greenhouse gas intensive in terms of embodied, operational and transport energy requirements. By intensifying such neighbourhoods, using alternative housing types, relying on public transport and renewable energy generation, the total requirements can be curbed and cities might be able to grow with a reduced environmental impact.

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