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Life cycle embodied, operational and mobility-related energy and greenhouse gas emissions analysis of a green development in Melbourne, Australia

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Abstract

At least 40% of the total greenhouse gas emissions driving environmental issues are related to the built environment, mostly because of energy coming from fossil fuels. In response, developments with an improved energy efficiency (e.g. so-called 'green' or 'net-zero energy' developments) have been built. Despite reductions in operational energy use in 'green' developments, previous studies have identified trade-offs in terms of embodied energy in construction materials and sometimes transport energy associated with the mobility of building users.

This research reconsiders the evaluation of green environmental claims through a life cycle approach. A multi-scale life cycle energy assessment software tool is employed to quantify the energy use and greenhouse gas emissions of a case study medium-scale green development in Melbourne, Australia over 50 years. Results show that the total life cycle energy use and greenhouse gas emissions of the development are 1,492 TJ (2,688 GJ per capita and 107 GJ/m² of GFA) and 81 ktCO$_2$-e (146 tCO$_2$-e per capita and 6 tCO$_2$-e/m² of GFA), respectively, compared to 2,220 TJ (4,001 GJ per capita and 159

GJ/m² of GFA) and 177 ktCO_2-e (318 tCO_2-e per capita and 13 tCO_2-e/m² of GFA) for a business-as-usual development with the same geometry. In fact, each of the embodied, operational and transport energy requirements represents an important contribution to the life cycle energy: 31%, 35% and 34%, respectively. Therefore, all life cycle stages and scales of the built environment are relevant to the overall energy and greenhouse gas emissions performance of green developments.

Keywords

Life cycle assessment; Neighbourhood; Embodied energy; Embodied carbon; Transport energy; Planning policy.

1. Introduction

Research on the environmental performance of the built environment has increased in significance over the last decades. Cities are responsible for nearly 70% of the total global greenhouse gas emissions [1], which drive global warming and climate change. The construction and operation of buildings are responsible for at least 36% of global final energy demand and approximately 40% of total direct and indirect CO_2 emissions [2], as most of this energy comes from fossil fuels. With two-thirds of the world population expected to reside in cities by 2035 [3], there is a critical need to deliver urban settlements with an improved environmental performance if we are to reduce greenhouse gas emissions as specified in Goal 11 of the United Nations 2030 Agenda for Sustainable Development [4].

Greenhouse gas emissions along with escalating pollution, the exhaustion of fossil fuels and the derived threat to climate have served as strong incentives for an increased focus in planning energy-efficient cities [4]. More is now known about the key drivers of energy use in the built environment, such as elements of the design and planning across scales: locally, regionally and globally. And the more these drivers are understood, the more prominent so-called 'green' developments which claim an improved environmental performance appear as a strategy to reduce energy use and the associated greenhouse gas emissions [5].

However, cities and buildings are complex systems and the full effects of the built environment on energy use and greenhouse gas emissions go beyond their operational phase, extending to all embodied environmental flows in materials (i.e., resources for raw material extraction, manufacturing, processing and transportation) in man-made structures and infrastructure, as well as transportation

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systems [6]. Integrated solutions are required to address this complexity. Hence, a systems-thinking approach [7, 8] is needed to better understand the improvements expressed by green developments.

There is no consensus on a definition for the label 'green' in relation to the built environment. From an energy-efficiency perspective, a core reference is the notion of net-zero energy building (NZEB) offered by the Intergovernmental Panel on Climate Change [9]. This is defined as a building that over a year generates as much energy as it uses, through renewable energy systems (i.e., solar photovoltaic panels, solar thermal, wind turbines, geothermal, among others). However, green development notions mostly focus on the operational phase and only a few consider the embodied and user-transport energy flows. Although green developments aim to surpass the minimal conditions for greenhouse gas emissions reduction established by scientists of the IPCC [10], a comprehensive analysis should be encouraged to validate the reliability of their claims of greater environmental performance. Hence, it is critical to achieve environmental performance across the life cycle of a building and across scales of the built environment, as opposed to solely during one phase or at one scale [11].

Numerous proforma energy reduction strategies (i.e., super-insulated building envelopes and on-site renewable energy sources) bear an embodied energy penalty that is left out of the zero-energy equation, giving rise to a trade-off in total energy use, from one life cycle stage to another [12-14]. In addition, transport energy demand related to the mobility of the users has been seldomly taken into consideration [15, 16]. In light of potential energy offsets across phases of the life cycle, there is a need to further develop and apply an integrated analysis to inform planning through life cycle assessment (LCA) and ensure that green developments achieve net life cycle environmental benefits.

1.1. Aim and scope

This research employs a multi-scale life cycle energy and greenhouse gas emissions assessment framework (MSLCEA) [11, 18] to quantify the energy use and greenhouse gas emissions of the Nightingale Village: an upcoming medium-scale green development in Melbourne, Australia. As such, the embodied, operational and user-transport energy flows of all buildings and users of the development are estimated over a period of 50 years. The main goal is to quantify and characterise the life cycle energy use and greenhouse gas emissions of green developments to help researchers, urban planners, developers, and consultants analyse the environmental performance of projects that claim green environmental credentials and propose solutions that result in a net increase in environmental performance. A broad scenario modelling, varying environmental and mobility-related parameters is conducted to broaden the applicability of the results to other locations and to identify critical parameters.

2. Existing life cycle assessment studies at the neighbourhood scale

Along with statistical models and simulations, life cycle assessment (LCA) is the conventional approach to quantify the environmental performance of the built environment across scales: buildings, neighbourhoods and cities. [19]. LCA is a standardised methodology that allows the study of a system from its production to its end of life. The assessment includes all the environmental effects of the system, including raw material extraction, manufacturing, transport, use, reuse, maintenance, recycling and final disposal. The methodology for LCA is described through a four-step framework defined in the ISO 14040:2006 [20]. First, the goal and scope of the evaluation are provided, including a definition of the system, functional units and boundaries. Subsequently, the inventory analysis is performed, listing the inputs and outputs related to the system at each stage of the life cycle. Following, an impact assessment is conducted using a set of indicators of the environmental effects of the system. Finally, the interpretation of findings enables opportunities for reductions of the environmental effects of the system.

The life cycle inventory (LCI) is a major determinant of the robustness of the methodology. There are three main methods to compile an LCI: process-based analysis, input-output analysis and hybrid-based analysis [21]. Process-based analysis is a bottom-up approach, where the system is dissected in a series of processes that constitute the life cycle. Input-output analysis is a top-down approach, which is informed by macro-economic analysis based on the economic sector associated to the system. Hybrid analysis, which is a combination of the first two approaches, attempts to address the data deficits of the other methods by using process data and filling in the gaps with input-output data. A detailed review of hybrid LCIs is provided in Crawford, et al. [21].

There is an inherent complexity in compiling all elementary flows related to the built environment. As such, most LCA studies of green developments at the neighbourhood scale are process-based analyses (see Table 1). Consequently, they carry the aforementioned shortfalls of this method, namely the underestimation of embodied energy [22]. In contrast, hybrid analysis is systemically complete and considers the whole supply chain, while incorporating detailed process data where available.

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A compilation of LCA studies of the built environment at the neighbourhood scale can be found in Lotteau, et al. [23] and Mastrucci, et al. [24]. In light of this review, the scarcity of LCAs focused on green developments emerges. Only Forsberg [25], Herfray, et al. [26] and Lausselet, et al. [27, 28] have performed LCAs on green developments through case studies in *Hammarby Sjöstad*, Sweden; *Freiburg*, Germany; and, *Bergen*, Norway respectively. Moreover, the review provides the scope of each study highlighting their limitations. By expanding this review and adding the LCI, it becomes apparent that these studies tend to rely on process-based life cycle inventories and as such do underestimate embodied flows, compared to using hybrid analysis. A more detailed summary of the existing literature is presented in

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Table 1. In light of the above, there is no study in the Australian context that has focused on a green development at a neighbourhood scale, using a hybrid LCI approach to quantify its life cycle energy use and greenhouse gas emissions performance.

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Table 1. Key analysis points of LCA studies at the neighbourhood scale.

Reference	Year of publication	Location	Case study	Size (km²)	Residential density (inhab./km²)	Scope	Period of analysis	LC stages	Type of neighbourhood	LCI method	Green development
Stephan *et al.* [30]	2013	Melbourne (Australia)	1	1.5	500	– B – OS – N – M	100	– Cons. – Op.	100% residential	H	X
Nichols, Kockelman [31]	2014	Austin (USA)	4	13.1 1.7 2.2 1.3	370 2 040 2 200 5 940	– B – OS – N – M	NA	– Cons. – Op.	91% residential 91% residential 71% residential 90% residential	P	X
Norman, et al. [32]	2006	Toronto (Canada)	2	NA NA	27 000 5 700	– B – OS – N – M	50	– Cons. – Op.	100% residential	IO	X
Forsberg [25]	2003	Hammarby Sjöstad (Sweden)	1	NA	NA	– B – OS – N – M	NA	– Cons. – Op.	100% residential	P	✓
Riera Perez, Gracia. [33]	2013	Lausanne (Switzerland)	1	0.07	14 700	– B – M	60	– Cons. – Op. – Decons.	97% residential	P	X
Davila, Reinhart [34]	2013	Cambridge (USA)	1	NA	NA	– B	100	– Cons. – Op. – Decons.	100% residential	P	X
Cherqui [35]	2005	La Rochelle (France)	1	0.02	32 500	– B	80	– Cons. – Op. – Decons.	100% residential	P	X
Colombert, et al. [36]	2011	Paris (France)	1	0.15	NA	– B – OS – N	80	– Cons. – Op. – Decons.	Mixed-use 36 670 m² dwellings 40 000 m² offices 6 500 m² activities 1 000 m² shops 15 000 m² public equipment	P	X
Herfray, et al. [26]	2011	Freiburg (Germany)	2	0.024 0.039	16 400 10 100	– B – OS – N	80	– Cons. – Op. – Decons.	Mixed-use 66% residents 20% employees 17% students	P	✓
Herfray, Peuportier, Roux, [37]	2011	Marne La Vallée (France)	1	0.095	9 340	– B – OS – N	80	– Cons. – Op. – Decons.	Mixed-use 39% residents 51% employees 10% students	P	X
Peuportier, et al. [38]	2006	Lyon (France)	1	NA	NA	– B – OS – N	80	– Cons. – Op. – Decons.	Mixed-use 60 000 m² dwellings 15 000 m² offices	P	X
Lausselet, et al. [27]	2018	Bergen (Norway)	1	0.092	14 565		60	– Cons. – Op. – Decons.	Mixed-use 85 164 m² dwellings 2 833 m² offices 1 061 m² schools 2 833 m² shops	P	✓
Lausselet, et al. [28]	2019	Bergen (Norway)	4	NA	NA	– B – OS – N – M – OE	60	– Cons. – Op.	100% residential	P	✓
Stephan and Athanassiadis [29], [39]	2017; 2018	City of Melbourne (Australia)	1	36.2	111 497	– B – OS – N – M	100	-Cons.	Mixed-use Offices/Education/Retail: 10.51 M m²	H	X

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Apartments: 8.93 M m²

Parkings: 6.47 M m²

Warehouses: 2.52 M m²

House/Townhouse: 1.71 M m²

Retail: 1.66 M m²

Hospital: 1.02 M m²

Source: Adapted from Lotteau, et al. [23] and Mastrucci, et al. [24]

Note: Scope – buildings (B), open spaces (OS), networks (N), mobility (M), on-site energy (OE). Life cycle inventory (LCI) – process-based (P), input-output (IO) and hybrid approach (H).

Considering the lack of assessments that integrate a holistic approach for the appraisal of green developments, the use of a comprehensive multi-scale life cycle energy assessment is needed to validate the reliability of green environmental claims in terms of energy use and greenhouse gas emissions. This study proposes to conduct this assessment in the Australian context, using the Nightingale Village in Brunswick, Victoria as a case study, and specifically, investigate the extent to which green developments might achieve a net-zero life cycle energy and greenhouse gas emissions performance across different scales using a hybrid approach to quantify it.

3. Method

3.1. Case study description: The Nightingale Village in Brunswick, Victoria.

In order to analyse the net environmental performance of green developments in the Australian context, a single-case study located in Brunswick, Victoria is used: The Nightingale Village. The development follows the Nightingale model [40] which is aligned with the three dimensions of sustainability [41], aiming to deliver homes that are environmentally, socially and financially sustainable. The environmental dimension is the main focus of this research.

The Nightingale Village is set to be the first attempt to progress the Nightingale model beyond the individual building scale. The development is expected to be finalised in 2021, and will deliver 185 dwellings and integrated services within 6 mixed-use multi-storey buildings and supporting ground level services across Duckett street and the rear laneways [40]. Assuming an average of 3 users per dwelling, the development will host approximately 555 residents. The total gross floor area (GFA) is 14,000 m², the site plot area is 0.005 km² and the computed density is 111,000 inhabitants per km². Illustrations of

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the development and its context can be found in Figure *1*. This is an appropriate instance for a revelatory single-case study [42] as it is an Australian development marketed as a 'green' development at the neighbourhood scale.

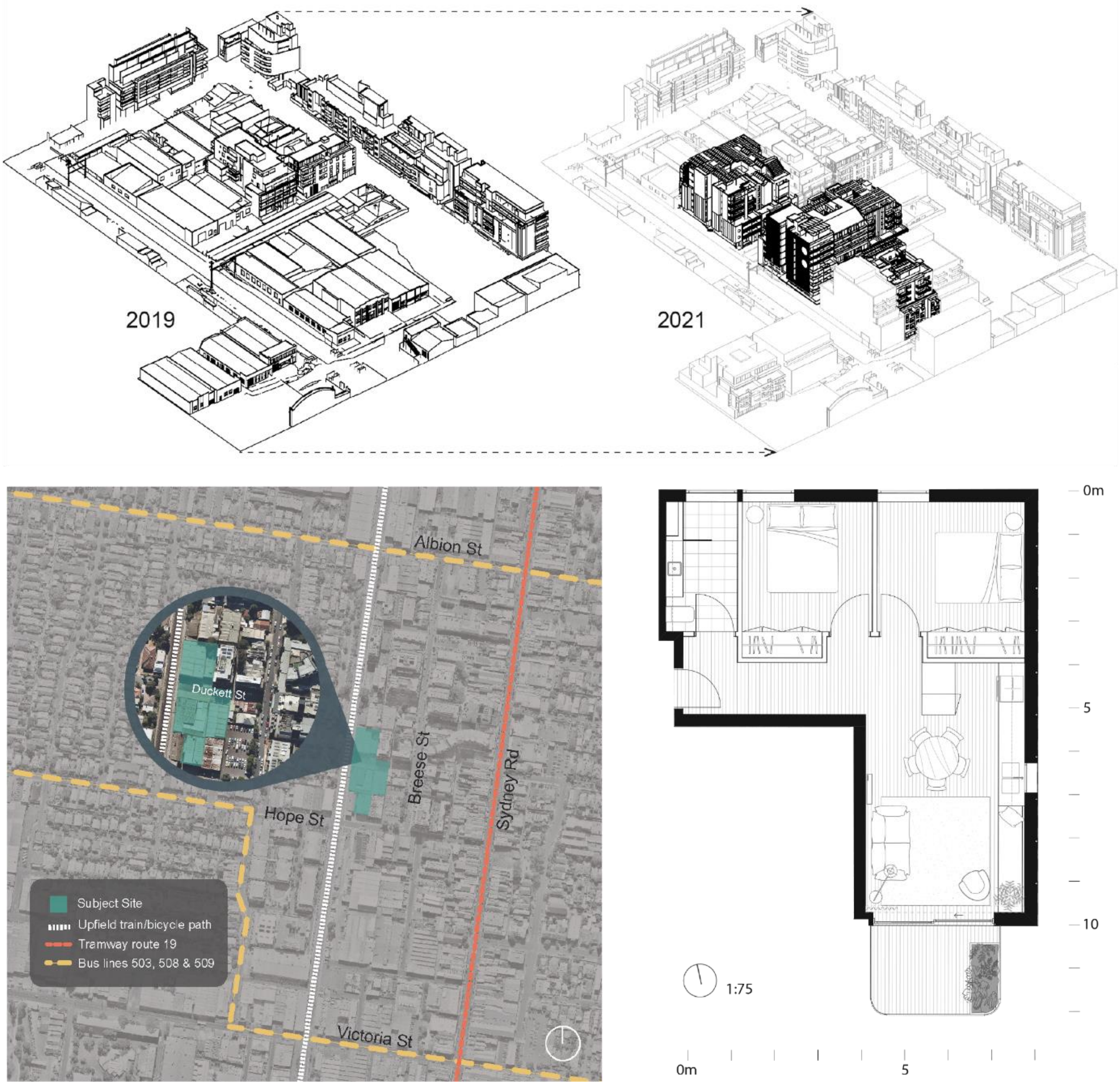

Figure 1 *Nightingale village master, context and sample floor plans.*
Source: Adapted from Moreland City Council *[43]*

The Nightingale Village is advertised as a green development following a comprehensive sustainability strategy [44] that touches on the embodied, operational and transport phases of the life cycle. Green environmental credentials are claimed through a minimum 7.5 Stars on the Nationwide House Energy

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Rating Scheme (NatHERS) rating (out of a maximum of 10 Stars) and an average 80% Built Environment Sustainability Scorecard (BESS) rating across all buildings [45].

Through a materiality reductionist approach [46] the development aims to reduce embodied energy. Operational energy is addressed through passive and active design strategies that aim to improve the building envelope thermal performance without relying on fossil fuels. In addition, a heat pump system is proposed for the provision of heating and domestic hot water. Other elements such as 93% of cross-ventilated units and on-site renewable energy generation [40] are incorporated to reduce energy use from the grid.

A reduction in transport energy is targeted by encouraging the future 555 residents to favour active and public transport modes. The development is located within walking distance to Anstey train station, route 19 tramway and multiple bus routes along Hope and Albion Street; these connections are illustrated in Figure *1***Error! Reference source not found.**. Furthermore, a reduction in the availability of total car parking to 6 private parking spaces combined with the provision of 14 car-share spaces and 526 bicycle spaces aim to reduce the reliance of occupants on private cars [40, 47].

Analysing the Nightingale Village using the proposed research methodology enables a comprehensive perspective on the energy and greenhouse gas emissions performance of the case-study, eliciting the key parameters that drive improvement in green developments.

3.2. Overall modelling approach

Compiling the data (e.g. bill of material quantities) required to conduct a life cycle energy analysis for an upcoming development can be a time-intensive and prohibitive endeavour; especially during the early design stages when specific building details are yet to be defined. Through computer assisted modelling this process can be streamlined, ensuring a systematic approach with the advantage of isolating key variables.

To address the aim of this research the Nightingale Village (NV) and a business-as-usual (BAU) case are modelled using Energy Metric (Beta 0.2), the advanced software tool developed by Stephan [11]. Energy Metric is a software program that enables conducting an integrated life cycle energy and greenhouse gas emissions analysis of buildings and neighbourhoods. The user interface serves as an input-output channel for the computing core which exchanges information with a set of databases;

subsequently, a plotter module produces graphic representations of the results. This tool allows specifying the dimensions of each building, estimating bill of quantities parametrically, varying the number of occupants and estimating the initial and recurrent embodied energy as well as the operational and transport energy flows over a specified period of analysis. Detailed information is available in Stephan [11].

The materials and construction assemblies of the case study are informed by the architectural plans and materiality schedules included in the planning application documentation advertised by Moreland City Council [43], to ensure the broadest possible representativeness. Table *2* contains the characteristics of the six buildings of the Nightingale Village. These comprise: exposed precast concrete sandwich panel walls with no render and an average 3 m height between floors; window to wall ratios varying from 60% to 80% depending on the number of main, blind and shared facades; medium standard finishes and high standard balconies from the Rawlinsons [48] construction cost guide as representative samples for costing purposes; insulation thicknesses based on achieving the R-values described on the ESD reports submitted to Moreland City Council; and, appliance efficiencies based on the most representative technology in Victoria, Australia [49]. In a similar manner the characteristics of the business-as-usual case, which is modelled according to conventional construction techniques present in neighbouring developments (based on [50]), are presented in Table *2***Error! Reference source not found.**. The BAU case provides a standard benchmark against which the green development can be compared.

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Table 2. Characteristics of the Nightingale Village

Characteristic	Business-as-usual	Nightingale Village
Average unit area	71.6 m² (including a 6 m² balcony)	
Number of units	195 (distributed across 6 buildings: 25, 27, 27, 35, 40, 41)	
Household size (number of occupants per unit)	3	
Height between floors	3 m	
Location	Brunswick, Victoria, Australia	
Period of analysis (years)	50	
Structure type	Concrete columns/beams; hollow core 18 cm slab with 7 cm concrete	Concrete columns/beams; reinforced concrete slab on ground
Façade	Heavyweight prefabricated concrete wall (with 20mm of EPS insulation) U-value= 1.18; single glazed aluminium framed windows (60% window to wall ratio) U-value= 5.8	Exposed precast concrete sandwich panel with no render (with 130 mm of EPS insulation) U-value= 0.25; double glazed aluminium framed windows (60% and 80% window to wall ratios) U-value= 1.2
Roof	Reinforced concrete roof (with 75 mm of EPS insulation) U-value= 0.4	Reinforced concrete roof (with 275 mm of EPS insulation) U-value= 0.125.
Flooring	Nylon carpets in bedrooms and living areas; ceramic tiles in wet areas; epoxy flooring in car parking.	Recycled hardwood timber flooring in bedrooms and living areas; precast terrazzo tiles for wet areas.
Internal walls	Timber framed internal walls with plasterboard	Timber framed internal walls with plasterboard
Operational energy sources	Reverse cycle heating/cooling (COP: 3.0) and gas cooking (eff.: 90%), gas DHW (eff.: 90%); natural ventilation	Heat pump (COP: 3.0) for hydronic heating and DHW; electric cooking system (eff.: 100%); mixed natural/mechanical ventilation (fans eff.: 90%).
Ventilation rate (hrs/day), mechanical and natural	3	0.25, 0.5
PV solar panels	NA	Monocrystalline (1.2 x 1.8 m)
Number of PV panels (per unit)	NA	2
PV solar fraction	NA	10.4%
Primary Energy Conversion factor for electricity	3.4 (Victorian grid)	1.7 (Hydro Tasmania)
Greenhouse gas emissions factors	Gas: 59.99 $kgCO_2e/GJ^{PRIMARY}$; Electricity: 93.11 $kgCO_2e/GJ^{PRIMARY}$	Electricity: 5.4 $kgCO_2e/GJ^{PRIMARY}$

Note: domestic hot water (DHW), photovoltaic (PV), efficiency (eff.), coefficient of performance (COP)

The system boundaries of this work account for energy and greenhouse gas emissions flows related to all phases of the life cycle over 50 years, with the exception of the end-of-life phase as this often represents less than 1% of the total life cycle energy use [13, 51, 52].

The estimated primary energy conversion factor (PEF) for electricity supplied by Hydro Tasmania (1.7 $\frac{GJ\ \text{primary}}{GJ\ \text{delivered}}$) amounts to half of the Victorian electricity grid factor (3.4 $\frac{GJ\ \text{primary}}{GJ\ \text{delivered}}$). This is attributed to the energy mix profile which is 91% pumped hydro and 9% gas (LPG), as opposed to the brown-coal-fuelled Victorian grid. Accordingly, the calculated greenhouse gas emissions factor for Hydro Tasmania (5.4 $kgCO_2$-e/GJ) is considerably less than that corresponding to the Victorian Grid (93.11 $kgCO_2$-e/GJ).

Afterwards, we vary key parameters to generate scenarios and insights necessary to evaluate the environmental performance of green developments. These 'what-if' scenarios [53] are presented in Table 3. Subsequently, the compilation of results and robustness evaluation are performed along with a sensitivity analysis to account for uncertainty and variability in the data. Finally, the interpretation of findings identifies key drivers and further opportunities for reducing the environmental effects of green developments. An outline of the method is provided in

Figure 2.

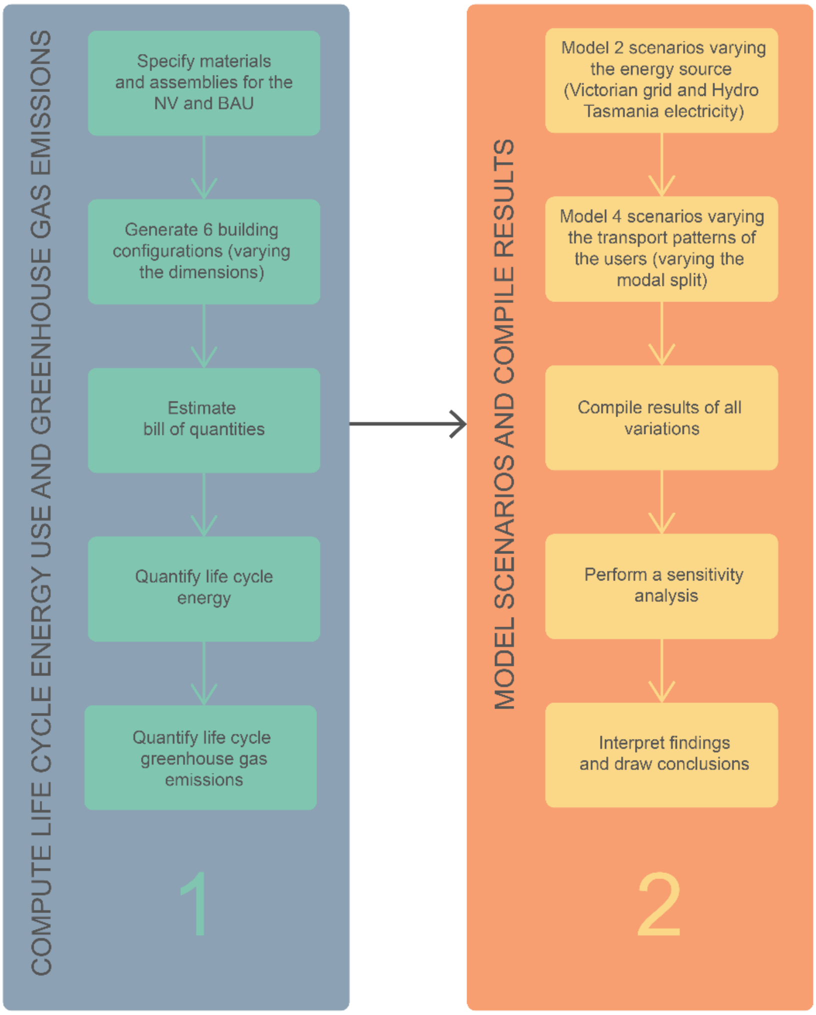

Figure 2 Flowchart diagram of the method.

3.3. Quantifying embodied energy and greenhouse gas emissions

Embodied energy is assessed based on the path-exchange method for hybrid analysis. This LCI method is detailed in [54] and [55] and is automated in [56]. The calculations rely on the EPiC database developed by Crawford *et al.* [57], for construction materials in Australia. Hybrid coefficients are multiplied by the quantity of materials used. Non-material inputs such as advertising and insurance are also taken into consideration; an additional embodied energy factor is added to account for these energy inputs. In a similar manner, recurrent embodied energy related to material replacements is considered based on the service life of each particular material. The same applies for embodied greenhouse gas emissions. The calculations are performed through the algorithm developed by Stephan [11], and automated in the Energy Metric software:

$$LCEF_d = \sum_{b=1}^{B}\sum_{u=1}^{U}\sum_{a=1}^{A}\sum_{m=1}^{M}(Q_{m,a,u,b,d} \times FC_m) + [(TFRRBS - \sum_{m=1}^{M} TFR_m) \times C_{u,b,d}] + \sum_{b=1}^{B}\sum_{u=1}^{U}\sum_{a=1}^{A}\sum_{m=1}^{M}[\left[\left[\frac{POA}{SL_m} - 1\right]\right] \times [(Q_{m,a,u,b,d} \times FC_m) + [(TFRRBS - TFR_m - NATFR_m) \times C_{m,a,u,b,d}]]]$$

Eq. 1

Where:

$LCEF_d$ = Life cycle embodied flow of the development (e.g. in GJ for energy) GJ; B = Total number of buildings in the development; U = Total number of apartment units in a building; A = Total number of construction assemblies in a building; M = Total number of materials in an assembly; $Q_{m,a,u,b,d}$ = Quantity of material *m* in assembly *a* in unit *u* within building *b*, located in development *d* (e.g., m^3 of timber window frames, in a unit within the Nightingale Sky House located in Nightingale Village); FC_m = Hybrid flow coefficient of material *m*, in environmental flow unit (e.g. GJ for energy) per functional unit; *TFRRBS* = Total environmental flow requirement of the residential building sector, in flow unit/AUD (e.g. GJ/AUD for energy); TFR_m = Total environmental flow requirements of the input-output pathway representing material *m*, in flow unit/AUD (e.g. GJ/AUD for energy); $C_{u,b,d}$ = Cost of unit *u* in building *b* in development *d*, in AUD; *POA* = Period of analysis, in years; SL_m = Service life of the material *m*, in years; $NATFR_m$ = Total environmental flow requirements of all input-output pathways not associated with the installation or production process of material *m* being replaced, in flow unit/AUD (e.g. GJ/AUD for energy); and, $C_{m,a,u,b,d}$ = Cost of the material *m* in assembly *a* in unit *u* within building *b* located in development *d*, in AUD.

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3.4. Quantifying operational energy and greenhouse gas emissions

Annual operational energy is calculated using the algorithm described in Stephan [11]. This is based on steady-state thermodynamic equations, which are adequate to use in cooling-dominated climates (such as in Melbourne) and for urban building energy modelling [59]. Thermal energy use for comfort temperatures indoors of 20°C and 26°C for heating and cooling are calculated using heat transfer equations by taking the heat transfer coefficient (U-value related to the building envelope) and multiplying it by the heating or cooling degree hours and the building heat loss area. Solar gains are also considered. Accordingly, multiplying the average ventilation rate by the thermal volume capacity of air and the heating and cooling degree hours yields the ventilation losses and gains.

Non-thermal energy use (i.e., for lighting, domestic hot water, appliances, etc.) are sourced from average local data published by the Department of Environment and Energy [49]. Domestic hot water (DHW) daily use is based on a hot water temperature of 55°C, an initial water temperature of 12°C, and 70 litres per capita. Energy used for lighting depends on the floor area of the average unit. All energy demand are assumed to be constant over the period of analysis (50 years). Finally, they are converted to primary energy based on the energy source.

$$LCPOPE_d = POA \times \sum_{b=1}^{B}\sum_{u=1}^{U}\sum_{e=1}^{E}\left(1 - SF_{e,u,b,d}\right) \times \frac{FOPE_{e,u,b,d}}{\eta_{e,u,b,d}} \times PEF_e$$

Eq. 2

Where: $LCPOPE_d$ = Life cycle primary operational energy of the development *d*; B and U are defined in Eq. 1; E is the total number of operational energy end-uses; *POA* = Period of analysis; SF_e = Solar fraction for the end-use *e* in unit *u* in building *b* in the development *d* in GJ (e.g. 0.2); $FOPE_{e,u,b,d}$ = Yearly operational final energy demand of the end-use *e* in unit *u* in building *b* in the development *d* in GJ; $\eta_{e,u,b,d}$ = Average efficiency of the end-use *e* in unit *u* in building *b* in the development *d*; and, PEF_e = Primary energy conversion factor for the energy source of the end-use *e* in $GJ^{PRIMARY}/GJ^{DELIVERED}$.
Operational greenhouse gas emissions are obtained by multiplying the primary operational energy use by a relevant greenhouse gas emissions factor [60], depending on the energy source, as per Eq. 3.

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$$LCOPGHG_d = \sum_{s=1}^{S} LCPOPE_{s,b} \times EF_s$$

Eq.3

Where: $LCOPGHG_b$ is the life cycle operational greenhouse gas emissions of the development *d* in $kgCO_2e$; S is the total number of fossil energy sources used in the development; $LCPOPE_{s,b}$ is the life cycle primary operational energy demand associated with source *s*, used in development *d*, in $GJ^{PRIMARY}$; and EF_s is the greenhouse gas emissions factor of source *s* in $kgCO_2e/GJ^{PRIMARY}$.

3.5. Quantifying transport energy and greenhouse gas emissions

Transport energy use comprises direct and indirect requirements [61]; both should be multiplied by the average travel distances of building occupants for every transport mode to obtain the total transport energy use. Transport modes considered in this work include private vehicles (petrol cars), trains, trams, buses and active transport (bicycles, walking and other transport modes [e.g., skateboards]). The need to consider mobility-related environmental flows is discussed in detail in [18, 62, 63].

First, the annual average local travel distances are sourced from the Victorian integrated survey of travel and activity (VISTA) [64]. Afterwards, the distances are collated with census population figures of the neighbourhood to obtain the annual local travel distances per capita. These are then multiplied by the direct and indirect energy and greenhouse gas emissions intensities for each transport mode [65] and the number of users in the development. Finally, the life cycle transport energy is calculated according to Eq.4:

$$LCTE_d = \sum_{y=1}^{POA} (TEC_{y,d} + TEP_{y,d})$$

Eq.4

Where: $LCTE_d$ = Life cycle transport energy of the development *d*; *POA* = Period of analysis; *y* = year of period of analysis; $TEC_{y,n}$ = Transport energy of cars associated to the development for year *y*, in GJ; and, $TEP_{y,n}$ = Public transport energy use associated to the development for year *y*, in GJ.

Use-transport greenhouse gas emissions are calculated using direct and indirect greenhouse gas emissions intensities for cars [66], and by converting the direct energy use of trams an trains into greenhouse gas emissions, considering the primary energy conversion factor and the greenhouse gas emissions intensity of the Victorian electricity grid. The remaining indirect greenhouse gas emissions for public transport are also sourced from [66].

3.6. Quantifying life cycle energy and greenhouse gas emissions

The life cycle energy demand and greenhouse gas emissions of the development and its users are the sum of its embodied, operational and transport life cycle energy use and greenhouse gas emissions, respectively. This is calculated through the following algorithm for primary energy (and the same for greenhouse gas emissions, by replacing energy with greenhouse gas emissions):

$$LCE_d = LCEE_d + LCPOPE_d + LCTE_d$$

Where: LCE_d = Life cycle energy demand of the development *d,* in GJ; $LCEE_d$ = Life cycle embodied energy demand of the development *d,* in GJ; $LCOPE_d$ = Life cycle operational energy demand of the development *d*, in GJ; and, $LCTE_d$ = Life cycle transport energy demand of the development *d,* in GJ.

Yet, key parameters such as greenhouse gas emissions factors, primary energy conversion factors, the energy intensities for each transport mode, and the annual travel modal splits are likely to evolve over the period of analysis (e.g., due to technical improvements). These are considered by relying on scenario forecasts.

3.7. Parametric variations and scenario modelling

To understand the energy and greenhouse gas emissions performance of the case study in relation to its context, a base case scenario representative of building techniques of the adjacent developments (i.e., without the special emphasis on passive design and on-site renewable energy generation) is modelled following the same dimensions of the Nightingale Village.

As part of a stringent zero fossil fuels policy [40], the Nightingale Village aims to fully operate on electricity purchased from Hydro Tasmania. Accordingly, a scenario adjusting the primary energy and greenhouse gas emissions factors is modelled.

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Moreland average annual travel distances from 2012-2016 serve as a baseline for modelling transport energy use scenarios [64]. The case study (labelled NV-HT75C) was modelled assuming a 75% reduction of private car use derived from the lack of parking spaces as well as the special emphasis placed on public transport and bicycle use [47]. Additionally, scenarios accounting for 25%, 50% and 100% reductions in car use are developed as part of the sensitivity analysis. The resulting travel modal splits are displayed in Figure 3. A summary of all scenarios can be found in Table 3. Finally, the analysis of these scenarios supports the external validity (extrapolation) of the results to other contexts.

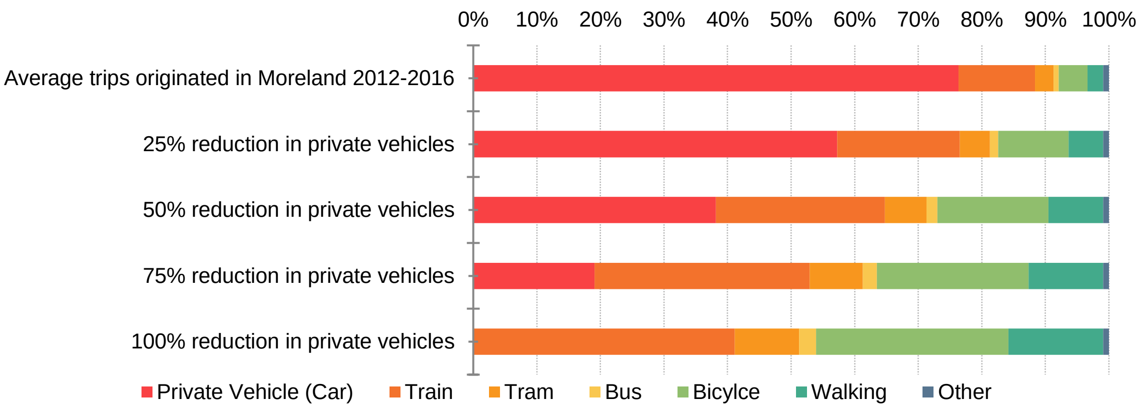

Figure 3 Total distance for trips originating on site, modal split.

Table 3. Scenarios modelled to analyse the energy and greenhouse gas emissions of the Nightingale Village.

Scenario	Description
Business-as-usual (BAU)	Building materiality informed by neighbouring developments mirroring the dimensions of the Nightingale Village. Energy source: Victorian grid.
Nightingale Village 1 (NV-BC)	Model with same transport patterns as Moreland baseline. Energy source: Victorian grid.
Nightingale Village 2 (NV-HT25C)	Model with 25% reduction of private car travel distances divided equally between public and active transport. Energy source: Hydro Tasmania.
Nightingale Village 3 (NV-HT50C)	Model with 50% reduction of private car travel distances divided equally between public and active transport. Energy source: Hydro Tasmania.
Nightingale Village 4 (NV-HT75C)	Model with 75% reduction of private car travel distances divided equally between public and active transport. Energy source: Hydro Tasmania.
Nightingale Village 5 (NV-HT100C)	Model with 100% reduction of private car travel distances divided equally between public and active transport. Energy source: Hydro Tasmania.

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3.8. Uncertainty and variability

Uncertainty and variability in the data are quantified using interval analysis. The technique establishes a symmetrical nominal value in the form of a range to encompass energy and greenhouse gas emissions figures. For embodied environmental flows, a range of ±20% is used for the process-based part of the data and ±50% for the input-output data based on Lenzen [67]. This results in an average uncertainty of more or less ±40%. For the operational and transport components a range of ±20% is set based on Pettersen [68].

There is uncertainty related to the potential technological innovations likely to occur over the period of analysis. Therefore, it is likely that some key factors including the primary energy conversion factor for electricity, the associated greenhouse gas emissions factors, the energy efficiency of appliances and the energy intensity of different transport modes are subject to evolution over the period of analysis. However, estimating the evolution of these parameters in detail is outside the scope of this work.

3.9. Data Sources and Availability

Notwithstanding the limited academic research on Nightingale developments, the model has drawn significant attention in the media and industry conferences [69]. Public discussion offers a favourable setting for data collection [42]. Documentation detailing the development was systematically collected from the Nightingale website, as well as the publicly advertised plans by Moreland City Council. A detailed summary of the data sources required to perform the assessment is presented in Table 4.

Table 4. Data sources used in the multi-scale life cycle energy assessment of the Nightingale Village.

Data	Source
Architectural drawings of each building of the Nightingale Village	Moreland CC [43]
Direct and indirect energy intensities for each transport mode	Lenzen [65]
Environmental Performance in Construction (EPiC) hybrid coefficients database for construction materials in Australia	Crawford [70]
Nightingale Village master plan	Moreland CC [43]
Nightingale Village general information	Nightingale Housing LTD [40]
Operational non-thermal requirements	DEWHA [49]
Primary energy to greenhouse gas emissions conversion factors	Crawford [71], Treloar [72], Hydro Tasmania [73] and Ecofys [74]
Energy Metric (Beta 0.2) software tool	Stephan [75]
Nightingale Village sustainability strategy	Moreland CC [43]
Yearly average travel distances	Department of Transport [64]

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The data used in this paper are available in open-access on Figshare[1] [76]. These include:

- A list of all assemblies and materials used in the business-as-usual and the Nightingale Village models
- All results and calculations that were performed on data obtained from Energy Metric
- Calculations of greenhouse gas emissions factors.
- Additional charts representing the results

4. Results

4.1. Life cycle energy and greenhouse gas emissions

The life cycle energy (LCE) and greenhouse emissions (LCGHG) of the Nightingale Village and all modelled scenarios pertaining to this work are displayed in Figure 4, Figure 5 and Figure 6 by breakdowns per life cycle stage and end use. First, NV-HT75C is analysed in relation to the business-as-usual case (BAU). The scenario sourcing energy from the Victorian grid (NV-BC) is also examined.

The LCE and LCGHG of the NV-HT75C over 50 years represent 1,492 TJ (2,688 GJ per capita and 107 GJ/m² of GFA) and 81 ktCO_2-e (146 tCO_2-e per capita and 6 tCO_2-e/m² of GFA), respectively. Accordingly, these figures for the BAU case amount to 2,220 TJ (4,001 GJ per capita and 159 GJ/m² of GFA) and 177 ktCO_2-e (318 tCO_2-e per capita and 13 tCO_2-e/m² of GFA). Hence, the life cycle energy use is reduced by 33% and the associated greenhouse gas emissions savings are 54%. In this instance, the energy requirements for each life cycle stage are nearly equivalent; 32% for LCEE and 34% for LCOPE and LCTE, respectively. However, in terms of greenhouse gas emissions the LCOPGHG sits at 4% which is considerably less than the LCEGHG (37%) and LCTGHG (59%). Considering that the majority of the greenhouse gas emissions related to transport are attributed to indirect requirements, the relative importance of reducing embodied emissions emerges. Especially, the initial greenhouse gas emissions which represent two thirds of the LCEGHG. This issue has an added temporal dimension which is further discussed in the following section.

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[1] https://doi.org/10.6084/m9.figshare.13350809.v1

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In contrast, the NV-BC requires 2,424 TJ (4,368 GJ per capita and 173 GJ/m² of GFA) and releases 204 ktCO_2-e (368 t CO_2-e per capita and 15 t CO_2-e/m² of GFA) over the life cycle. Consequently, the life cycle energy use is 8% more than the base case and the associated greenhouse gas emissions increase by 13%. This result underlines the critical role of the energy source and its related greenhouse gas emissions.

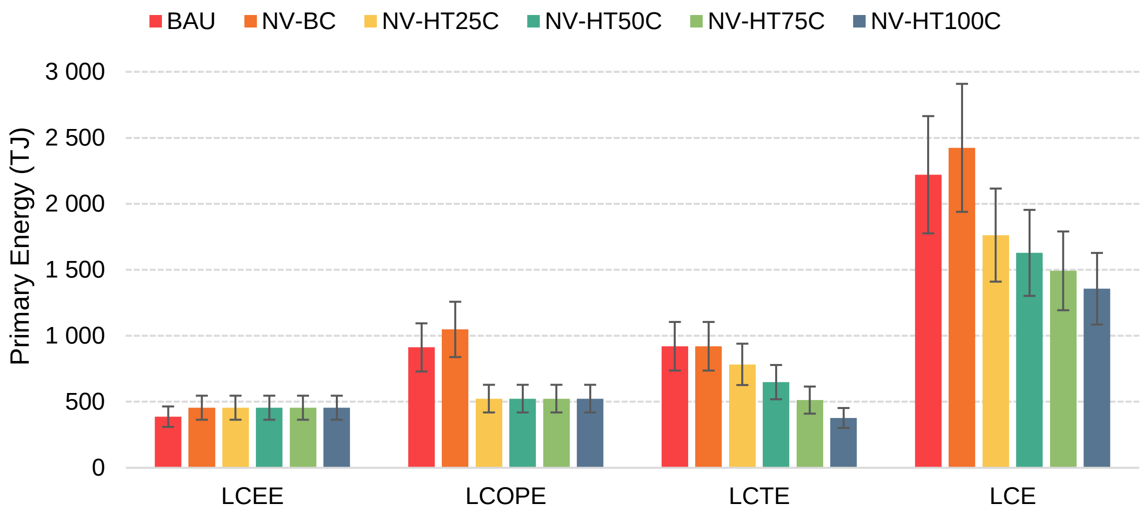

Figure 4. Life cycle energy of the Nightingale Village (NV) and the business-as-usual case (BAU), by stage, in TJ.

Note: LCEE – Life cycle embodied energy, LCOPE – Life cycle operational energy, LCTE – Life cycle transport energy, LCE – Life cycle energy.

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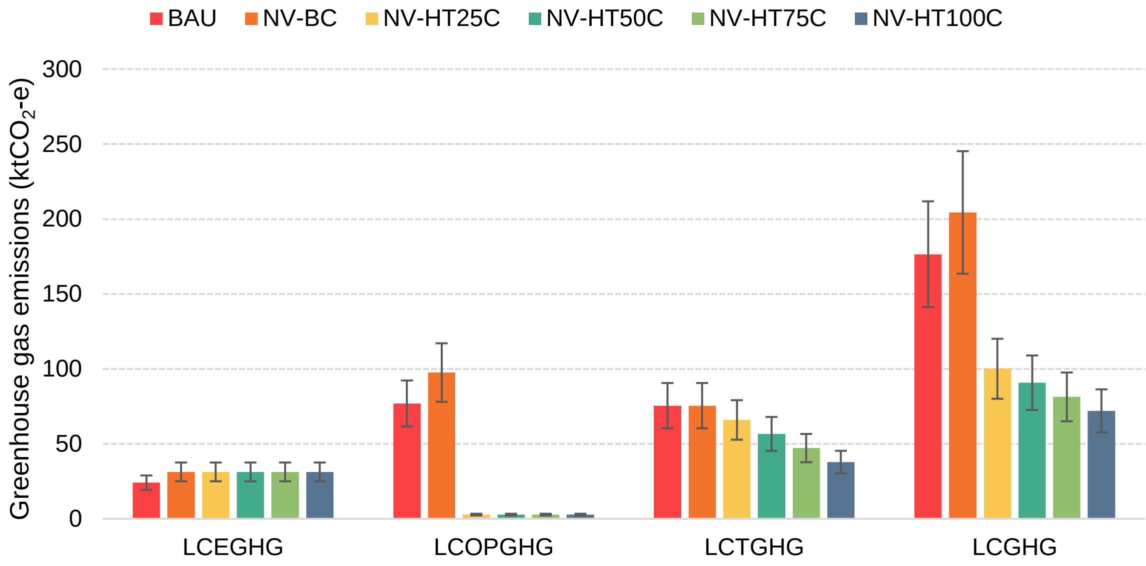

Figure 5. Life cycle greenhouse gas emissions of the Nightingale Village (NV) and the business-as-usual case (BAU), by stage, in $ktCO_2$-e.

Note: LCEGHG – Life cycle embodied greenhouse gas emissions, LCOPGHG – Life cycle operational greenhouse gas emissions, LCTGHG – Life cycle transport greenhouse gas emissions, LCGHG – Life cycle greenhouse gas emissions.

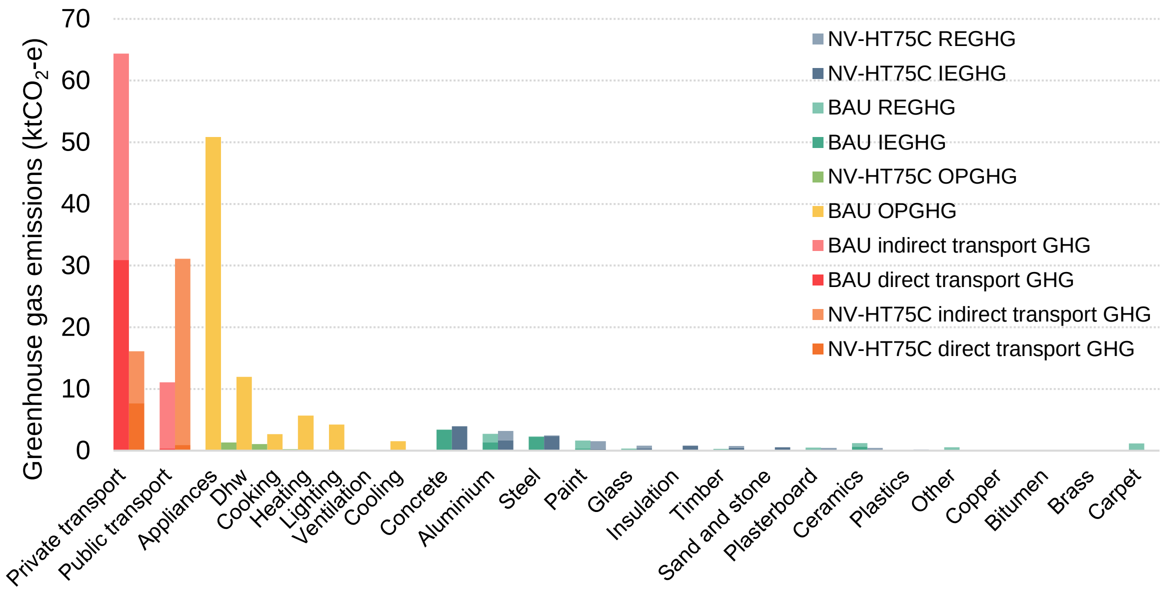

Figure 6: Life cycle greenhouse gas emissions of the Nightingale Village (NV-HT75C) and the business-as-usual case (BAU), over 50 years, by use, in $ktCO_2$-e .

Note: Contrast between the business-as-usual and the Nightingale Village with 75% reduction of private car travel distances divided equally between public and active transport and Hydro Tasmania as the energy source.

The most prominent feature of the analysis is related to the greenhouse gas emissions intensity of the energy source. In essence, relying fully on electricity during the operational phase causes the NV to be highly dependent on the decarbonisation of the supply systems to perform better than the BAU; otherwise, the NV-BC uses 8% more LCE and entails 13% more LCGHG. As displayed in Figure 10, this is mainly related to the increased delivered energy demand for appliances and domestic hot water. In contrast, the NV4 reduces its operational emissions to a near net-zero state assuming electricity supplied by Hydro Tasmania. However, 3 ktCO2-e remain present over the life cycle of the development; these emissions are predominantly associated to the 9% LPG gas contained in the electricity mix of this source. Notwithstanding the clear reductions of LCE and LCGHG presented by the case study, there is no scenario with a single use that is net-zero energy or greenhouse gas emissions across the life cycle.

Another critical factor is that the materials used in the NV bear a 17% increase in LCEGHG, most of which are initial embodied flows (71%). This is in line with Chastas *et al.* [77], where the authors estimated an increased embodied energy range for low-energy buildings (10-83%) with respect to conventional buildings (5-36%). As LCOPE and LCOPGHG decrease, reducing embodied flows becomes critical, as recently called for by the World Green Building Council [78]. The need to reduce initial (and recurrent) embodied greenhouse gas emissions is further reinforced in light of the critical role of reducing present emissions in relation to those of coming decades to mitigate global warming, as suggested by the IPCC [9].

Finally, in all scenarios the combined embodied and transport flows represent more than half of the life cycle energy use and greenhouse gas emissions. This finding is aligned with those of Fuller and Crawford [79], Stephan *et al.* [30], Bastos *et al.* [16] as well as Huang *et al.* [80] and further confirms the need to consider these flows when conducting a life cycle assessment at a neighbourhood level.

4.2. Embodied energy and greenhouse gas emissions

The life cycle embodied greenhouse gas emissions (LCEGHG) of the Nightingale Village (NV) and the business-as-usual (BAU) cases are presented in Figure 7. The LCEGHG of the NV account for 31 $ktCO_2$-e (2,236 $kgCO_2$-e/m² of GFA; 6,262 $ktCO_2$-e/km² of neighbourhood; and, 56,415 $kgCO_2$-e per capita), while those of the base case represent 24 $ktCO_2$-e (1,721 $kgCO_2$-e/m² of GFA; 4,820 $ktCO_2$-

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e/km² of neighbourhood; and, 43,423 kgCO_2-e/per capita). In terms of life cycle embodied energy, the NV requires 455 TJ (33 GJ/m² of GFA; 91,023 TJ/km² of neighbourhood; and, 820 GJ per capita) while the BAU uses 387 TJ (28 GJ/m² of GFA; 77,476 TJ/km² of neighbourhood; and, 698 GJ per capita). Over the period of analysis, the NV requires 17% more embodied energy and emits 30% more embodied greenhouse gases than the BAU, respectively; this difference is related to the use of additional technologies and materials required for passive design (i.e., improved thermal envelope).

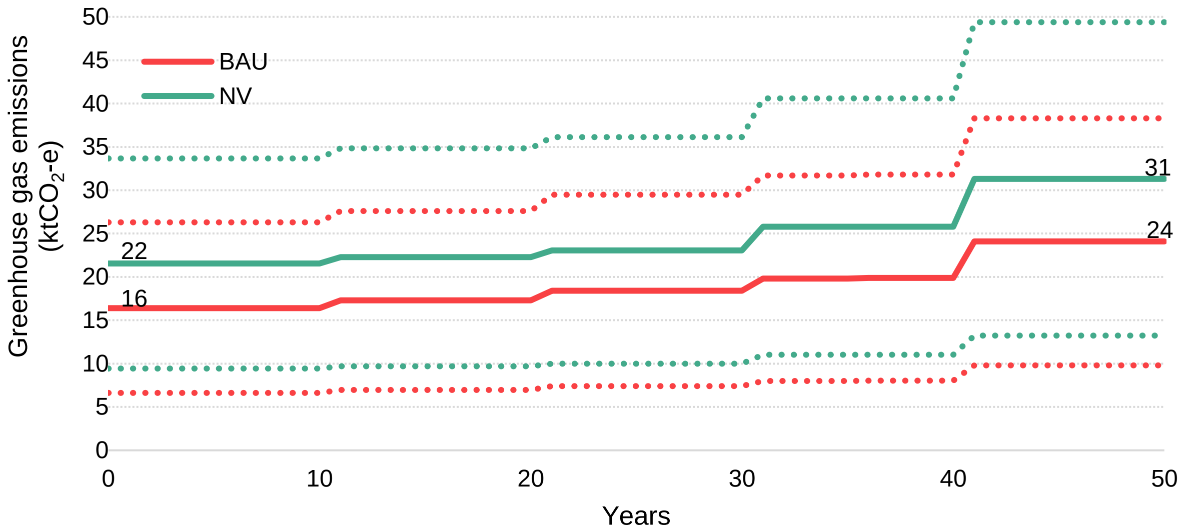

Figure 7. Life cycle embodied greenhouse gas emissions of the Nightingale Village (NV) and the business as usual case (BAU), over 50 years, in ktCO_2-e.

Breakdowns of the LCEGHG by materials and assemblies are displayed in Figure 8 and Figure 9. Concrete is the most greenhouse gas emissions intensive material in both instances, followed by aluminium and steel; when compared to the BC embodied flows in glass are more than double.

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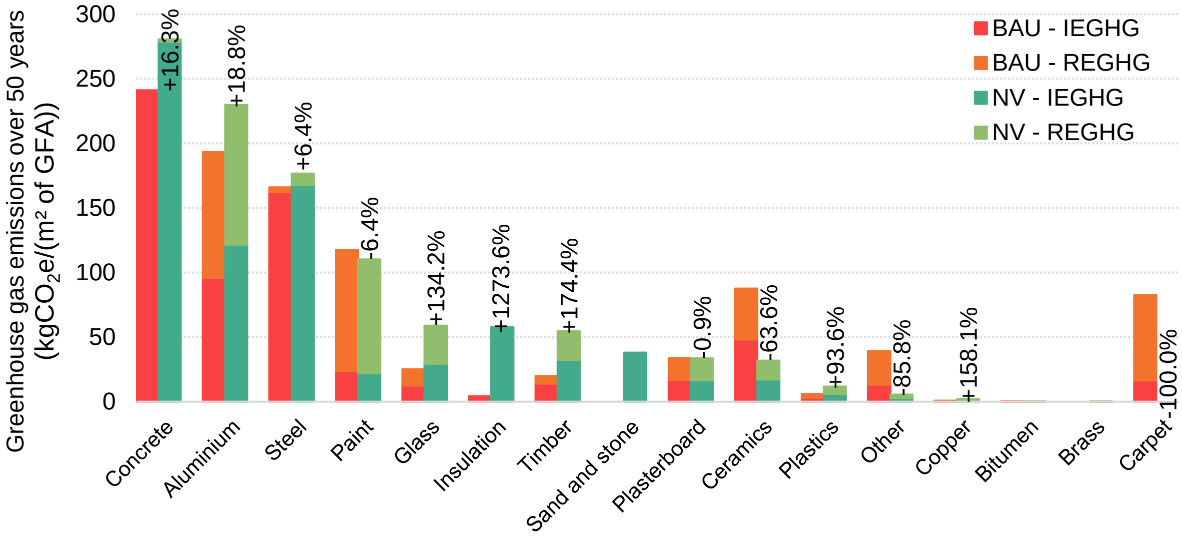

Figure 8. Initial (IEGHG) and recurrent (REGHG) life cycle embodied greenhouse gas emissions of the Nightingale Village (NV) and the business-as-usual case (BAU), in kgCO_2e/(m² of gross floor area (GFA)), by material.

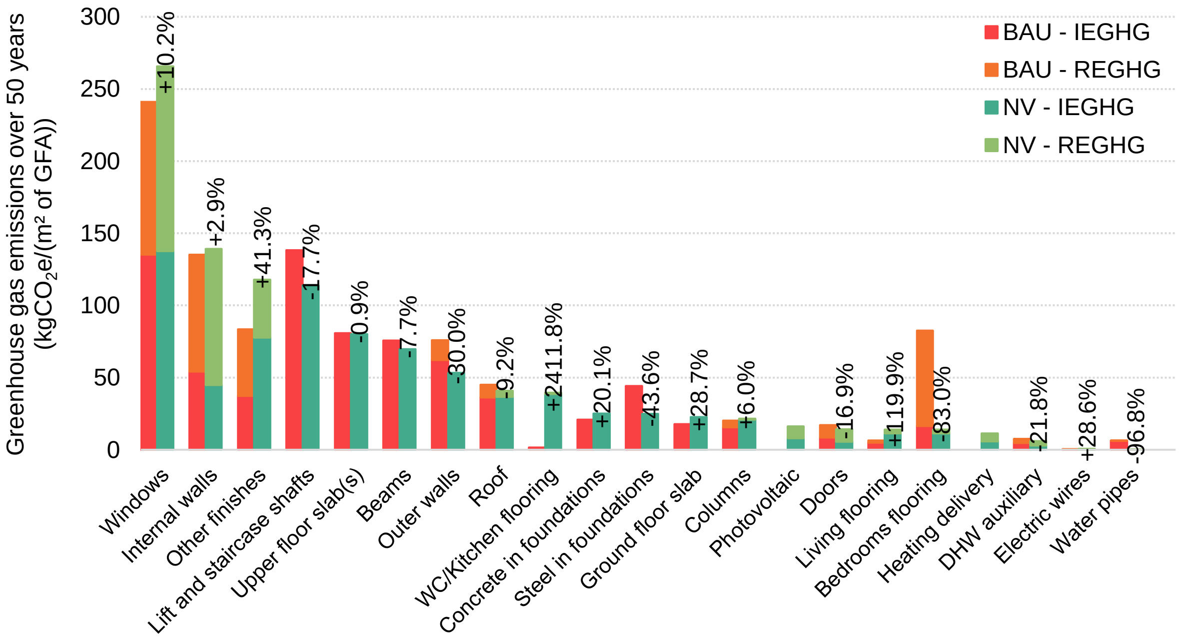

Figure 9. Initial (IEGHG) and recurrent (REGHG) life cycle embodied greenhouse gas emissions of the Nightingale Village (NV) and the business-as-usual case (BAU), in kgCO_2-e/(m² of gross floor area (GFA)), by assembly.

From an assembly perspective, the maximum contribution is related to windows. Hence, it becomes apparent that the increase in glass is attributed to the proposed double-glazed windows. The effect of designing with a reductionist approach and using materials with a longer service life appears in terms of increased initial emissions (69%) and recurrent savings (31%) along the life cycle (i.e., the substitution of carpets, ceramics and painted surfaces for exposed construction materials).

4.3. Operational energy and greenhouse gas emissions

The delivered and primary life cycle operational energy use (LCOPE) and greenhouse gas emissions (LCOPGHG) of the Nightingale Village (NV) and the business-as-usual case (BAU) are presented in Figure 10 and Figure 11, respectively. It is important to reiterate that this model assumes energy supplied by the Victorian grid for the BAU and by Hydro Tasmania for the NV. To investigate the effect of the energy source, scenarios powering the NV with energy from both the Victorian grid and Hydro Tasmania are presented (defined as NV-BC and NV-HT in Table 3 in section 3.7).

Appliances dominate the life cycle energy use and greenhouse gas emissions in all instances. In terms of delivered energy, the NV requires 15% more than the BAU case; hence, it becomes apparent that using electricity for domestic hot water and cooking is more energy-intensive than the conventional gas approach. Notwithstanding the thermal energy demand reduction presented by the NV, this amount is negligible in relation to the LCOPE non-thermal energy requirements.

Considering electricity from the Victorian grid, the LCOPE of the NV-BC (1,048 TJ) is 15% more than in the BAU case (912 TJ). In contrast, the NV-HT requires 43% less LCOPE (524 TJ) assuming electricity from Hydro Tasmania. Contrasting the breakdown by delivered and primary energy in the NV-BC and NV-HT demonstrates the benefit of renewable energy sources in reducing conversion losses (from delivered to primary).

Using electricity instead of gas in the NV-HT (3 ktCO_2-e/GJ) represents a significant 96% reduction of LCOPGHG compared to the BAU case (77 ktCO_2-e/GJ) provided that the NV-HT is powered by Hydro Tasmania. Conversely, the NV-BC (98 ktCO_2-e/GJ) entails 27% more greenhouse gases than the BAU case when covering its electric needs with energy from the Victorian grid. These findings highlight the critical role of the energy source, which concords with the findings of Gustavsson and Joelsson [81] in Sweden, and of Stephan [11] in Melbourne and Brussels .

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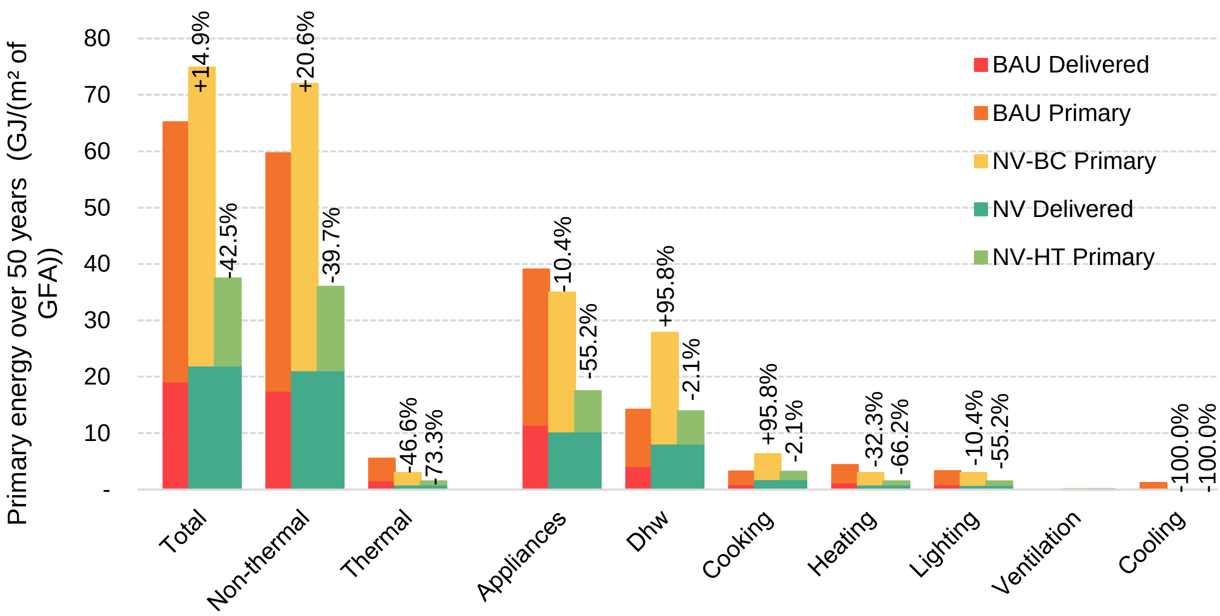

Figure 10. Delivered and primary life cycle operational energy use of the Nightingale Village scenarios (NV-BC, NV-HT) and the business-as-usual case (BAU), in GJ/m² of gross floor area, by end use.

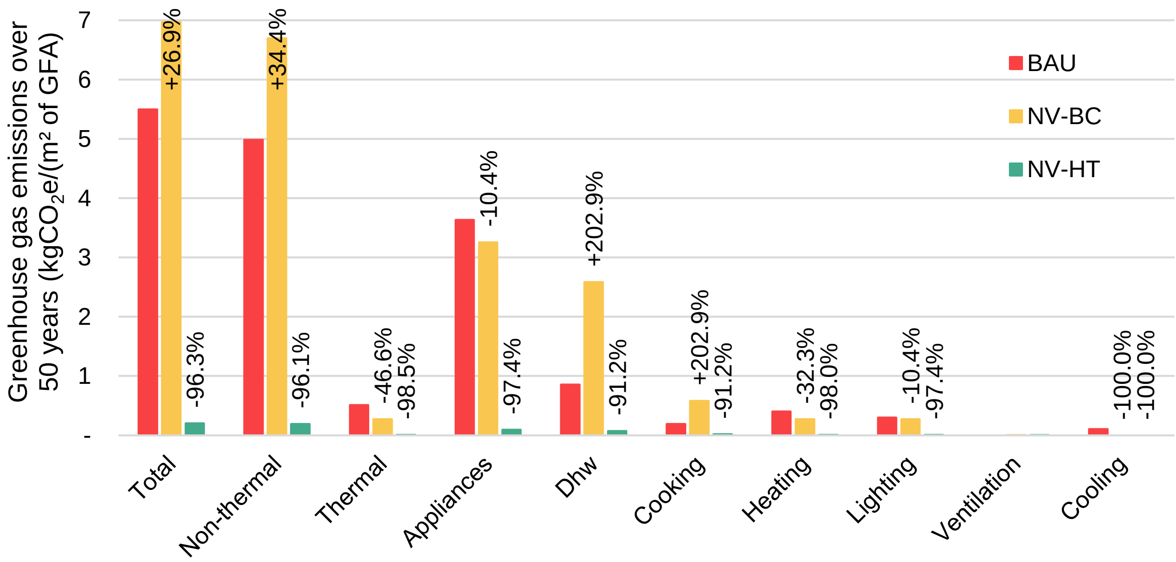

Figure 11. Life cycle operational greenhouse gas emissions of the Nightingale Village (NV) and the business-as-usual case (BAU), in $kgCO_2$-e/m² of gross floor area (GFA), by end use.

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4.4. Transport energy and greenhouse gas emissions

The life cycle transport greenhouse gas emissions (LCTGHG) associated with the mobility of occupants are displayed in Figure 12 and the related energy use (LCTE) is presented in the supplementary information Figshare (see Section 3.8). Assuming a 75% reduction of private car use, the LCTE and LCTGHG of the Nightingale Village (NV-HT75C) are 512 TJ (924 GJ per capita) and 44 ktCO_2-e (85 tCO_2-e per capita), respectively. In contrast, the business-as-usual case (BAU) requires 920 TJ (1,660 GJ per capita) and the associated emissions are 75 ktCO_2-e (136 tCO_2-e per capita). This represents a 44% of reduction in energy use and a 40% reduction in greenhouse gas emissions. In stark contrast, the results in Stephan et al. [82] for Wyndham (1,697 GJ per capita and 130 tCO_2-e per capita), a low-density neighbourhood in Melbourne, represent 35% more emissions than NV-HT75C for the same period of analysis. This penalty is related to urban sprawl and increased reliance on private transport.

Each modelled scenario proposing incremental 25% reductions in private transport use (NV-HT25C, NV-HT50C, NV-HT75C and NV-HT100C) represents net savings with constant returns of 15% with regard to energy and greenhouse gas emissions. Hence, it becomes clear that favouring public transport represents a beneficial strategy. However, when looking at the LCTGHG, the importance of considering indirect requirements in the analysis emerges; particularly, in terms of the increasing indirect emissions related to the operation of electric public transport, notably tramways and trains. This is due to the greenhouse gas emissions intensity of the electrical grid in Victoria.

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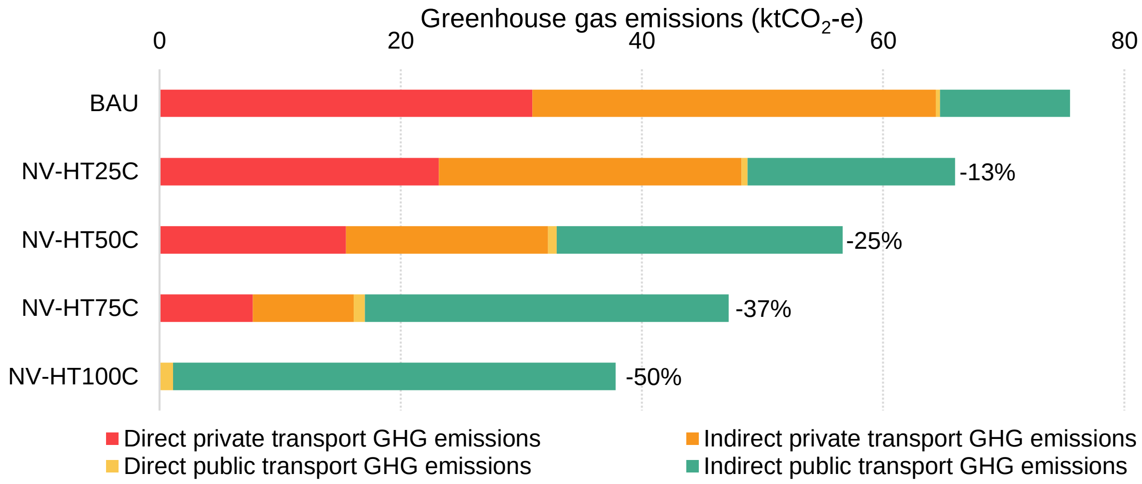

Figure 12. Direct and indirect life cycle transport greenhouse gas (GHG) emissions of the Nightingale Village scenarios (NV-X) and the business-as-usual case (BAU), by category, in $ktCO_2$-e.

5. Discussion

5.1. The importance of the energy source and the temporal dimension of greenhouse gas emissions

The findings presented in Section 4 highlight the critical role of the energy source and its associated greenhouse gas emissions. In green developments this role becomes even more significant. If a green development relies on an energy source with high greenhouse gas emissions for its operational energy, greenhouse gas emissions reductions can be significantly reduced, and in some cases energy efficiency measures can become counterproductive in terms of greenhouse gas emissions (e.g. NV-BC). This is in line with Gustavsson and Joelsson [81], where the energy supply system emerged as the most important factor with regard to energy and greenhouse gas emissions over building envelope optimisation. Hence, in contexts similar to the Victorian grid which relies heavily on brown coal, green developments need to contemplate this dilemma when selecting energy efficiency measures. From a public transport (and electric cars) greenhouse gas emissions perspective, the electricity grid is also very significant, as clearly depicted in Figure 12.

Life cycle assessment unveils the issue of energy use as not being a direct reflection of environmental effects. As said by Carlisle [83] “not all megajoules are created equally”. Energy sources have specific contexts that should be carefully considered on a case-by-case basis by green developments from the early design stages onwards. Additionally, the temporal dimension of greenhouse gas emissions rises as a critical factor to consider in green developments if we are to remain under the emissions threshold specified by the IPCC [9] for this decade.

In the Victorian context, assuming that green developments source their energy from supply systems with low greenhouse gas emissions (whether it is from Hydro Tasmania or on-site renewable energy sources), questions related to the utility of super-insulating buildings emerge, as the thermal operational greenhouse gas emissions are minimised and the relative importance of the initial embodied greenhouse gas emissions rises [22, 84]. What is the relationship between greenhouse gas emissions and embodied energy reduction efforts? To what extent is it useful to super-insulate developments in contexts with relatively low thermal energy requirements?

For Melbourne and Brisbane in Australia, findings presented by Crawford, Bartak, Stephan, and Jensen [85] show that thermal energy savings provided by improved building envelopes can be offset by the additional embodied energy required by insulation materials and additional glazing. Notably, supplementary insulation measures stop yielding life cycle energy benefits around the current minimum energy efficiency requirements (7-star NatHERS rating). This consideration is critical for the case-study of this work, which proposes a minimum 7.5-star across all buildings.

In terms of the energy source proposed by the case-study, Hydro Tasmania [73] identified two constraints that limit the inter-regional energy swaps (IRS) between Victoria and Tasmania. Physical constraints involving enough energy to be sold in the Victorian market (i.e., pumped hydro plants and the associated reliance on water stocks, transmission constraints across grids through bass-link, and the related losses along the way); and, economic constraints related to IRS (i.e. the negotiation of energy prices through a market-based approach). Hence, the ability of the Nightingale Village to source all electricity from Hydro Tasmania is limited by these factors, and as such the computed emissions factor for the NV-HT cases is underestimated.

In summary, we recommend exploring options increasing the on-site renewable energy generation and reducing the initial embodied greenhouse gas emissions, simultaneously. More broadly, awareness of the importance of the energy source and the temporal dimension of greenhouse gas emissions [86, 87] should be incorporated in the green development discourse to increase transparency and more holistic greenhouse gas emissions reduction strategies that consider all life cycle stages.

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5.2. Implications for planning policy

The implications of the case study results with regard to urban planning stem from the necessity of considering embodied, operational, and transport energy and greenhouse gas emissions across the life cycle of green (and conventional) developments [75].

Operational and transport energy requirements and the related greenhouse gas emissions are currently addressed through land use and transportation policies in Victoria (e.g., minimum 7-star NatHERS ratings for new developments and transit oriented development strategies) [88]. The case study results confirmed the benefit of promoting public and active transport use, providing a 15% reduction of the life cycle transport greenhouse gas emissions for every 25% reduction of private transport use (see Figure 12). However, examining the current planning legislation, a lack of efforts to address greenhouse gas emissions holistically through a life cycle approach emerges. For instance, a simple search of the keyword greenhouse gas in the Melbourne Planning Scheme [88] yields 64 results, while life cycle is absent.

The connection between the results of this work and previous research [71, 75, 85] highlights the importance of considering embodied energy and associated greenhouse gas emissions over the life cycle of the built environment; particularly, in green developments [22, 84]. The absence of consideration of these flows through a systems thinking approach [8] – using life cycle assessment, for instance – can prolong the thirst for urban environmental performance present in Australian cities and abroad.

'Embodied energy' is mentioned only one time in the Melbourne Planning Scheme within Clause 21.06-3, Objective 4, Strategy 4.2 as following: *"Support new developments that minimise their embodied energy by their use of materials, construction and retention of reusable building fabric."* [88]. However, there are no enforcement mechanisms, standards, benchmarks or performance indicators to support such strategy. Planning policy must cease to omit embodied energy and the associated emissions in development approvals, and urban planners should embrace the power granted by life cycle assessment enabled tools to expand their agency as custodians of urban environmental performance. This has also been recently called for by international bodies such as UN-Habitat [89] or the World Green Building Council [78].

Two policy recommendations are presented to summarise the key ideas of this synthesis:

1. Embodied, operational and transport energy and related greenhouse gas emissions (and other environmental flows, such as water [63]) should be addressed holistically in strategic plans and statutory planning regulation. Hence, a life cycle assessment should be undertaken for the grant of development approvals.

2. To support the former recommendation, the implementation of a strategic framework stipulating green development standards encompassing all life cycle stages coupled with a tool to streamline the assessment of life cycle energy and greenhouse gas emissions is urgently needed.

5.3. Implications for future green developments

In addition to the importance of the energy source and the temporal dimension of greenhouse gas emissions, it is critical to consider that green environmental claims based on a single life cycle stage can be misleading (contrast NV-BC and NV-HT75C in Figure 5). The potential energy and greenhouse gas emissions offsets across life cycle stages [11] should be carefully considered through life cycle assessment to verify green environmental claims and prevent *greenwashing*.

Along these lines, awareness of the social dimension of this issue emerges when asking: Why is life cycle assessment only required for green development certifications? In an essay on embodied energy and design Benjamin [90] articulates:

> *"Embodied energy is a social issue as well as a technical one, and a meaningful understanding of embodied energy involves understanding the relationship between the two… In this sense, embodied energy offers a lens through which to study the current state of architecture – a lens that trains our eyes on the perspectives of both engineering and politics"*

This issue extends from embodied energy into all life cycle stages that currently escape consideration but continue to re-shape social [17] and ecological landscapes far from our cities – the flows that life cycle assessment attempts to quantify. The uptake of life cycle assessment in urban planning can transform planners into advocates against extractivism and in favour of 'decarbonising' the energy sources of our cities, creating a faster and more equitable distribution of green developments.

Otherwise, life cycle assessments can remain part of a tick-box exercise to secure points for green environmental credentials [91].

Moving forward, to fully take advantage of life cycle assessment enabled tools, the possibility of shifting from the present state of sustaining the status quo to a new paradigm of regenerative [92, 93] net-surplus energy developments should be pursued to not only reduce life cycle greenhouse gas emissions across scales of the built environment, but also contribute positively in environmental, social and/or economic terms. Hence, the notion of green developments should be reinterpreted as it does not ensure the required environmental performance to address the current climate emergency and resource depletion. Moving to regenerative net-surplus energy developments can help mitigate greenhouse gas emissions and resource use while attempting to provide benefits to the broader system.

5.4. Applicability of the results to other locations

Although this work focuses on a medium-scale green development in Melbourne, Australia and is analysed with respect to its relevant climate, materiality, energy mix and mobility patterns, the findings presented and discussed are applicable to other contexts and locations. The main conclusion of this study, i.e. awareness of the importance of addressing all life cycle stages and consideration of the energy source and the temporal dimension of greenhouse gas emissions, is valid for locations with a temperate oceanic climate (Cfb) following the Köppen-Geiger climate classification [94]. London, Amsterdam, Paris, Seattle and Vancouver are among a number of European and North American cities which share this same climate classification. Moreover, the consideration of different greenhouse gas emissions intensities of the energy grid and transport mode shares expands the external validity of the results across a broad spectrum of scenarios and thus locations. For example, the combination of a grid emissions intensity of 49 $kgCO_2e/GJ^{PRIMARY}$ and a transport mode share of 80% cars, 12% buses, 7% rail, 3% bikes, is representative of Brussels, Belgium [95].

5.5. Limitations and future research

This study has conducted a comprehensive life cycle energy and greenhouse gas emissions analyses of a green development in Melbourne, Australia, using a hybrid approach. Yet, like any research work, this work suffers from a number of limitations. Firstly, while care has been taken to select a representative case study green development, the results are specific to this instance. Therefore, typology, design or location variations may yield different results.

Notably, data constraints related to the lack of detailed building plans disclosing the full bill of quantities of the development resulted in a series of assumptions. However, each assumption has been diligently noted along this work. In addition, the primary energy conversion factor for Hydro Tasmania was estimated based on an average of previous years energy mixes. Ideally, publicly available conversion factors should be used to perform the calculations.

Despite the uncertainty and variability in the data, a more detailed analysis for each variable should be performed separately. For instance, operational energy figures suffer from variability that can greatly affect the reliability of the estimation. This can be linked to user behaviour amongst other factors. Therefore, post-occupancy surveys should be undertaken to verify the reliability of the results of this work.

Additionally, the potential technological innovations likely to occur during the period of analysis were not considered. These include the primary energy conversion factor for electricity, the associated greenhouse gas emissions factor, the energy efficiency of appliances and the energy intensity of different transport modes. In a similar manner, the development of scenarios modelling an increased renewable energy fraction presents an opportunity for future research. In spite of these limitations, this work delivers one of the most detailed life cycle energy analyses of green developments, beyond the single building scale, in the Australian context, to date.

6. Conclusion

At least 40% of the total carbon dioxide emissions are related to the built environment [2]. The urgency of curtailing these greenhouse gas emissions rises if we are to remain under the threshold specified by the IPCC [9] to mitigate climate change. In light of the rapid urbanisation expected to take place in the immediate decades [96], green net-zero energy developments represent an important approach to accomplish this goal.

Despite the clear reductions of energy use in green developments during the operational phase, energy offsets have been identified across life cycle stages [15, 23, 97, 98]. Therefore, developments that claim green environmental credentials should be assessed through a life cycle approach to understand their performance across scales in order to prevent misleading claims and unsubstantiated prerogatives (i.e. greenwashing).

This study has conducted a comprehensive life cycle energy and greenhouse gas emissions assessment of the Nightingale Village, an upcoming green development in Melbourne, Australia. The use of the Energy Metric software tool [11] has enabled the energy and greenhouse gas emissions modelling of the case study over 50 years. In a similar manner, one base case representative of adjacent conventional developments and five scenarios varying the energy source and transportation patterns have been modelled to analyse the energy and greenhouse gas emissions performance of the case study.

The assessment has revealed that there is no scenario presenting net-zero energy or greenhouse gas emissions; and each of the embodied, operational and transport energy requirements represent an important contribution to the life cycle energy. Therefore, all life cycle stages are relevant to the energy and greenhouse gas emissions performance of green developments, as advocated by previous studies [22, 84].

Relying fully on electricity during the operational phase has caused the case study to be highly dependent on the decarbonisation of the supply systems to present life cycle greenhouse gas emissions savings. This underlines the critical role of the energy source. If a green development relies on an energy source with high greenhouse gas emissions for its operational energy (and its electrically-driven transport modes), savings can become eroded, and in some instances energy efficiency measures can become counterproductive in terms of greenhouse gas emissions.

In particular, operational energy savings provided by improved building envelopes can be offset by the additional embodied energy required by insulation materials and additional glazing. Hence, embodied energy and greenhouse gas emissions must cease to be omitted from consideration in green developments.

The case study results confirmed the benefit of green developments that promote public and active transport use, providing a 15% reduction of the life cycle transport greenhouse gas emissions for every 25% reduction of private transport use. More broadly, this supports the benefit of urban planning strategies that favour higher population densities coupled with energy efficient public transportation systems.

Ultimately, policy makers, urban planners and building designers have a shared responsibility in ensuring green developments reduce their life cycle energy use and associated greenhouse gas emissions. Furthermore, the uptake of life cycle assessment in urban planning can transform planners into advocates against extractivism and in favour of decarbonising the energy sources of our cities, creating a faster and more equitable distribution of green developments. Hence, this work advocates for the development and implementation of a strategic planning framework that stipulates development standards comprising all life cycle stages, coupled with a tool to streamline the assessment of life cycle energy and greenhouse gas emissions.

In essence, awareness of the importance of addressing all life cycle stages and consideration of the energy source and the temporal dimension of greenhouse gas emissions should be incorporated in the green development discourse to increase transparency and holistic greenhouse gas emissions reduction strategies that ensure an improved environmental performance.

Author’s contributions

ALA and AS conceptualised the research. ALA performed all calculations, under the supervision of AS. ALA wrote the first version of the paper. AS and ALA revised the paper.

References

[1] International Energy Agency. World Energy Outlook 2019. 2019.
[2] International Energy Agency. 2018 Global Status Report: Towards a zero-emission, efficient and resilient buildings and construction sector. Paris: Global Alliance for Buildings and Construction; 2018.
[3] UN-Habitat. Global State of Metropolis 2020. Population Data Booklet. Nairobi 2020.
[4] UN. Transforming our world: the 2030 Agenda for Sustainable Development. 2015.
[5] UN-Habitat. The climate is changing, so must our homes & how we build them. Nairobi 2019.
[6] Anderson JE, Wulfhorst G, Lang W. Energy analysis of the built environment—A review and outlook. Renew Sust Energ Rev. 2015;44:149-58. doi:http://dx.doi.org/10.1016/j.rser.2014.12.027
[7] Forrester JW. System dynamics, systems thinking, and soft OR. System Dynamics Review. 1994;10:245-56. doi:http://www.doi.org/10.1002/sdr.4260100211
[8] Davidson KM, Venning J. Sustainability decision-making frameworks and the application of systems thinking: an urban context. Local Environment. 2011;16:213-28. doi:http://www.doi.org/10.1080/13549839.2011.565464
[9] IPCC. Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (eds.)]. Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press; 2014.
[10] Low N, Gleeson B, Green R, Radović D. The Green City: Sustainable homes, sustainable suburbs.2012.
[11] Stephan A. Towards a comprehensive energy assessment of residential buildings. A multi-scale life cycle energy analysis framework [Ph.D. thesis]. Brussels: Université Libre de Bruxelles and The University of Melbourne; 2013.

[12] Blengini GA, Di Carlo T. The changing role of life cycle phases, subsystems and materials in the LCA of low energy buildings. Energ Buildings. 2010;42:869-80. doi:https://www.doi.org/10.1016/j.enbuild.2009.12.009
[13] Dahlstrøm O, Sørnes K, Eriksen ST, Hertwich EG. Life cycle assessment of a single-family residence built to either conventional- or passive house standard. Energ Buildings. 2012;54:470-9. doi:10.1016/j.enbuild.2012.07.029
[14] Stephan A, Crawford RH, de Myttenaere K. A comprehensive assessment of the life cycle energy demand of passive houses. Applied Energy. 2013;112:23-34. doi:http://www.doi.org/10.1016/j.apenergy.2013.05.076
[15] Stephan A, Crawford R, De Myttenaere K. Towards a comprehensive life cycle energy analysis framework for residential buildings. Energy and Buildings. 2012;55:592-600. doi:http://www.doi.org/10.1016/j.enbuild.2012.09.008
[16] Bastos J, Batterman SA, Freire F. Significance of mobility in the life-cycle assessment of buildings. Build Res Inf. 2015:1-19. doi:https://www.doi.org/10.1080/09613218.2016.1097407
[17] Dean J. The Anamorphic Politics of Climate Change. e-flux. 2016;69.
[18] Stephan A, Crawford RH. A multi-scale life-cycle energy and greenhouse-gas emissions analysis model for residential buildings. Archit Sci Rev. 2014;57:39-48. doi:http://dx.doi.org/10.1080/00038628.2013.837814
[19] Anderson JE, Wulfhorst G, Lang W. Energy analysis of the built environment - A review and outlook. Renewable and Sustainable Energy Reviews. 2015;44:149-58. doi:http://www.doi.org/10.1016/j.rser.2014.12.027
[20] ISO. ISO 14040:2006 Environmental Management - Life Cycle Assessment - Principles and Framework. Switzerland: International Organization for Standardization; 2006.
[21] Crawford RH, Bontinck PA, Stephan A, Wiedmann T, Yu M. Hybrid life cycle inventory methods – A review. Journal of Cleaner Production. 2018;172:1273-88. doi:http://www.doi.org/10.1016/j.jclepro.2017.10.176
[22] Stephan A, Crawford R, de Myttenaere K. A comprehensive assessment of the life cycle energy demand of passive houses. 2013;112:23-34. doi:http://www.doi.org/10.1016/j.apenergy.2013.05.076
[23] Lotteau M, Loubet P, Pousse M, Dufrasnes E, Sonnemann G. Critical review of life cycle assessment (LCA) for the built environment at the neighborhood scale. Building and Environment. 2015;93:165-78. doi:http://www.doi.org/10.1016/j.buildenv.2015.06.029
[24] Mastrucci A, Marvuglia A, Leopold U, Benetto E. Life Cycle Assessment of building stocks from urban to transnational scales: A review. Renewable and Sustainable Energy Reviews. 2017;74:316-32. doi:https://doi.org/10.1016/j.rser.2017.02.060
[25] Forsberg A. Environmental Assessment of the Urban Environment – Development and First Application of the Environmental Load Profile for Hammarby Sjöstad. Stockholm, Sweden: Royal Institute of Technology; 2003.
[26] Herfray GV, E; Peuportier, B. Life cycle assessment applied to urban settlements and urban morphology studies. 2011.
[27] Lausselet C, Borgnes V, Brattebø H. LCA modelling for Zero Emission Neighbourhoods in early stage planning. Building and Environment. 2018;149:379-89. doi:https://doi.org/10.1016/j.buildenv.2018.12.034
[28] Lausselet C, Ellingsen LA-W, Strømman AH, Brattebø H. A life-cycle assessment model for zero emission neighborhoods. Journal of Industrial Ecology. 2019;24:500-16. doi:https://10.1111/jiec.12960
[29] Stephan A, Athanassiadis A. Quantifying and mapping embodied environmental requirements of urban building stocks. Building and Environment. 2017;114:187-202. doi:http://dx.doi.org/10.1016/j.buildenv.2016.11.043
[30] Stephan A, Crawford RH, de Myttenaere K. Multi-scale life cycle energy analysis of a low-density suburban neighbourhood in Melbourne, Australia. Building and Environment. 2013;68:35-49. doi:http://dx.doi.org/10.1016/j.buildenv.2013.06.003
[31] Nichols BG, Kockelman KM. Life-cycle energy implications of different residential settings: Recognizing buildings, travel, and public infrastructure. Energy Policy. 2014;68:232-42. doi:https://doi.org/10.1016/j.enpol.2013.12.062
[32] Norman J, MacLean HL, Kennedy CA. Comparing High and Low Residential Density: Life-Cycle Analysis of Energy Use and Greenhouse Gas Emissions. Journal of Urban Planning and Development. 2006;132:10-21. doi:https://10.1061/(ASCE)0733-9488(2006)132:1(10)
[33] Riera Pérez MG, Rey E. A multi-criteria approach to compare urban renewal scenarios for an existing neighborhood. Case study in Lausanne (Switzerland). Building and Environment. 2013;65:58-70. doi:http://10.1016/j.buildenv.2013.03.017
[34] Davila CC, Reinhart C. Urban energy lifecycle : An analyitical framework to evaluate the embodied energy use of urban developments. BS2013 13th Conf Int Build Perform Simul Assoc. Chambéry, France 2013. p.1280-7.
[35] Cherqui F. Méthodologie d'évaluation d'un projet d'aménagement durable d'un quartier - méthode ADEQUA 2005.
[36] Colombert M, de Chastenet C, Diab Y, Gobin C, Herfray G, Jarrin T, et al. Analyse de cycle de vie à l'échelle du quartier: un outil d'aide à la décision? Environnement Urbain / Urban Environment. 2011;5.
[37] Peuportier B, Roux C. Eco-design of urban sttlements using LCA. 3rd Int Conf Life Cycle Approaches2011. p.1-6.
[38] Peuportier B, Popovici E, Trocmé M. Analyse de cycle de vie à l ' échelle du quartier – Bilan et perspectives du projet. ADEQUA 2006.
[39] Stephan A, Athanassiadis A. Towards a more circular construction sector: Estimating and spatialising current and future non-structural material replacement flows to maintain urban building stocks. Resources, Conservation and Recycling. 2018;129:248-62. doi:https://doi.org/10.1016/j.resconrec.2017.09.022

[40] Nightingale Housing LTD. *Nightingale*, Available from https://nightingalehousing.org, 2019 (Accessed 24, April, 2019).
[41] UN ESCAP. Integrating the three dimensions of sustainable development: A framework and tools. Greening of Economic Growth Series. Bangkok, Thailand: CSIRO and Univeristy of Sydney; 2015.
[42] Yin RK. Case study research and applications : design and methods. Sixth edition. ed: SAGE; 2018.
[43] Moreland City Council. Nightingale Village Masterplan: Town Planning Application. Melbourne, Australia: Advertised Document under PEA 1987 and Moreland Planning Scheme; 2018.
[44] Hip V. Hype Sustainability. Nightingale Village Brunswick: Masterplan Sustainability Strategy. Melbourne, Australia 2018.
[45] Hansen Partnership. Nightingale Village: Urban Planning Report. Melbourne, Australia 2018.
[46] Doyon A, Moore T. The acceleration of an unprotected niche: The case of Nightingale Housing, Australia. Cities. 2019;92:18-26. doi:http://www.doi.org/10.1016/j.cities.2019.03.011
[47] GTA Consultants. Nightingale Village Duckett Street, Brunswick: Green Travel Plan. Melbourne, Australia 2018.
[48] Rawlinsons. Rawlinsons construction cost guide for housing, small commercial & industrial buildings. 27 ed: Rawlhouse Publishing; 2019.
[49] DEWHA. Energy use in the Australian residential sector 1986-2020. In: Department of the Environment W, Heritage and the Arts, editor. Canberra 2008.
[50] Stephan A, Jensen CA, Crawford RH. Improving the Life Cycle Energy Performance of Apartment Units through Façade Design. Procedia Eng. 2017;196:1003-10. doi:https://doi.org/10.1016/j.proeng.2017.08.042
[51] Winistorfer P, Chen ZJ, Lippke B, Stevens N. Energy consumption and greenhouse gas emissions related to the use, maintenance, and disposal of a residential structure. 2005. p.128-39.
[52] Crowther P. Design for disassembly to recover embodied energy. Passive and Low-Energy Architecture. Melbourne 1999.
[53] Pesonen H, Ekvall T, Fleischer G, Huppes G, Jahn C, Klos Z, et al. Framework for scenario development in LCA. Int J Life Cycle Ass. 2000;5:21-30. doi:10.1007/bf02978555
[54] Lenzen M, Crawford RH. The Path Exchange Method for Hybrid LCA. Environ Sci Technol. 2009;43:8251-6. doi:https://www.doi.org/10.1021/es902090z
[55] Crawford RH, Bontinck P-A, Stephan A, Wiedmann T, Yu M. Hybrid life cycle inventory methods – a review. J Clean Prod. 2018;172:1273-88. doi:https://doi.org/10.1016/j.jclepro.2017.10.176
[56] Stephan A, Crawford RH, Bontinck P-A. A model for streamlining and automating path exchange hybrid life cycle assessment. Int J Life Cycle Ass. 2018;24:237-52. doi:https://www.doi.org/10.1007/s11367-018-1521-1
[57] Crawford RH, Stephan A, Prideaux F. Environmental Performance in Construction (EPiC) database. Melbourne: The University of Melbourne; 2019.
[58] Almarcegui L. Materiales de construcción de la sala de exposiciones Espacio 2. In: Lara Almarcegui Exhibition, editor. Malaga, Spain: CAC Malaga; 2007.
[59] Reinhart CF, Cerezo Davila C. Urban building energy modeling – A review of a nascent field. Building and Environment. 2016;97:196-202. doi:http://dx.doi.org/10.1016/j.buildenv.2015.12.001
[60] Treloar G, Crawford RH. Database of embodied energy and water values for materials. Melbourne 2010
[61] Chester M, Horvath A. Environmental assessment of passenger transportation should include infrastructure and supply chains. Environ Res Lett. 2009;4.
[62] Stephan A, Crawford RH, de Myttenaere K. Towards a comprehensive life cycle energy analysis framework for residential buildings. Energ Buildings. 2012;55:592-600. doi:https://www.doi.org/10.1016/j.enbuild.2012.09.008
[63] Stephan A, Crawford RH. A comprehensive life cycle water analysis framework for residential buildings. Build Res Inf. 2014;42:685-95. doi:https://www.doi.org/10.1080/09613218.2014.921764
[64] Department of Transport. Victorian integrated survey of travel and activity 2016.
[65] Lenzen M. Total requirements of energy and greenhouse gases for Australian transport. Transportation Research Part D: Transport and Environment. 1999;4:265-90. doi:http://www.doi.org/10.1016/S1361-9209(99)00009-7
[66] Lenzen M. Total requirements of energy and greenhouse gases for Australian transport. Transport Res D-Tr E. 1999;4:265-90. doi:https://doi.org/10.1016/S1361-9209(99)00009-7
[67] Lenzen M. Errors in Conventional and Input-Output-based Life-Cycle Inventories. Journal of Industrial Ecology. 2000;4:127. doi:http://www.doi.org/10.1162/10881980052541981
[68] Pettersen TD. Variation of energy consumption in dwellings due to climate, building and inhabitants. 3 ed. Switzerland 1994. p.209.
[69] Moore T, Doyon A. The uncommon Nightingale: Sustainable housing innovation in Australia. Sustainability (Switzerland). 2018;10. doi:http://www.doi.org/10.3390/su10103469
[70] Crawford R. EPiC Database. University of Melbourne. 2019. doi:https://doi.org/10.26188/5dd4cd6ad1e2e
[71] Crawford R. Life cycle assessment in the built environment. London: Spon Pres; 2011.
[72] Treloar G. Comprehensive embodied energy analysis framework. Australia: Deakin University; 1998.
[73] Hydro Tasmania. Annual Report 2018. Hobart, Tasmania 2018.
[74] Molenbroek E, Stricker E, Boermans T. Primary energy factors for electricity in buildings. Toward a flexible electricity supply. Utrecht, Netherlands: ECOFYS; 2011.

[75] Stephan A. Towards a comprehensive energy assessment of residential buildings. A multi-scale life cycle energy analysis framework [Joint Thesis]. Melbourne, Australia; and, Brussels, Belgium. : The University of Melbourne; and, Université Libre de Bruxelles; 2013.
[76] Lara Allende A, Stephan A. Data used in the life cycle energy and greenhouse gas emissions analysis of the Nightingale Village. Figshare 2020, https://doi.org/10.6084/m9.figshare.13350809.v1.
[77] Chastas P, Theodosiou T, Bikas D. Embodied energy in residential buildings-towards the nearly zero energy building: A literature review. Building and Environment. 2016;105:267-82. doi:https://doi.org/10.1016/j.buildenv.2016.05.040
[78] WGBC. Bringing embodied carbon upfront. London: World Green Building Council,; 2019. p.35.
[79] Fuller R, Crawford RH. Impact of past and future residential housing development patterns on energy demand and related emissions. Journal of Housing and the Built Environment. 2011;26:165-83. doi:10.1007/s10901-011-9212-2
[80] Huang B, Xing K, Pullen S. Carbon assessment for urban precincts: Integrated model and case studies. Energ Buildings. 2017;153:111-25. doi:https://doi.org/10.1016/j.enbuild.2017.07.087
[81] Gustavsson L, Joelsson A. Life cycle primary energy analysis of residential buildings. Energ Buildings. 2010;42:210-20. doi:10.1016/j.enbuild.2009.08.017
[82] Stephan A, Crawford R, de Myttenaere K. Multi-scale life cycle energy analysis of a low-density suburban neighbourhood in Melbourne, Australia. Building and Environment. 2013;68:35-49. doi:http://www.doi.org/10.1016/j.buildenv.2013.06.003
[83] Carlisle S. Getting Beyond Energy: Environmental Impacts, Building Materials, and Climate Change. Embodied energy and design: making architecture between metrics and narratives2016. p. 165-77.
[84] Blengini GA, Di Carlo T. The changing role of life cycle phases, subsystems and materials in the LCA of low energy buildings. 2010. p.869-80.
[85] Crawford R, Bartak L, Stephan A, Jensen C. Evaluating the life cycle energy benefits of energy efficiency regulations for buildings. 2016;63:435-51. doi:http://www.doi.org/10.1016/j.rser.2016.05.061
[86] Säynäjoki A, Heinonen J, Junnila S. A scenario analysis of the life cycle greenhouse gas emissions of a new residential area. Environ Res Lett. 2012;7:034037.
[87] Stephan A, Stephan L. Achieving net zero life cycle primary energy and greenhouse gas emissions apartment buildings in a Mediterranean climate. Appl Energ. 2020;280:115932. doi:https://doi.org/10.1016/j.apenergy.2020.115932
[88] DELWP. Melbourne Planning Scheme. In: Department of the Environment L, Water and Planning, editor. Melbourne, Victoria 2019.
[89] UN-Habitat. Building sustainability assessment and benchmarking - an introduction. United Nations Settlements Programme (UN-Habitat); 2017. p.67.
[90] Benjamin DN. Embodied energy and design: making architecture between metrics and narratives: Columbia University GSAPP; 2017.
[91] Lee WL. Benchmarking energy use of building environmental assessment schemes. Energy and Buildings. 2012;45:326-34. doi:https://doi.org/10.1016/j.enbuild.2011.11.024
[92] Hes D, Bush J. Enabling eco-cities: Defining, planning, and creating a thriving future2018.
[93] Lehmann S. Urban Regeneration: A Manifesto for Transforming UK Cities in the Age of Climate Change: Springer; 2019.
[94] Kottek M, Grieser J, Beck C, Rudolf B, Rubel F. World map of the Koppen-Geiger climate classification updated. 2006. p.259-63.
[95] EEA. *The European environment — state and outlook 2020: knowledge for transition to a sustainable Europe*, Available from https://www.eea.europa.eu/soer, 2020 (Accessed March 2021).
[96] UN-Habitat. World Cities Report 2016. Nairobi, Kenya 2016.
[97] Dixit MK. Life cycle embodied energy analysis of residential buildings: A review of literature to investigate embodied energy parameters. Renewable and Sustainable Energy Reviews. 2017;79:390-413. doi:http://www.doi.org/10.1016/j.rser.2017.05.051
[98] Sartori I, Hestnes AG. Energy use in the life cycle of conventional and low-energy buildings: A review article. Energy and Buildings. 2007;39:249-57. doi:https://doi.org/10.1016/j.enbuild.2006.07.001