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Published in:
Journal of Architecture

DOI:
10.1080/13602365.2023.2280849

Published: 03/01/2024

Document Version
Publisher's PDF, also known as Version of record

Please cite the original version:
Kuittinen, M., Ruuska, K., Viriyaroj, B., & Zubillaga, L. (2024). Are 'tiny homes' good for the environment? Focus on materials, land-use, energy, and carbon footprint. *Journal of Architecture*, *28*(5), 698-722. https://doi.org/10.1080/13602365.2023.2280849

The Journal of Architecture

ISSN: (Print) (Online) Journal homepage: https://www.tandfonline.com/loi/rjar20

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To cite this article: Matti Kuittinen, Ksenia Ruuska, Bergpob Viriyaroj & Laura Zubillaga (2023) Are 'tiny homes' good for the environment? Focus on materials, land-use, energy and carbon footprint, The Journal of Architecture, 28:5, 698-722, DOI: 10.1080/13602365.2023.2280849

To link to this article: https://doi.org/10.1080/13602365.2023.2280849

Published online: 03 Jan 2024.

Are 'tiny homes' good for the environment? Focus on materials, land-use, energy and carbon footprint

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Material consumption and greenhouse gas emissions are rising in building stocks. At the same time, the floor area of residential buildings per capita has been increasing. New houses can be very energy efficient but are often built from energy and emission-intensive materials. We investigated the potential of tiny homes for reducing material use, energy consumption, and associated emissions, as well as land use. For this study, comparative life cycle assessments and energy simulations were conducted on tiny homes, detached houses, and apartments in the context of Finland, Northern Europe. The results allow comparison between different building types. The studied tiny homes had lower energy consumption and carbon footprints than the reference buildings when comparing these indicators per capita or per building. However, when using floor area as a unit of comparison, the tiny homes perform worse. When looking at land use efficiency, tiny homes and apartment blocks performed better than detached houses. We conclude that, as tiny homes are strongly related to individual lifestyles, their overall relevance for lowering environmental impacts should be compared in relation to consumption habits and use of public services. Furthermore, the environmental benefits of tiny homes need to be interpreted in a broader sustainability context, especially in relation to indicators of social and economic sustainability.

Introduction

Climate change mitigation and housing

The role of the built environment, and especially housing, is vital for the reduction of anthropogenic greenhouse gases (GHGs). Construction and operation of the built environment account for over a third of global GHG emissions and consume around half of annually extracted raw materials.[1] According to the Intergovernmental Panel on Climate Change (IPCC), limiting global

1360-2365 https://doi.org/10.1080/13602365.2023.2280849

warming to 1.5 degrees Celsius requires 80–90% reduction of building emissions by 2050.[2] Residential buildings are the most common building type, constituting 59–98% of the total area of the building stock in different European countries.[3]

The need for new homes is rising, as the global population is expected to reach 11 billion by the end of the century.[4] At the same time, the average household sizes are declining in most countries.[5] Also, increasing wealth or opportunities to live in more spacious apartments may lead to larger homes or holiday get-aways. As a result of these drivers, the floor areas *per capita* are increasing. Thus, a rising global population and declining household size can cause the demand for homes to grow faster than the population does. This can lead to severe environmental implications, as pointed out by Mason Bradbury, Nils Peterson, and Jianguo.[6] For example, Peter Berrill and Edgar Hertwich projected that GHG emissions from residential buildings would reach 2000–3000 $MtCO_2e$ in the United States by 2060.[7]

Thanks to advances in both technology and policies, new houses can be very energy efficient. Still, energy efficiency is often measured in relation to the floor area of the buildings, but not in relation to the number of users of the building. Despite improvements in energy efficiency, new houses tend to have more floor area per capita and can be equipped with more energy-consuming appliances than in earlier decades. In addition, energy-efficient houses are often built from energy and GHG-intensive materials. Such materials can lead to intolerable GHG emissions over their life cycle, as reported by Material Economics.[8] Furthermore, recent statistical analyses have shown that especially material-related *embodied emissions* (i.e. those arising from the production of materials, construction works, and end-of-life processes) are increasing in both absolute and relative terms in building stocks.[9]

This trend is related to both better thermal insulation as well as improved building service systems for saving, generating, recovering, or storing energy. Hence, mere improvements in the efficiency of residential construction will not help in emissions reductions if the sum of materials and energy used per household does not decrease. According to IPCC, *sufficiency measures* are needed (i.e. measures which lead to consuming less in absolute terms), for example, to optimise the use of the building, repurpose unused existing spaces, or downsize apartments.[10] If sufficiency measures are not introduced, IPCC forecasts that the GHG emissions from construction can increase by 54% by 2050, in practice eradicating the emissions savings achieved by energy *efficiency measures.*[11] In fact, 'our current energy systems worldwide are overwhelmingly a continuation of the 1960s rich-world pattern of dependency on very high levels of energy use', as stated by Barnabas Calder and Alex Bremner.[12]

Linking the 'tiny home' trend and individual resource use

'Tiny home' or 'tiny house' usually refers to small individual housing units that have considerably smaller floor areas than conventional homes. Although 'tiny home' could refer to any small apartment, such as in a block of flats, the focus of this article is on individual, detached tiny homes.

There are several definitions for the tiny home typology, as summarised by Heather Shearer and Paul Burton.[13] Majority of them are small in size but also refer to the possibility of relocating the dwelling. The 2018 International Residential Code (IRC) gives a very general definition of what is a tiny house.[14] The code defines a tiny house as a single dwelling unit with a maximum floor area of 37 m^2 excluding loft, maximum ceiling heights for different spaces, minimum space dimensions, as well as some other building features. Principles of the IRC have been applied by a handful of states.

Although affordability appears to be the most typical reason for choosing a tiny home, ecological sustainability has been found to be among the key drivers as well.[15] From the definition of a tiny home, it logically follows that the need for space and construction materials per capita is smaller than in conventional homes. However, there appear to be very few studies in which the environmental sustainability and resource use have been quantified and compared to other types of residential buildings.

Robert Crawford and André Stephan estimated the life cycle GHG emissions of an Australian tiny trailer house and concluded that it could be 70% less per capita than in a traditional house.[16] Herbert Leindecker and Daniel Kugfarth studied the energy efficiency of mobile tiny houses in Austria and found them 'in no way inferior' to conventional residential buildings.[17] On the contrary, Jaya Mukhopadhyay measured the indoor environmental quality and energy consumption of two tiny homes in Montana, USA, and reported issues related to overheating.[18]

Although the tradition of environmental research on tiny homes is short, the relationship between building size and environmental performance has been studied broadly. Stephen Clune, John Morrissey, and Trivess Moore found a clear relationship between the size of the building, its energy performance, and associated GHG emissions.[19] Sudip Pal and Atsushi Takano studied the life cycle energy demand for different building types and concluded that smaller building units have a larger life cycle energy demand per floor area than larger ones.[20]

Currently, the most often used regulatory environmental indicators for construction include consumption of energy and GHG emissions. Energy efficiency is typically compared based on energy declarations and in the EU these are based on the Energy Performance of Buildings Directive (EPBD). GHG emissions are an emerging field of building policies.[21] The Netherlands has pioneered a mandatory declaration of 11 different environmental indicators, including GHGs.[22] The reporting of GHG emissions has been required in France since 2020, in Sweden and Norway since 2022, in Denmark since 2023, and will be mandatory in Iceland from 2024 and in Finland from 2025.[23] In the case of Denmark, Finland, Iceland, and Sweden, the regulation is based on an introduction of GHG limit values for buildings. Introducing similar limits to the entire EU building stock sparked lively debate during the revision of EPBD.[24]

Housing-related GHG emissions result mainly from the use of energy and from the life cycles of materials used for construction. Globally, housing-related emissions seem to be rising. In 2020, material-related GHG emissions were approximately 3.5 $GtCO_2e$ and are expected to increase around 0.7% per year between 2020 and 2060, mostly in low and middle-income classes.[25] According to European statistics, annual heating-related GHG emissions range from 35 to 1,660 $kgCO_2e$ per capita in European households.[26] Annual housing-related GHG emissions have been estimated to be 2.5 metric tonnes of CO_2e per capita in Finland, 2.4 tonnes in Japan, 1.4 tonnes in China, 0.5 tonnes in Brazil, and 0.4 tonnes in India, respectively.[27]

For transparently quantifying the share of GHG reductions for the housing sector, several methodological studies have been made. Alexander Hollberg, Thomas Lützkendorf, and Guillaume Habert calculated an emission budget for single-family homes in Switzerland.[28] They concluded that 360 $kgCO_2e$ per capita could be allowed by 2050 to limit global warming to 2 degrees Celsius. In New Zealand, Chanjief Chandrakumar, Sarah McLaren, David Dowdell, and Roman Jaques calculated a GHG target budget for new detached houses.[29] Their findings result in an annual carbon budget of 614 $kgCO_2e$ for a typical detached house. These budgets are unfortunately not comparable, as they were based on differing methodologies, system boundaries, and data.

Aim and scope of this article

The essential role of housing-related GHG emissions combined with the fact that many tiny home residents are justifying their choices with smaller environmental impacts lead us to ask, what would be the potential of tiny homes for reducing GHG emissions or other environmental impacts? As smaller buildings need fewer resources for their construction and less land for their site, can they lead to environmental improvements?

To contribute to the emerging research on the environmental performance of tiny homes, we have investigated the material use, land use, energy consumption, and associated GHG emissions in tiny homes. For setting the results in context, we compared them to results of contemporary detached homes as well as apartments in residential blocks of flats. Because we have carefully followed the same methodologies in these calculations, we can compare the performance of tiny homes in relation to other housing types.

In the first part of this article, we will summarise the background of building-related environmental impacts and their trends, as well as introduce the tiny home as a concept. In the second part, we will explain our methods, data, and their limitations for this study. And, the third part will present our results, which are further discussed and compared to the wider context in the final part.

With the help of this study, we aim to bring more understanding to the life cycle impacts of tiny homes. Although the case studies come from Northern Europe, we consider our approach replicable for a wider geographic context.

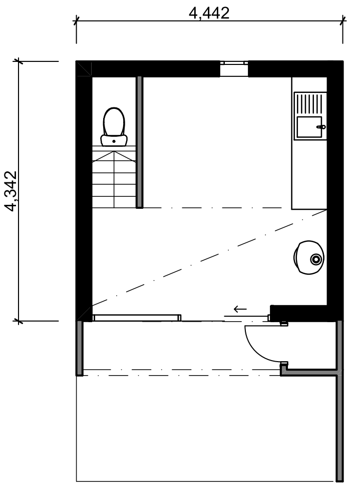

Figure 1.
Plan and exterior view of tiny home 'Garden Village'

Materials and methods

Case study buildings

Our geographical scope is in Finland, where climate declarations for buildings are becoming a prerequisite for building permission by 2025.[30] We are investigating two different tiny home projects and comparing them to a group of typical residential buildings.

The first of the tiny homes is a building from 'Garden Village' project, located in the city of Espoo, Southern Finland (Fig. 1).[31] The area of the development consists of 54 tiny homes. The studied building has a floor area of 14 m^2 and a loft area of 8 m^2, with a lot size of approximately 90 m^2. It has an open living space with a kitchenette, a loft that serves as a sleeping space, stairs, an unheated storage closet, as well as a covered deck, which serves as a summertime living space. The house is built from wood and has a wooden façade with a metal sheet slate roof.

The second tiny home is a concept house designed by the students of Aalto University's Wood Program (Fig. 2).[32] This 'Wood Program' tiny home includes a central core, which accommodates services, kitchen, bathroom, and working area. The surrounding area includes a lounge space and the loft is a resting space. The floor area is 18 m^2 and the loft area is 5 m^2. The house is made from cross-laminated timber (CLT) and its roof structures are from laminated veneer lumber (LVL).

Details of both studied tiny homes have been compared in detail (Table 1). For adding diversity to our study, we developed altogether seven alternative versions of these tiny home models by varying their insulation, heating, and ventilation systems. These alternatives are further described in later parts.

We compared these tiny homes with typical single-family homes and residential blocks of flats that were all built for the national housing fair held in 2021 in

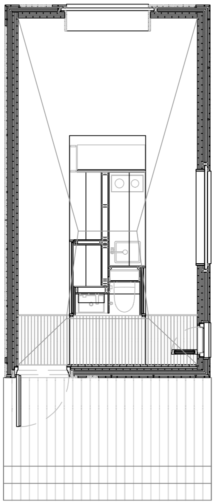


Figure 2.
Plan and exterior view of tiny home 'Wood Program'

Finland.[33] As the geographical, temporal, and technological representativeness of both tiny homes and their reference group is good, we can draw conclusions with a relative high degree of certainty.

The reference group consists of 18 detached houses and 3 residential blocks of flats. The detached houses are made from different materials: 11 from timber, 2 from steel, and 5 from concrete blocks. They have one or two storeys and represent the two best energy efficiency classes (A and B). Their sizes vary from 118 to 229 m^2 of heated floor area.

The residential blocks of flats are built from structurally insulated prefabricated concrete panels, which is the mainstream method for residential

Table 1. Features of the studied tiny homes

Name	Garden Village	Wood Program
Location	Espoo, Finland	Fiskars, Finland
Occupants	2 (planned)	2 (planned)
Floor area	14 m^2	18 m^2
Volume	49,4 m^3	54,5 m^3
Plot area	90 m^2	n/a
Load-bearing frame material	Wood (timber stud frame)	Wood (cross-laminated timber)
Building service system	Natural ventilation, electrical floor heating	Natural ventilation, electrical floor heating
Year of completion	2022	2022

construction in Finland. Their floor areas range between 2,448 and 2,828 m^2 of heated floor area. Their energy performances represent the two best energy classes (A and B).

Material quantification and life cycle assessments of this reference group buildings were conducted in a pilot project launched by the Ministry of the Environment of Finland.[34] Energy performance data is based on the energy declarations of the buildings.

Estimation of environmental performance

In this article, we focus on four aspects: material use, land use, energy use, and GHG emissions. These key indicators are currently part of building policies or are being developed towards policies, as described in the introduction.

Quantification of materials. The material quantities were calculated from construction drawings of the case study buildings. After making an inventory of the building products and materials, we calculated their weights based on the information provided in Environmental Product Declarations (EPDs) or from known densities of different raw materials.

For our study, we have included the following building parts:

- Exterior walls (including windows and doors)
- Roofs
- Ceilings (including covering and finishing)
- Floor slabs (including covering and finishing)
- Foundations
- Interior walls and doors
- Electric wiring
- Water and sewage pipes
- Ventilation and other HVAC machines
- Lamps and sockets

The selected components were chosen based on the significance of their impacts and the quality of the data. Moreover, the data for these elements in both case studies of this article were readily available with low uncertainty. The building technical system was included because its assessment can explain a trade-off between operational energy savings, improved living comfort, and embodied energy of technical systems.

Uncertainties related to material trade-off are related to the estimation of loss at the construction site. To address this, we applied a conservative loss factor of 5% to all those materials that require on-site construction work. For products that come prefabricated and are installed on site, we assumed no material losses. It is, in theory, possible that some materials were replaced during the construction work. However, as we had no information indicating such, we did not consider such changes in this study.

Assessing the efficiency of land use. The efficiency of land use was compared from two perspectives. First, we compared the ratio of the internal floor area of the apartments to the land area of the development area, including the sites and required internal roads and parking areas. Secondly, we compared the used land area to the number of inhabitants in the area.

The areas for the buildings were retrieved from the building documents. The areas for the sites, roads, and entire development areas were measured from the site plans.

Simulating the use of energy. We simulated the consumption of energy by using the dynamic energy simulation software Indoor Climate and Energy (IDA ICE), version 4.8.[35] The software is based on a Modelica-like Neutral Model Format (NMF) and is compliant with standards such as ASHRAE 140, 2004, standards EN 15255, EN 15265, and EN 13791, as well as LEED and BREEAM.

A geometrical model was created for the energy simulation. The building's mechanical, electrical, and other systems, as well as schedules and loads, were defined in accordance with the design documents. Five different models for simulating energy efficiency were then created to represent design alternatives. Four of the models simulate the impacts of different heating (direct floor heating vs air source heat pump) and ventilation (natural ventilation vs mechanical ventilation with heat recovery unit) solutions. As tiny homes are not required to fulfil the energy efficiency requirements of Finland, we created a fifth model to represent the code-compliant version with an air source heat pump and mechanical ventilation with a heat recovery unit. By adding this fifth alternative, we were able to study the energy-efficiency potential of tiny homes in the cold climate of Finland (Table 2).

There were some uncertainties concerning the energy simulations and used data. Some of the data, such as plug-in loads, had to be estimated and calculated. Some assumptions were also made, for instance, regarding the performance of mechanical systems products, number of users, user profiles, internal loads, schedules, and electricity and water usage. In the case of uncertainties, information and data from official building codes and guidelines or product data sheets were used.

Calculating the carbon footprint. Carbon footprint — or GHG emissions over the building´s life cycle — was estimated using life cycle assessment (LCA). It is a method for quantitatively estimating impacts that are associated with a building, including impacts before use, during use, and after the use of the building. To ensure comparability to the carbon footprint estimations of conventional buildings, we applied an attributional, process-based LCA, as defined in European standard EN 15978.[36] It is the foundation for all above-mentioned regulatory schemes for declaring the climate impacts of buildings in Europe.

We identified only one scientific article that had applied quantitative LCA to tiny homes. However, this pioneering study by Crawford and Stephen uses an LCA method that differs from the mainstream policy approach (standard EN 15978) and is therefore less comparable to other building's LCA. As the

Table 2. Energy simulation alternatives: Heating and ventilation systems in tiny homes Garden Village and Wood Program

Tiny home	Alternative	Heating system	Coefficient of Performances (COP)	Ventilation system	ρ
Garden Village	Version 1	Direct electrical floor heating	1	Natural ventilation	0%
	Version 2	Direct electrical floor heating	1	Mechanical ventilation with energy recovery unit	80%
	Version 3	Air source heat pump	3	Natural ventilation	0%
	Version 4	Air source heat pump	3	Mechanical ventilation with energy recovery unit	80%
	Version 5	Air source heat pump	3	Mechanical ventilation with energy recovery unit	80%
Wood Program	Version 1	Direct electrical floor heating	1	Natural ventilation	0%
	Version 2	Direct electrical floor heating	1	Mechanical ventilation with energy recovery unit	80%
	Version 3	Air source heat pump	3	Natural ventilation	0%
	Version 4	Air source heat pump	3	Mechanical ventilation with energy recovery unit	80%

pioneering study has been conducted in Australia, and as it focuses on a mobile trailer home, there are need for complementary studies. In addition, we aimed to compare the impacts of tiny homes to their typical alternatives in the European context. Furthermore, the question of whether tiny homes can contribute to lowering per capita GHG emissions has remained uncertain.

Carbon footprint was estimated for the same building parts that were included in the estimation of material quantities. Where data inventory was incomplete, we replicated such inventories according to typically used designs based on our experience as building designers.

We covered the full life cycle of the case study buildings according to the requirements of Finland´s national method for whole life carbon assessment:[37] production of building products (life cycle modules A1–3 in EN 15978), construction stage (modules A4–5), use stage (modules B4 and B6), and end-of-life stage (modules C1–4).

In the applied LCA tool (OneClickLCA),[38] we selected product-related data from either manufacturer-specific EPDs, if the exact products were reported, or from the national generic database CO2data.fi, if information on the exact products was not available.[39] Scenarios for the construction stage, use stage, and end-of-life stage, and associated data, were gathered according to the national LCA method.[40] For further analysis and possible replication of our results, we have also presented a more detailed overview of the LCA system boundaries, applied data, and scenarios (Table 3).

Reporting, comparison, and supplementary materials

We have presented the results using various units for comparison. To enable comparison between buildings, we present the results divided by their internal floor area. For enabling per capita comparison, we also divide the results per number of known or planned occupants. We show the results for both studied tiny home types as well as for the reference detached houses and reference apartment blocks. This nuanced comparison helps to identify how efficient each building type appears in different comparisons.

Results

Material efficiency

The tiny homes' material quantities range from 0.5 to 0.6 t/m^2 and 3.6 to 5.8 t per capita, on average, and the weights of the tiny homes have been compared to the reference buildings (Table 4).

In comparison to the studied tiny homes, the reference detached houses are slightly more material intensive (0.8 t/m^2), and the reference apartment blocks are considerably more material intensive (1.8 t/m^2), when weight is compared in relation to floor area. However, when weights per capita are compared, the reference detached houses show very high figures (39.7 t/capita), whereas the reference apartment blocks appear very material efficient (2.6 t/capita).

Land use efficiency

The efficiency of land use depends on the chosen indicator (Table 5). However, we could only compare the land use efficiency between the 'Garden Village' tiny homes and reference buildings, as the 'Wood Program' tiny home did not yet have a dedicated site at the time of the assessment.

Table 3. Description of the applied system boundaries, data, and scenarios for the life cycle assessment of the studied tiny homes

Summary of the methods and data applied to the- LCA of the case study buildings.

Life cycle stages	Studied impact	Applied method	Inventory data	Data for emissions or scenarios	Uncertainties and limitations
A Before use					
A1-3 Production	• Material quantities • GHG emissions	• EN 15804 (2019)	• Bill of quantities retrieved from the design documents	• Environmental Product Declarations (EPDs), database CO2data.fi	• Losses of materials from the prefabrication are not documented. • Materials removed from the site are not included. • Groundworks, fills, piling, stabilisations, and excavations are not included.
A4 Transport A5 Construction	• GHG emissions	• Ministry of the Environment (2019)	• Generic representative distances, site activities and emissions from national database CO2data.fi	• Database CO2data.fi	• True transportation distances or fuel consumption on the building site have not been documented and estimations are prone to uncertainties.
B During use					
B1 Use in building	• Not included, outside of the scope of this study and the applied national assessment method.				
B2 Maintenance	• Not included, outside of the scope of this study and the applied national assessment method.				
B3-4 Repairs and replacements	• GHG emissions	• EN 15978 (2011), Ministry of the Environment, (2019)	• Replacement intervals from database CO2data.fi	• EPDs, database CO2data.fi	• Actual replacements may differ from scenarios.
B5 Refurbishment	• Not included, outside of the scope of this study and the applied national assessment method. • Smaller repairs are included in B3-4. A full refurbishment would include mandatory energy upgrade with alternative technologies that are uncertain to predict yet.				
B6 Operational energy use	• Emissions from the production of energy	• EN 15978 (2011), Ministry of the Environment, (2019)	• Energy declaration of the building	• Database CO2data.fi with national energy decarbonisation scenario	• Predicted energy demand may differ from actual use.
B7 Operational water use	• Not included, outside of the scope of this study and the applied national assessment method. • Heating of domestic water is included into B6.				

(*Table continued*)

Table 3. Continued

Summary of the methods and data applied to the- LCA of the case study buildings.

Life cycle stages	Studied impact	Applied method	Inventory data	Data for emissions or scenarios	Uncertainties and limitations
B8 Users´ activities	• Not included, outside of the scope of this study and the applied national assessment method.				
C After use					
C1 Deconstruction	• GHG emissions	• Ministry of the Environment, (2019)	• Database CO2data.fi	• Database CO2data.fi • Consumption of energy for demolition based on the scenario of CO2data.fi.	• Predicted end-of-life scenarios in the future have uncertainties that relate to e.g. energy demand, energy GHG emissions, transport distances, utilisation of demolition waste and waste manage technologies.
C2 Transport	• GHG emissions	• Ministry of the Environment, (2019)	• Database CO2data.fi	• Database CO2data.fi • Consumption of energy for transport based on the scenario of CO2data.fi.	
C3 Waste processing	• GHG emissions	• Ministry of the Environment, (2019)	• Database CO2data.fi	• Database CO2data.fi • National scenarios utilised for the reuse, recycling, and energy recovery rates of different demolition materials.	
C4 Final disposal	• GHG emissions	• Ministry of the Environment, (2019)	• Database CO2data.fi	• Database CO2data.fi	
D Beyond system boundary					
• Module D would belong to the system boundary of the national assessment method. It is not included in our study, due to limited data for the reference buildings.					

As the ratio of indoor area to overall land use is compared, reference buildings have a higher relative share (13%) to the studied tiny homes (9%). On the contrary, when we compare the use of land per capita, tiny homes require much less land per capita (77 m^2) than the reference detached houses (370 m^2), but still more than the reference apartment buildings (55 m^2).

Energy efficiency

The energy consumption in the studied tiny homes ranges considerably from 170 to 450 kWh/m^2/year. When allocated per capita, the building-related

Table 4. Comparison of average material efficiencies. Smaller figures indicate better efficiency

Results (in metric tons)	Tiny home Garden Village	Tiny home Wood Program	Reference detached houses	Reference apartment blocks
Materials per building (t)	7,20	11,60	133,97	4 658,42
Materials per floor area (t/m^2)	0,50	0,62	0,82	1,80
Materials per capita (t)	3,60	5,80	39,70	2,59

energy use in the studied tiny homes varies from 1,240 to 4,160 kWh per person each year (Table 6).

As we compare these figures to the reference buildings in terms of kWh/m^2/year, the tiny homes appear very inefficient: they have close to 300% higher energy consumption. However, when compared per capita, tiny homes appear more energy efficient and have on average only 60% of the energy consumption per capita in comparison to the reference buildings.

Greenhouse gas emissions

According to our results, the studied tiny homes have annual carbon footprints that range from 18 to 40 kgCO_2e/m^2/year. When allocated per capita, the annual carbon footprints vary from 130 to 370 kgCO_2e. When compared per building, the annual figures vary between 260 and 730 kgCO_2e, respectively (Table 7).

As we compare the average carbon footprints of tiny homes and reference buildings (Table 8), we can see that tiny homes perform worse

Table 5. Comparison of average land use efficiencies

Results	Tiny home Garden Village	Reference detached houses	Reference apartment blocks
Ratio of indoor floor area to site area (larger figure is more efficient)	9%	13%	64%
Land use per capita (smaller figure is more efficient)	77 m^2	370 m^2	55 m^2

Table 6. Comparison of minimum and maximum and average energy efficiencies. Smaller figures indicate better efficiency

Results		Tiny home Garden Village	Tiny home Wood Program	Reference detached houses	Reference apartment blocks
Total energy consumption	**kWh/year (aver.)**	**3 629,06**	**5 106,44**	**14 739,57**	**213 367,00**
	Total kWh/year (min.)	2 469,35	3 093,18	10 400,00	203 524,00
	Total kWh/year (max.)	5 669,50	8 319,78	220 320,00	220 320,00
Energy consumption in relation to floor area	**kWh/m^2/year (aver.)**	**250,28**	**274,54**	**96,13**	**81,50**
	kWh/ m^2/year (min.)	170,30	166,30	62,00	73,00
	kWh/ m^2/year (max.)	391,00	447,30	122,00	90,00
Energy consumption per person	**kWh/capita/year (aver.)**	**1 814,53**	**2 553,22**	**4 367,28**	**2 863,99**
	kWh/capita/year (min.)	1 234,68	1 546,59	3 081,48	2 731,87
	kWh/capita/year (max.)	2 834,75	4 159,89	65 280,00	2 957,32

when annual carbon footprints are compared in relation to floor areas. Especially, their use stage (B6) is very emission intensive, due to worse energy performance (per floor area) than in the reference buildings. However, if we use annual carbon footprints per capita or per buildings as units of comparison, tiny homes appear to perform better than the reference buildings (Fig. 3).

The studied tiny homes have timber frames and cladding. Therefore, it is also relevant to compare their GHG emissions to those reference detached houses that have the same structural solutions. This will help to understand if the trend of the results would change depending on the structural material. A similar comparison could not be done to the apartment blocks, as they had concrete frames. Although the wood-framed reference detached houses performed better than all detached houses on average, the overall comparison to the

Table 7. Life cycle carbon footprints of the studied tiny home alternatives. Smaller figures are more climate friendly

	Tiny home Garden Village					Tiny home Wood Program				
Results	Ver.1	Ver.2	Ver.3	Ver.4	Ver. 5	Ver.1	Ver.2	Ver.3	Ver.4	Average
Total annual carbon footprint per area kgCO$_2$e /m^2/year	29,65	21,37	20,59	17,93	17,63	39,11	32,24	26,56	25,17	**25,58**
Total annual carbon footprint per capita kgCO$_2$e/capita/year	214,96	154,93	149,28	129,99	127,82	363,72	299,83	247,01	234,08	**213,51**
Total annual carbon footprint per building kgCO$_2$e	429,93	309,87	298,56	259,99	255,64	727,45	599,66	494,02	468,16	**427,03**

Table 8. Comparison of average life cycle carbon footprints of tiny homes and reference buildings. Smaller figures are more climate friendly

Carbon footprint	Studied tiny homes	Reference detached houses	Wooden reference detached houses	Reference apartment blocks
A1-3 Production stage	−4,24	0,87	−1,27	8,40
A4-5 Construction stage	1,42	1,11	1,11	1,20
B4 Replacements of products	3,28	0,78	0,70	1,45
B6 Use of energy	15,85	4,99	5,29	6,85
C End-of-life stage	9,28	6,34	7,39	2,84
Total annual carbon footprint per area $kgCO_2e\ /m^2/year$	25,58	14,09	13,22	20,74
Total annual carbon footprint per capita $kgCO_2e/capita/year$	213,51	723,20	551,89	728,51
Total annual carbon footprint per building $kgCO_2e$	427,03	2160,87	1931,14	54362,11

tiny homes did not change (Table 8). Additional information on the life cycle emissions of the studied tiny homes in comparison to the reference buildings is also provided (Table 9).

On sensitivity and uncertainties

In our study, we have assumed that each house type serves the theoretical number of users it is planned for. Because the tiny homes are the smallest, they have the highest sensitivity in per capita comparisons. We assumed two users per tiny home, but if there was only one user, the results would show considerably worse performance for tiny homes. Similarly, if three persons shared one tiny home, the results would be considerably better. This variable is less critical for detached houses or apartment blocks, as they have larger floor areas per capita.

Another aspect of sensitivity is in the materials that were used in the studied buildings. The tiny homes and most of the detached houses had wooden frames and considerable amounts of wood in their claddings and surfaces. In several studies, the use of wood has been shown to lead to low GHG emissions, when compared to other materials.[41] If the

Figure 3.
Carbon footprints of the compared buildings using two units for comparison: (a) per floor area and (b) per capita

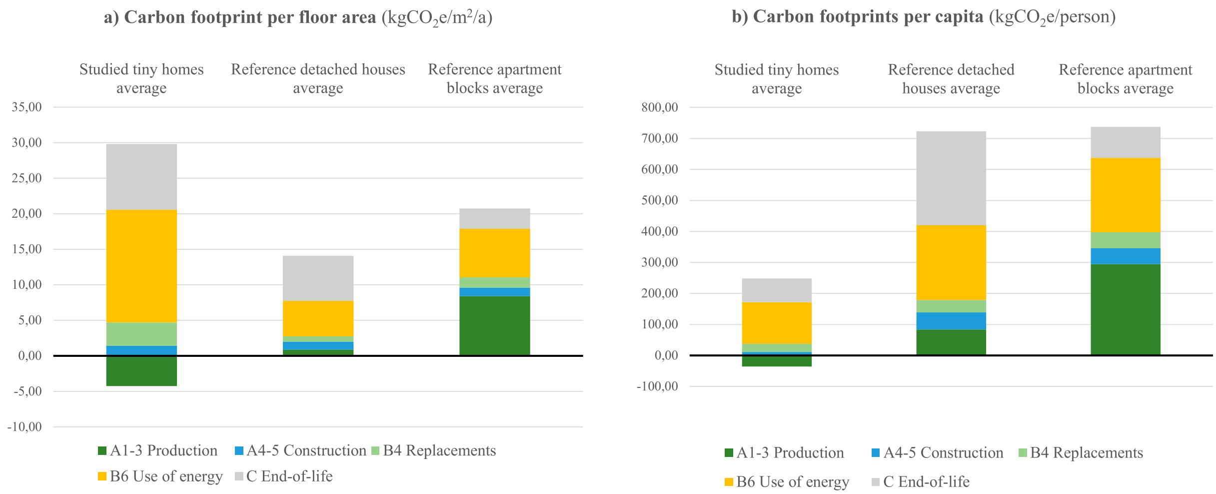

Table 9. Detailed comparison of life cycle carbon footprints as well as benefits and loads beyond the system boundary for the studied tiny homes. Positive numbers indicate emissions and negative emission removals. Smaller positive numbers and larger negative numbers describe better performance

	Tiny home "Garden Village"				Tiny home "Wood Program"					Studied tiny homes average	Reference buildings (average)		
Life cycle stage	**Ver.1**	**Ver.2**	**Ver.3**	**Ver.4**	**Ver. 5**	**Ver.1**	**Ver.2**	**Ver.3**	**Ver.4**		**Detached houses**	**Wooden detached houses**	**Apartment blocks**
A1-3 Production	-4,06	-3,97	-2,64	-2,54	-2,63	-6,19	-6,1	-5,08	-4,99	**-4,24**	0,87	-1,27	8,40
A4-5 Construction stage	1,38	1,38	1,39	1,39	1,52	1,43	1,44	1,44	1,45	**1,42**	1,11	1,11	1,20
B4 Replacements	2,53	2,58	3,97	4,03	4,03	1,9	3,16	3,02	4,28	**3,28**	0,78	0,70	1,45
B6 Use of energy	21,96	13,54	10,03	7,21	5,92	31,14	22,9	16,35	13,59	**15,85**	4,99	5,29	6,85
C End-of-life stage	7,84	7,84	7,84	7,84	8,79	10,83	10,84	10,83	10,84	**9,28**	6,34	7,39	2,84
Total carbon footprint per area $kgCO_2e/m^2$	**29,65**	**21,37**	**20,59**	**17,93**	**17,63**	**39,11**	**32,24**	**26,56**	**25,17**	**25,58**	**14,09**	**13,22**	**20,74**
Carbon footprint per capita $kgCO_2e$/capita	**214,96**	**154,93**	**149,28**	**129,99**	**127,82**	**363,72**	**299,83**	**247,01**	**234,08**	**213,51**	**723,20**	**551,89**	**728,51**
Total carbon footprint per building $kgCO_2e$	**429,93**	**309,87**	**298,56**	**259,99**	**255,64**	**727,45**	**599,66**	**494,02**	**468,16**	**427,03**	**2160,87**	**1931,14**	**54362,11**
D Benefits and loads beyond the system boundary $kgCO_2e/m^2$ (not included in the calculations above)	-9,86	-9,88	-9,89	-9,91	-10,3	-11,73	-11,95	-11,75	-11,97	**-10,80**	**n/a**	**n/a**	**n/a**

studied tiny homes were built from, for example, conventionally manufactured steel or concrete frames, their material efficiency and carbon footprints would have been worse. However, even when the wood-framed tiny homes were compared to only those reference buildings that were made from wood, the conclusions did not change. In our study, the size of the tiny homes and their energy performance can be concluded to be more relevant contributors to the results than the choice of building materials.

Uncertainties in the results are mostly related to the simulated use of energy. We had no possibility of following the measured consumption of energy, as the buildings were just built, and measurement data were not available. Hence, the well-known discrepancy between simulated and measured energy consumption applies to our study as well.[42]

Discussion

Towards a transparent comparison

A general view of the results gives a good example of the importance of choosing a suitable unit of comparison. Tiny homes appear to perform better or worse in comparison to the reference buildings depending on the chosen unit of comparison. In most cases, tiny homes perform best if we look at total impacts either per building or per capita. However, if we compare impacts divided by floor area, tiny homes look worse than conventional reference buildings. Therefore, choosing a suitable unit for comparison requires transparency and explanation of results, which is especially important to decision makers in a city planning process. Our case study reveals in detail, how the same results could be presented in ways that lead to opposite conclusions. Therefore, it would be necessary to present the results using several units of comparison.

We argue, however, that comparing the environmental impacts per capita should be increasingly favoured in the future. The current mainstream policy of setting goals per floor area addresses *efficiency*, but not *sufficiency*. After all, the housing needs of the growing global population may ultimately require establishing a top-down benchmarking method that is related to the number of households and their inhabitants.[43]

Less size, less resource consumption

The results are not by no means surprising, as smaller buildings require less materials, land area, and energy than larger ones. However, our results present quantitative and methodologically coherent comparisons to other housing options. For the first time, the relative differences between tiny homes and conventional options can be compared because the studies are carried out by using the same mainstream methodology for all buildings. This information — and especially the benchmarking indicators introduced in this study — can be applied to housing development projects, in which tiny homes are considered as an option.

Regarding material consumption, tiny homes perform clearly better than the reference detached homes. This is self-evident because tiny homes are smaller and, in our case, are used by similar amounts of residents than detached homes. Interestingly, the studied tiny homes consume more construction materials per capita when compared to the studied apartment blocks. Even though the apartment blocks in this comparison were made from heavy materials (concrete and bricks), they house more inhabitants per floor area and therefore are more material efficient when compared per capita.

In terms of land use efficiency, the studied tiny homes and apartment blocks are — logically — more efficient than the studied detached homes. However, this result is strongly related to city planning in the case studies, and different results could be achieved from different case studies. The density of both tiny homes and detached home settlements is a question of building regulations, such as fire safety or daylight. Still, relatively high land use efficiencies in the studied tiny homes suggest that they could also attract services and public transport connections within a city structure.

Energy efficiency is also greatly dependent on building regulations. Our results show a relatively high degree of variation in energy performance. This is partly due to the local regulations that exclude very small buildings from those energy-efficiency requirements that apply to the reference buildings. Therefore, the studied tiny homes have not been designed in an energy-efficient manner, and they perform worse when their energy consumption is allocated to their floor area. Should the energy-efficiency regulations have been applied to tiny homes as well, the conclusions would have been different. Regardless of this contextual explanation, tiny homes still perform well when we compare their energy use per capita. Arguably, similar savings in energy use could also be achieved through the sharing of residential spaces in conventional buildings.[44] It must be kept in mind, however, that the applied standardised energy simulation cannot give a realistic result to the individually different patterns of energy use; therefore, reality always differs from simulations.

As has become clearer year by year, the availability of clean energy is essential for societies to achieve carbon neutrality. It is an enormous challenge, and tiny homes could be a viable part of the solution. When looking at the use stage, tiny homes can be comparable to conventional houses in terms of energy demand and, in some cases, substantially lower. Tiny homes could provide the missing link to ensure the availability of clean energy, especially if they are connected to onsite renewable energy systems, such as solar energy.

The same pattern of results can be seen as we compare the life cycle carbon footprints. Tiny homes have the largest emissions per floor area, but the lowest per capita and per building. This is a logical outcome of the performance in the categories of material and energy efficiency.

As stated in the introduction, the requirement for reducing 80–90% of GHG emissions from buildings by 2050 will be an immense challenge. When it comes to reducing material use and related GHG emissions, tiny homes can be part of the solution. Still, it is important to keep in mind that the studied tiny homes showed a very broad range of emissions; the worst tiny home had over two times as much annual GHG emissions as the best-performing variant. However, we should be careful in drawing too narrow-minded conclusions based just on the quantitative results or their variability. Users are in a key position; therefore, linkages to sustainable lifestyles would need to be understood better.

In addition to the results presented in this article, there are several additional indicators of ecological sustainability and many other impact categories that could be compared with the method of life cycle assessment. We stress that, although the selected four indicators are very relevant for mitigating the excess use of materials and energy and for reducing related GHG emissions, they are but a tiny fraction of all environmental impacts of construction. Therefore, it would be recommended to assess the performance of tiny homes considering other aspects of sustainability in the following studies. In addition, the spatial, functional, architectural, and haptic quality of tiny homes, as well as adjustability, flexibility, and recyclability in different use scenarios would deserve considerably more attention.

Sustainable lifestyles and tiny homes

So far, we have been looking only at the buildings themselves. Living in tiny homes, detached houses, or apartment blocks is, however, part of larger consumption behaviour. If a tiny home is used as a holiday get-away, it is an addition to the housing-related impacts of an individual. In such case, tiny homes can bring benefits only if they substitute and outperform larger holiday cottages. If a tiny home replaces a detached house, the conclusions lead to the opposite direction: tiny homes become an important part of reducing personal housing-related environmental impacts (assuming that the previous apartment would not be left vacant). Furthermore, the overall usage and efficiency of the buildings stocked in a city, region, or country is yet another aspect that would deserve more modelling. Migration and the need for temporary accommodation are also an aspect in which the question of tiny homes would require additional studies.

A central question in all these considerations is whether tiny homes can support their inhabitants in leading a less resource-intensive life. If tiny homes are seen as an expression of minimalism or criticism of consumption, they can point to ways to make future housing more sustainable.[45] On the other hand, if tiny homes are very individually designed and not well suited for the different life situations of their inhabitants (e.g. birth of a child or ageing), they could lead to the need to build new homes for different lifecycle stages of their inhabitants. For example, tiny homes' adjustability to remote working from home — an example familiar to many during the COVID-19 pandemic — might not be as good as in larger apartments. Furthermore, if tiny homes would become an object of real-estate investments, their building would not necessarily reflect the real housing needs in an area.

As we consider the relation of tiny homes and services, there would likely be a need for supporting facilities near-by, to meet the multiple needs of the lives of different residents and over the life cycles of the buildings themselves. Studying the environmental benefits of tiny homes should therefore be linked

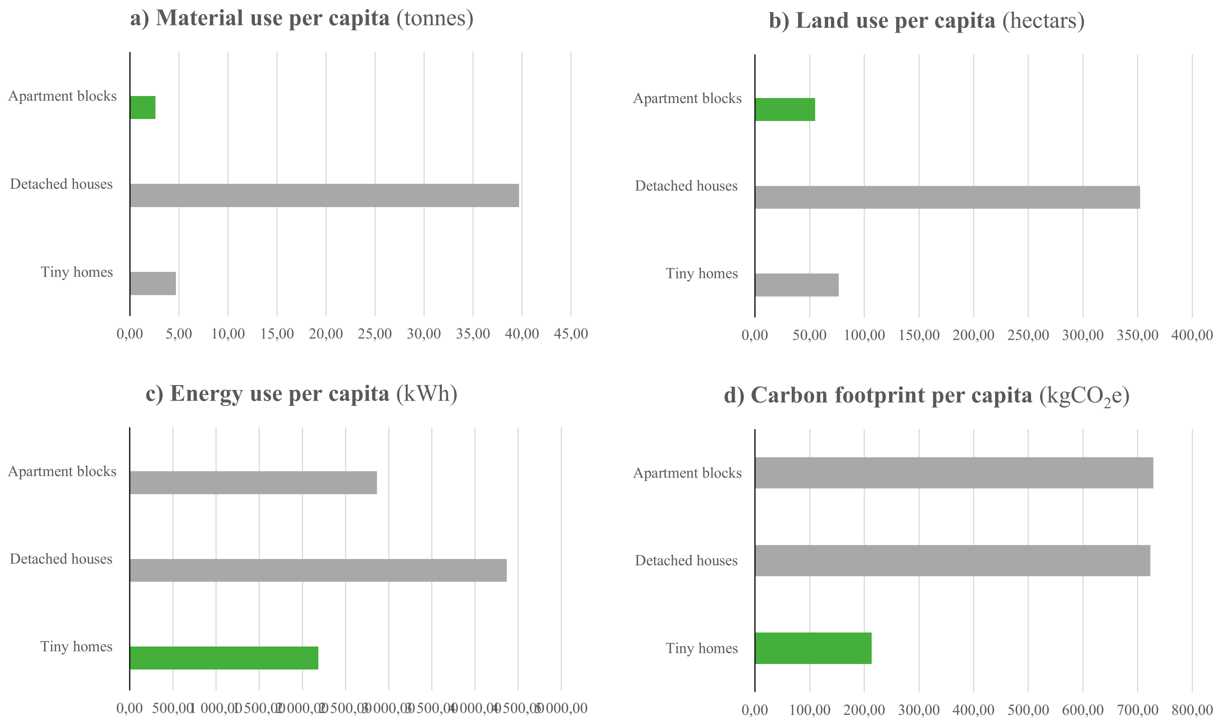

Figure 4.
Summary of results per capita: (a) material use, (b) land use, (c) energy use, and (d) carbon footprint, where shorter columns indicate better performance, compiled by the authors

to lifestyle studies, as well as to the need for public and private services outside of the apartment. The location of a tiny home settlement also determines whether its inhabitants can utilise public transportation, bicycle commuting, or would have to invest in a car. Because of the observed diversity in the per capita impacts of tiny homes, the location of a tiny home settlement can be even more important additional factor to the overall sustainability of living in a tiny home. One way to improve the flexibility of housing options on the building stock level (instead of trying to improve it on the individual building level) would be to use tiny homes as relocatable living modules that can be placed in different locations, according to the needs of residents and the society.

In our context, the tiny homes appear to be a voluntarily chosen alternative for other housing types. This is, however, not always the case, as tiny homes can be a forced housing option because of, for instance, lack of funds or marginalisation. Several studies have documented social and economic drawbacks related to small buildings in trailer parks and residential boats or camping ground settlements.[46] Therefore, we make no claims or recommendations on the social or economic sustainability of tiny homes; our results apply to the chosen environmental indicators only. We suggest continuing the investigation of the sustainability of tiny homes by cross-comparing their environmental, social, and economic performance through a

Table 10. Comparison of resource use and environmental impacts per capita in the studied house types. Smaller figures indicate better performance, shaded cells indicate the best-performing options

Results per capita	Tiny homes	Detached houses	Apartment blocks
Material use kg/capita	4 700	39 696	2 593
Land use m^2/capita	77	370	55
Energy use kWh/capita/year	2 184	4 367	2 864
Carbon footprint $kgCO_2e$/capita/year	214	723	729

combination of simulations, onsite measurements, surveys, and statistical analyses.

Conclusions

From the perspective of inhabitants, our results suggest that a voluntarily chosen tiny home may be a viable option for lowering individual housing-related energy consumption and carbon footprint over the full life cycle of the building. Regarding land use efficiency, much depends on the city plan. In our examples, the studied apartment blocks required the least land area per capita. The use of materials seems to be lowest in the studied apartment blocks, but tiny homes performed clearly better than detached houses. The striking contrast is mostly explained by the fact that the detached houses had much greater floor area per capita than other studied house types (Fig. 4), which has been further summarised (Table 10).

We conclude that tiny homes can offer a suitable solution for sustainable living in conditions, where they support voluntarily chosen simplified lifestyles and where the surrounding network of services and transport options support such lifestyles. In our findings, tiny homes perform clearly better than reference detached homes. However, the adjustability of tiny homes to different use needs was not studied and could indicate the needs for changing homes more often than in detached homes.

As tiny homes are still an emerging trend and there is not much research from the field, we look forward to comparable and expanded studies from other countries, so that the benefits and drawbacks of tiny homes can be adequately identified. Reducing housing-related environmental impacts should be a possibility for all. Voluntarily chosen tiny homes are one promising option for this purpose.

Acknowledgements

The authors wish to thank Aalto University and University of Massachusetts Amherst for facilitating research exchange that made this study possible, as well as the reviewers for their constructive feedback.

Disclosure statement

No potential conflict of interest was reported by the authors.

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