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Comparative carbon footprint analysis of residents of wooden and non-wooden houses in Finland

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Abstract

Sustainable forest management and harvested wood products together can create a growing carbon sink by storing carbon in long-lived products. The role of wood products in climate change mitigation has been studied from several perspectives, but not yet from a consumer's view. In this study, we examine the impact of wooden housing on consumer carbon footprints in Finland. We use the 2016 Finnish Household Budget Survey and Exiobase 2015, a global multi-regional input-output model. The sample size is 3700 households, of which 45% live in a wooden house. We find that residents of wooden houses have a 12(±3)% (950 kg CO_2-eq/year) lower carbon footprint on average than residents of non-wooden houses, when income, household type, education of the main income provider, age of the house, owner-occupancy and urban zone are controlled in regression analysis. This is not fully explained by the impact of the construction material, which suggests that the residents of wooden houses may have some features in their lifestyles that lower their carbon footprints further. In addition, we find that an investment in a new wooden house in an urban area has a strong reducing impact on a consumer's carbon footprint, while investments in other types of housing have a weaker or no reducing impact. Our findings support wooden housing as a meaningful sustainable consumption choice.

1. Introduction

The management and increase of carbon sinks have been highlighted as an important part of effective climate strategies and sustainable pathways [1–3]. According to Global Carbon Budget 2020 [4], total anthropogenic CO_2 emissions were 42.2 ± 3.3 Gt CO_2 in 2019. Around half of the emissions remain in the atmosphere, while the net carbon sink of land and ocean was around −21 Gt CO_2-eq. In recent decades global sinks have grown, but not as fast as global emissions. Tropical deforestation has reduced global sinks and continues to do so, but this has been outweighed by reforestation and forest growth in other regions so far [5–7].

In Finland, the territorial greenhouse gas (GHG) emissions were 53 Mt CO_2-eq in 2019, and their level has been quite stable over the previous five years [8]. Consumption-based emissions, meaning the life cycle emissions caused by household and public consumption and investments, were 60 Mt CO_2-eq in 2016 [9]. At the same time, the average net carbon sink of the land use and land use change and forestry sector varied from −10.3 to −18.9 Mt CO_2-eq between 2015 and 2019 [8] depending on annual logging. The Finnish government has set a goal to be carbon-neutral by 2035 [10].

Sustainable forest management and harvested wood products (HWP) can create a growing carbon sink and storage [11–13], which can help to achieve carbon-neutral targets. Recent studies have highlighted that the climate benefits of HWP are often underestimated in traditional life cycle assessment (LCA) [12, 14–17]. In traditional LCA, raw wood products from sustainable sources have usually been considered carbon-neutral, since in a continuous production system, the same amount of carbon is sequestered and released [18]. However, this approach ignores the climate benefits of temporary carbon storage related to long-lived wood products

[12, 14, 15, 19], such as wooden buildings. The delay between the harvesting and oxidation of wooden products reduces the global warming potential of products within short- and mid-term time horizons.

The role of HWP in climate change mitigation has been studied from the forest [12, 20, 21] and construction [22, 23] sectors' perspectives, for example. In addition, there are numerous LCA case studies on wooden buildings (see a recent review [23]). Since the construction of buildings and infrastructure is an increasing driver of global GHG emissions [24, 25], the mitigation potential of wooden construction can be significant [22]. However, the GHG implications of wooden housing have not been previously studied from the perspective of sustainable consumption.

The consumer's perspective provides unique insights that cannot be studied by traditional building LCAs and are rarely considered in economy-wide scenario models. In particular, consumer carbon footprints can reveal rebound effects of consumption [26–28]. Since consumers have a limited budget, any consumption choice may limit or enable other types of consumption [29–31]. When consumers make sustainable consumption choices, meaning choices that aim to reduce their carbon footprint, there may be unintended consequences, i.e. rebound effects, in the rest of their consumption [29, 32, 33]. There are two types of rebound effects. First, if the sustainable choice leads to monetary savings, it may induce new consumption and subsequent emissions, which is called undesirable rebound effect [29, 34, 35]. Second, in case the sustainable choice requires monetary spending or investment, it may limit other consumption and reduce the related emissions [26, 34, 36], which can be called a desirable rebound effect [28, 31] or negative rebound effect (because negative amount of emissions rebound) [26, 34]. Thus, household-level rebound effects can either offset the expected emission reductions or bring about additional emission savings, depending on the circumstances [26, 30, 34].

The purpose of the study is to examine the impact of the choice of wooden housing on consumer carbon footprint. We aim to identify and evaluate the different influencing factors and to estimate the size of their impact. We consider several aspects of the issue: (a) lower LCA emissions of wooden compared to non-wooden construction; (b) temporary carbon storage of wooden housing; and (c) potential changes in the rest of consumption aside from the housing material choice. Our study is located in Finland, where wood is a common and traditional construction material, particularly in detached houses. According to the Statistics Finland's household budget survey (HBS), 45% of households live in wooden housing (see supporting information, SI, for trends of wooden housing in Finland (available online at stacks.iop.org/ERL/16/074006/mmedia)).

We first compare the average carbon footprints between residents of wooden and non-wooden houses. Second, we focus on residents who have recently invested in new wooden housing. The respective research questions are:

RQ1.How do carbon footprints differ between residents of wooden and non-wooden houses?

RQ2.How does an investment in new wooden housing affect the residents' carbon footprint compared with residents of non-wooden and old housing?

In addition, in the discussion section we discuss and analyse the potential longer term (50 year) impacts of a new wooden and non-wooden housing investment on a consumer's carbon footprint. The carbon footprint model of the study is based on the Finnish HBS 2016 and Exiobase 2015, a global multi-regional input-output model. Furthermore, we use hybrid-LCA to assess the life cycle emissions of wooden housing and some GHG intensive consumption categories more accurately.

2. Materials and methods

2.1. Materials

The main materials of the study are Statistics Finland's HBS 2016 and Exiobase 2015, a global multi-regional input-output (MRIO) model [37, 38]. The HBS includes detailed expenditure data and socioeconomic background variables on 3673 households. The sample is representative of the entire Finnish population. The expenditure data is categorised according to the Classification of Individual Consumption by Purpose (COICOP). In addition, the Finnish HBS includes details on housing, such as living space, house type, construction year and main building material. These enable the analyses to compare the residents of wooden and non-wooden housing.

The Exiobase model is one of the most widely-known global MRIO models alongside Eora, GTAP and WIOD. It has been developed from the European perspective. It covers 44 countries and five 'rest of the world' regions, and includes 200 product categories. Here we use Exiobase to calculate the consumption-based GHG intensities (kg CO_2-eq/ €) for different products and services in Finland. The GHG accounting in Exiobase is based on the Emissions Database for Global Atmospheric Research [38]. It covers several other GHG emissions in addition to CO_2, such as CH_4, N_2O and fluorinated GHGs, but it does not cover the GHG emissions related to land use and land use change [37].

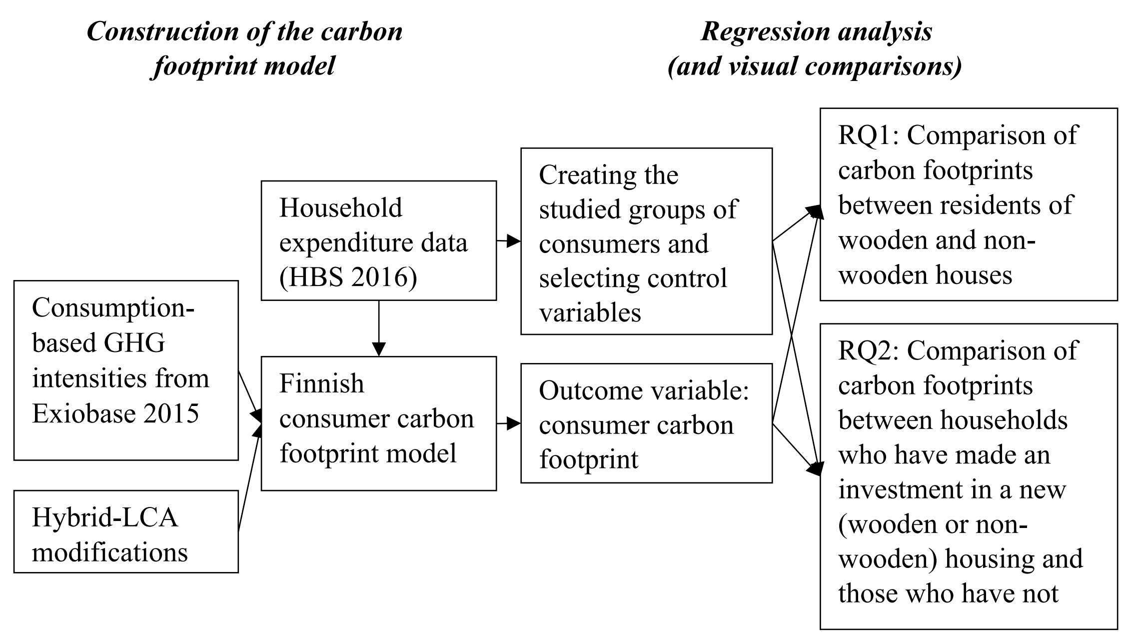

Figure 1. Research design.

2.2. Research design

The research was conducted in two major phases: (a) construction of the consumer carbon footprint model and (b) statistical and descriptive comparisons of the carbon footprints between the studied groups (figure 1). The research process is described in more detail in the following sub-sections.

2.3. Carbon footprint model of the study

The carbon footprint model used is a hybrid LCA model, meaning that it combines environmentally extended input-output (EE IO) modelling (see SI) and process LCA data. The model is based on Exiobase 2015. However, the territorial GHG emissions of Finland seem to be underestimated in Exiobase, so we upscaled them to match the total emissions in 2015 as reported by Statistics Finland [8] before calculating the consumption-based GHG intensities using equation S1 in SI.

The intensities for each of the 200 Exiobase products were calculated and with the COICOP categories used in the HBS. The concordance matrix is the same as in [35], which is largely based on [39]. The concordance matrix shows the matching of COICOP categories and the product classification of Exiobase. The carbon footprints were calculated by multiplying the household expenditure in a specific consumption category by the GHG intensity (kg/€) of the category. We made hybrid modifications to the model regarding construction, housing energy, rentals, private transport and air travel. We put the most effort into modelling the carbon footprint and carbon storage of wooden housing as described below. The other hybrid modifications in our model are presented in SI. For illustrations, we grouped the consumption categories as presented in table 1.

Table 1. Grouping of consumption categories.

Tangibles	Clothes, furniture, electronics, appliances etc tangible items
Services	Health, cultural, sport, financial, hotel, restaurant, etc services
Food	Food and beverages
Other travel	Public, air, sea, inland waterway and combined passenger transport, package holidays, and miscellaneous consumption abroad
Motor fuels	Gasoline and diesel
Vehicles and maintenance	Purchases, maintenance and repair of cars, motorcycles, and boats
Housing energy	Heating and electricity
Housing other	Housing maintenance and repair
Construction	Construction (based on m^2, not €)
Carbon storage of wooden housing	Carbon storage of construction (based on m^2, not €)

2.4. Carbon footprint of construction

The Finnish HBS includes information on house type (detached, row house, apartment building) and the main construction material of housing. In addition, it includes the living space. We used two existing review studies to estimate the emissions of wooden and non-wooden construction per square metre [23]. First, according to Säynäjoki *et al* [40], the average emissions of construction are 0.9 t CO_2-eq/gross-m^2 in previous hybrid and EIO-LCA studies, and there is no clear pattern regarding the house type or material. Thus, we use here the average emissions for all non-wooden houses. We converted the emissions from per gross to per net area by applying the following conversion factors (net area/gross area) commonly used by the City of Helsinki: detached houses 0.83; row houses 0.85, and apartment buildings 0.76. This leads to the following average emissions per m^2 of living space: detached and row houses 1.1 t CO_2-eq m^{-2}, and apartment buildings 1.2 t CO_2-eq m^{-2}.

In addition, we assumed that the carbon footprint of wooden construction is 25% lower for detached houses, 23% lower for row houses and 20% lower for apartment buildings compared to the non-wooden alternative. These estimates are based on previous literature as explained next. First, we found only two comparative hybrid or EIO-LCA studies comparing wooden and non-wooden buildings, which are both from Australia, and show around 10% lower emissions for the wooden option [41, 42]. In order to estimate the impact of wooden housing in Finland (and Europe in general), we decided to rely on comparative process LCA studies from Europe and North America. These studies show 35%–56% and 9%–48% lower emissions for wooden than non-wooden detached houses and apartment buildings respectively (table S1 in SI). Typically, the difference is larger for detached houses than apartment buildings [43]. However, process LCA studies give in general lower estimates for the embodied emissions per square metre (0.12–0.44 t CO_2-eq/net-m^2, table S1, SI) than hybrid and EIO-LCA studies discussed above. Lenzen and Treloar [44] demonstrated how the truncation error, typical for process LCA studies, affects the carbon balance that can be calculated for wooden buildings. It is also likely to affect the substitution factors, as the upstream emissions excluded from process LCAs may be similar in size (or not) for wooden and non-wooden buildings. For these reasons, we decided to use estimates that are in between what is presented in table S1, and the two above-mentioned EIO-LCA studies from Australia [41, 42].

Furthermore, we used a recent review of 50 case studies [23] to estimate the carbon storage of wooden construction per square metre in different types of buildings. Among these case studies, the carbon storage, transformed into CO_2 emissions, varies from 95 to 286 kg CO_2/gross-m^2 in wooden detached houses and from 109 to 296 kg CO_2/gross-m^2 in wooden apartment buildings. Here, we use an approximate average estimate, 200 kg CO_2/gross-m^2 for all types of houses. The conversion from gross to net area was performed similarly to the above, leading to the following carbon storages *per living space*: 240 kg CO_2-eq m^{-2} for detached and row houses, and 270 kg CO_2-eq m^{-2} for apartment buildings.

In order to calculate the cross-sectional carbon footprints in 2016, we divided the construction phase emissions and carbon storage by 50 years and allocated them only to buildings that were 50 years old or younger. We disregarded the end-of-life phase of all houses. Since the climate benefits of temporary carbon storages are still under debate [16, 45], we calculated the consumer carbon footprints both with and without the negative emissions from the carbon storage.

2.5. Statistical analyses

We first analysed the whole dataset (3673 households) and used multivariable regression analysis to test the impact of wooden housing on total consumer carbon footprint. We used several socioeconomic and housing related variables included in the HBS. The basic regression model is as follows:

$$\begin{aligned}&\ln(\text{Carbon footprint})\\&=\beta_0+\beta_E\ln\ (\text{Income})+\beta_h\text{Life phase}_h\\&\quad+\beta_i\text{Education}_i+\beta_j\text{New}+\beta_k\text{Owner}\\&\quad+\beta_m\text{BEvariable}_m+\beta_n\text{Wood}+u,\end{aligned}\tag{1}$$

where

Carbon footprint is consumer carbon footprint per capita

Income is disposable income per capita

Life phase is a categorical variable with seven categories: young (16–24 years), working-age singles, working-age couples, single parents and young families (one or more children under 5), other families with children, senior singles (⩾65 years), and senior couples (⩾65 years)

Education refers to the education of the main income provider, and it has six categories: basic education, secondary education, post-secondary non-tertiary education, bachelor's or equivalent, master's or equivalent, and doctoral or equivalent level.

BEvariable is a selected built environment variable (see details below)

New refers to new housing (construction year ⩾2003)

Owner refers to owner-occupant, and

Wood refers to wooden housing.

Betas are regression coefficients, and u is an error term. We tested four different built environment variables and ran separate regression models for each of them to avoid collinearity problems. The tested variables and respective models were:

Model 1a: *House type* (detached, row house, apartment building).

Model 1b: *Urban zone* (inner-urban, outer-urban, peri-urban and rural areas).

Model 1c: *Degree of urbanisation* (metropolitan area, cities, towns and suburbs, rural areas).

Model 1d: *Square metres of living space.*

Table 2. Sample sizes and descriptive statistics of the studied groups.

	Reference groups		Households who have invested in new housing		
	Old housing	Rental housing (old and new)	New non-wooden: urban	New wooden: urban	New wooden: rural
Sample size (households)	1456	314	81	116	90
Household size	2.6	2.3	2.7	3.7	3.1
Age of main income provider	53	40	51	43	46
Disposable income per capita	22 300 €	18 800 €	23 600 €	21 100 €	22 300 €
Expenditure per capita	18 200 €	17 100 €	20 700 €	17 100 €	18 800 €
Living space (m^2)	118	69	90	137	134
Living space per capita (m^2)	45	30	33	37	44
Share of households living in:					
Apartment buildings	17%	72%	59%	3%	0%
Row houses	13%	19%	21%	12%	10%
Detached houses	69%	9%	20%	85%	90%
Urban areas	56%	80%	100%	100%	0%

The urban zone classification is based on a rural-urban classification created by the Finnish Environment Institute (FEI) and Oulu University [46]. Inner urban areas are dense city centres, outer urban areas mixed high- and low-rise areas with good accessibility to public transport, peri-urban areas low-rise suburban areas with less accessibility, and rural areas sparsely populated areas outside urban development. The classification covers all of Finland and is based on a 250 × 250 m^2 grid.

The degree of urbanisation is based on municipal boundaries. Cities have at least 15 000 inhabitants, of which 90% or more live in urban areas. Towns have at least 4000 but fewer than 15 000 inhabitants, of which 60% or more live in urban areas. The rest are rural municipalities. In addition, we separate the Helsinki metropolitan area (HMA), which covers Helsinki, Espoo and Vantaa.

We calculated the variance inflation factors (VIFs) after each regression model to check for multicollinearity. The VIFs were below 3 for all variables in models 1b–d. High correlation between house type and wooden housing was reflected in the VIFs of model 1a: VIFs were 3.6 for detached houses and 2.4 for wooden housing. The correlation matrix of the used variables is provided in table S2 in SI.

In addition, we used statistical analysis to study the impact of investment in new wooden and non-wooden housing on consumer carbon footprint, as explained below.

2.6. Analysis of new housing investment

Our second aim was to study the impact of investment in new wooden housing on the carbon footprint of its residents. Since our data is cross-sectional, we could not directly study the causal impacts of the investment. However, the causal impacts of consumer choices are projected onto the cross-sectional carbon footprints, and can be demonstrated by comparing groups that have or have not made specific consumption choices [26]. We followed this methodology, and by 'impact' we refer here to the impact according to the regression model, not necessarily a causal impact.

To conduct the comparisons, we grouped the studied households into the following mutually exclusive categories according to the type of residence:

(a) Reference group 1: Old housing (construction year <2003), including both wooden and non-wooden housing, owner-occupants.
(b) Reference group 2: Rental housing (old and new).
(c) New non-wooden housing located in urban areas, owner-occupants.
(d) New wooden housing located in urban areas, owner-occupants.
(e) New wooden housing located in rural areas, owner-occupants.

The two reference groups represent households that have not made an investment in new housing, and the new housing groups households that have. Households living in rented properties have been separated into their own group. All other groups include only owner-occupants, because we are interested in the impact of the personal investment. In the case of new housing, we further separated urban and rural areas, since the location may affect consumption significantly. Urban areas refer to both urban and suburban areas here (meaning inner-, outer- and peri-urban areas in the FEI's classification). New non-wooden houses are mainly located in urban areas. The sample size of non-wooden houses in rural areas is too small to be representative, so we excluded this group from the analyses. In addition, we excluded the highest and lowest income deciles (per capita) to alleviate the income differences between the compared groups, and single-person households since our main interest here is wooden housing. New wooden houses are predominantly detached and row houses, which are rarely occupied by single people. The studied groups are named and described in table 2.

The used categorisation covers the age of the housing, owner-occupancy, main construction material, and partly the house type and urban zone. We used the following regression model to test the statistical significance of the differences in carbon footprint between the groups:

$$\begin{aligned}&\ln(\text{Carbon footprint})\\&= \beta_0 + \beta_E \ln(\text{Income}) + \beta_h \text{Life phase}_h\\&\quad + \beta_i \text{Education}_i + \beta_j \text{Investment}_j + u, \qquad (2)\end{aligned}$$

where *Investment* refers to the above presented investment categories, and the other variables are the same as in equation (1), except that the *Life phase* variable only includes households with two or more members. The model is consistent with the presented illustration, meaning that we excluded the highest and lowest income deciles (per capita) and single-person households.

3. Results and discussion

3.1. Carbon footprints of residents of wooden and non-wooden houses

Residents of wooden houses have on average 12($\pm$3)% lower carbon footprint per capita than residents of non-wooden houses, when income, household type, education of the main income provider, age of house, owner-occupancy, and a selected variable describing the built environment are controlled for (table S3, models 1a–c, SI). Without the carbon storage, the difference is slightly smaller: 10($\pm$3)% (table S4, SI). The selected built environment variable: living space (m^2), house type, urban zone or the degree of urbanisation has a minor impact on this main finding.

When socioeconomic variables are not controlled for, the residents of wooden houses have on average a lower carbon footprint than the residents of non-wooden houses despite their higher average income (figures S2 and S3 in SI). However, their larger household size reduces the carbon footprint per capita. There are some significant differences in the composition of consumption: the residents of wooden houses have higher emissions from private transport, but lower from housing, other travel (public transport and holiday travel), services, and tangibles. This seems to reflect the differences in household size and residential location. In the construction year, the carbon spike of construction is on average 40.5 t CO_2-eq and 46.3 t CO_2-eq per capita for the residents of wooden- and non-wooden houses, respectively (figure S3). The negative emissions of carbon storage in wooden houses are −11.8 t CO_2-eq per capita, leading to a total difference of −17.6 t CO_2-eq per capita in the construction year.

Regarding the regression analysis, since the average carbon footprint of Finland is 7.9 t CO_2-eq/year per capita according to our model, a 12% difference corresponds to 950 kg CO_2-eq/year. The direct impact of wooden construction, calculated by using average living space (45 m^2 per capita) and the emission savings and carbon storage given in section 2, is 460 kg CO_2-eq/year. Thus, our findings suggest that there are additional differences in the consumption behaviour, and the subsequent carbon footprint, between the residents of wooden and non-wooden houses, even when household size and built environment variables are controlled for.

There are small differences in living expenses that may provide some explanation. The residents of wooden houses have a little higher mortgage payments on average. This might be explained by the green signalling hypothesis, i.e. green products have a signalling benefit, which act as an incentive for consumers to pay a premium for environmentally friendly products that even out their price disadvantage [47]. In this case it would mean that the residents of wooden houses are willing to pay more for their housing.

Another explanation could be lifestyle differences. Although the residents of wooden houses have higher incomes than the general population, this does not hold true if only the residents of detached houses are considered. While wooden detached houses are common and traditional in Finland, high-end detached houses are often constructed from other materials, such as stone and glass. Thus, the regression model that controls house type may capture this type of 'high-end consumer lifestyle' of the residents of non-wooden detached and row houses. In general, such a lifestyle is probably not environmentally oriented. Instead, environmentally conscious consumers may prefer wooden housing, which is commonly perceived as a sustainable alternative [48]. Old wooden houses also fit well with a bohemian lifestyle. In this case, wooden housing would not be a cause of the lower carbon footprint, but a manifestation of a lifestyle, which affects the rest of the carbon footprint as well.

3.2. Impact of new housing investment on consumer carbon footprint

Household investments, such as vehicles [36, 49, 50], increased insulation [34, 51], solar panels [34], household appliances [36] and housing itself [27, 52] can have a negative rebound effect on other consumption. It means that the investment reduces the rest of consumption, which leads to a reduced carbon footprint, if the investment itself is not too carbon-intensive to offset this impact. Here we examine the negative rebound effect for investing in new wooden or non-wooden housing.

Investment in new wooden housing in an urban area seems to have a particularly strong impact on personal carbon footprints (figure 2), although it should be noted that the large household size in this group, 3.7 on average (table 2, section 2), also reduces

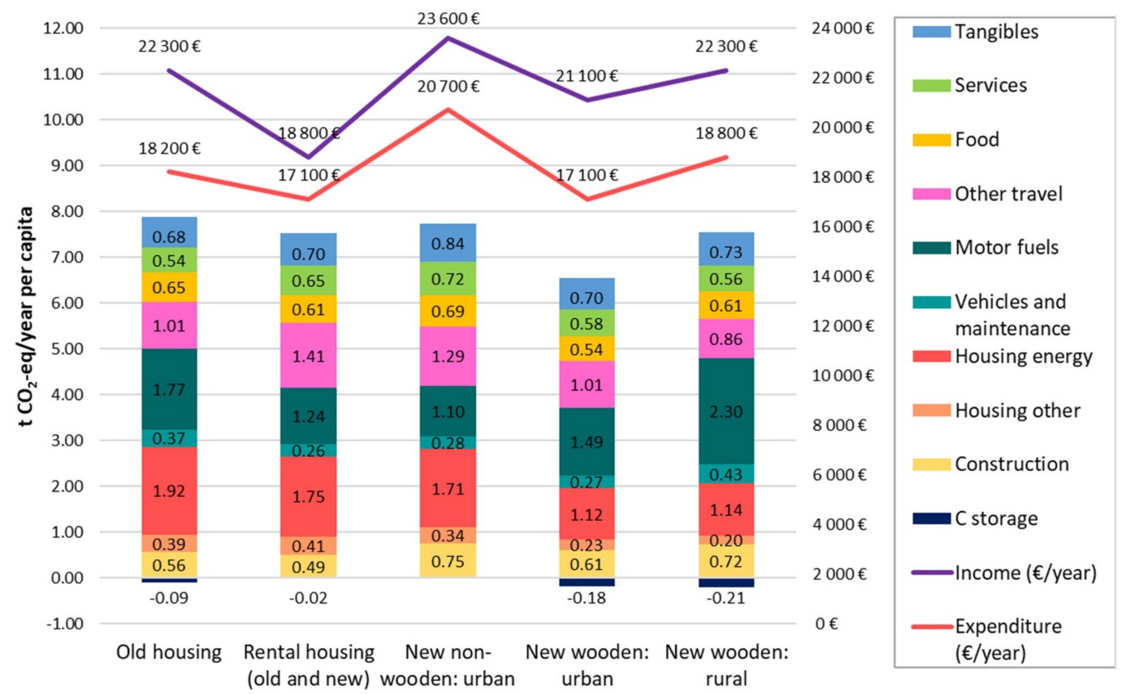

Figure 2. Carbon footprint comparison between the residents of old- and rental housing versus residents who have invested in various types of new housing (old housing: construction year <2003; urban: inner-, outer- and peri-urban areas combined).

carbon footprint per capita. According to regression analysis, the carbon footprints of this group are on average 13(±6)% lower than those of residents of old houses (table S5), or 11(±6)% if the impact of temporary carbon storage is excluded (table S6). The regression model suggests that the carbon footprint of the residents of new wooden houses may be lower in rural areas as well (−10 ± 8% compared to the residents of old houses), but the result is not statistically significant ($p > 0.05$). It seems that households who have invested in a new wooden house in rural areas have relatively high average income, which increases their carbon footprints. While the carbon footprint of housing energy is low in this group, and the carbon storage of the wooden housing slightly higher than that of their urban counterparts, the carbon footprint of motor vehicles and driving offsets these benefits. Energy efficiency has increased more strongly in detached houses than apartment buildings recently [52], which is evident when comparing the carbon footprints of housing energy between the studied groups. The reason lies likely in the ownership of properties and high investment costs of energy efficiency: apartment buildings are constructed by developers, who do not directly benefit from making new buildings energy efficient (since they are not the operators or users of the buildings), whereas detached houses are often constructed by the residents themselves in Finland [53].

The residents of new non-wooden housing have the highest average income among the studied groups, which complicates the analysis. However, it is surprising that their carbon footprint is so similar to that of residents of rented properties despite the large income difference. This may again suggest a negative rebound for investment. Purchase of a new house or an apartment is very expensive particularly in urban areas, which is likely to limit the rest of consumption. Thus, the consumption profile is very similar to the residents of rental housing aside the higher housing costs. It should be noted though, that after the housing loan has been paid, the owner-occupants gain significant savings compared to the residents of rental housing, which is likely to increase consumption and carbon footprints in the long run.

3.3. Potential long-term impacts of new housing investment

While the impact of investment in new wooden housing is clear when comparing the cross-sectional carbon footprints (figure 2, table S5), it is likely that the impact declines as the years go by and the size of the mortgage reduces. For this reason, we created some simplified scenarios to estimate the potential impacts of investments in different housing types over a 50 year timeframe.

With some preconditions, the investment in new wooden housing seems to be beneficial from a GHG perspective in the long run (figure 3). The underlying assumptions and methods are presented in SI in detail. In short, we assumed that the average reducing impact of new housing investment on carbon footprint, calculated in the study, lasts 14 years, since the studied new houses were constructed between 2003 and 2016. After this, we assumed that the impact decreases linearly to zero, 20 years after the

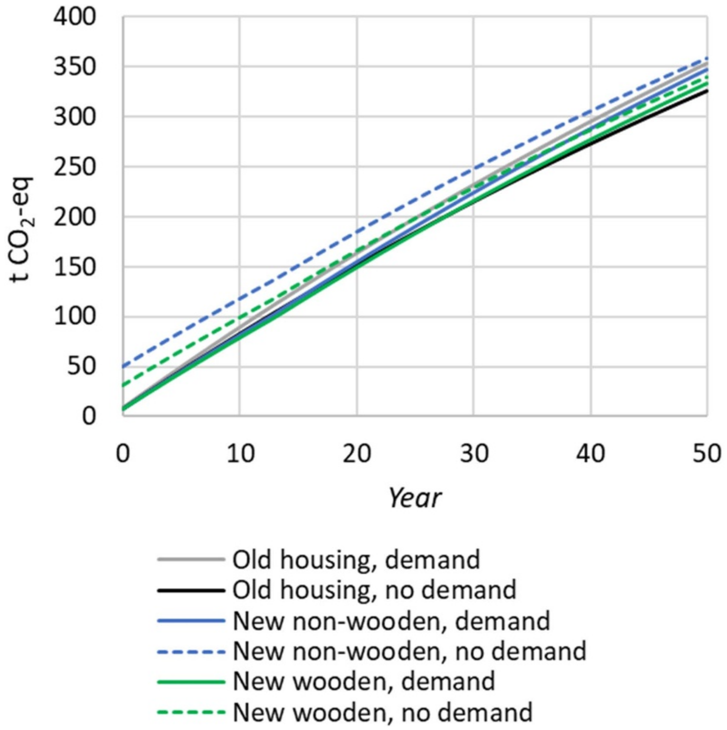

Figure 3. Scenario models illustrating the potential impacts of various housing investment options on a consumer's carbon footprint over a 50 year timeframe.

investment, which is a common loan payment time in Finland. We considered the demand for new housing by allocating the emissions of new construction to all residents (residents of old and new housing) in areas with an increasing demand for housing. However, we allocated no carbon footprint from construction to the residents of old housing in areas where there is no demand for new construction, meaning areas with more supply than demand for housing. In these cases, we allocated the whole carbon footprint of construction to the residents of new housing, which causes a carbon spike in year zero (figure 3, dashed lines).

When we examine the scenario results 50 years after construction, new wooden housing performs very well (figure 3). While the best option, from a carbon footprint perspective, is to purchase an old house in an area where there is no pressure for new construction, this is only a whisker away from the option of investing in new wooden housing in an area with growing demand for housing. Investing in wooden housing in an area with no demand performs surprisingly well too, despite the initial carbon spike of construction in year zero. It is noteworthy that even investing in new non-wooden housing performs better than the old housing option in areas with growing demand. This is because of the negative rebound effect of the investment. Nevertheless, the worst option from a carbon footprint perspective is to invest in new non-wooden housing in areas with no pressure for new construction. The negative rebound effect of new housing investment is not strong enough to offset the carbon spike of construction in this case.

As figure 3 reveals, in the long run, a consumer achieves the lowest carbon footprint by investing in an old house in an area where there is no pressure for new construction. However, this is not recommendable from an economic perspective since the value of the property is likely to decline. Thus, we find new wooden housing in areas with increasing demand for housing as a recommendable option on a societal scale.

It should be noted that our analyses assume a sustainable forestry sector, meaning a stable or increasing forest carbon sink in this context [12, 17]. There is an increasing concern that the growth of the bioeconomy may cause pressure to increase harvesting in Finland [54, 55] and in the EU [56] to an unsustainable level. This would be counterproductive from a climate change perspective, particularly when considering short- and mid-term climate targets [54, 55, 57].

If the use of wood in construction is going to increase substantially in the future, it must be combined with measures that protect the forest carbon sinks. These measures can include afforestation of new areas, intensified forest management [21], production of composite materials from side and waste flows [21, 58], and the cascading of end-of-life wooden products [11, 58, 59], for example. Cascading means using materials in several cycles before incineration, which is usually the last treatment for wooden and composite materials.

3.4. Uncertainties of the study

We aimed to reduce the uncertainties related to the selected time frame and climate impacts of temporary carbon storage as discussed above. In addition, there are some uncertainties related to the carbon footprint model of the study. It should be noted that different EE IO models yield different results. The models have differences in the source datasets, aggregation of the economic sectors, and balancing of the models, for example [60]. We found that the used Exiobase model generally yields lower estimates for consumption-based GHG intensities in Finland than for example ENVIMAT, a semi-MRIO model of the Finnish economy [9]. However, this does not necessarily mean that our main findings regarding the impact of wooden construction would be different if an alternative model was used. The differences between the groups arise primarily from the differences in expenditure, i.e. the used HBS data, and the hybrid LCA model of wooden construction that we built specifically for this study. The GHG intensities of other consumption categories have a lower impact on the results.

4. Conclusion

Our findings reveal that residents of wooden houses have a 12($\pm$3)% (950 kg CO_2-eq/year) lower carbon footprint on average than residents of non-wooden houses, when socioeconomic variables, age of the house, owner-occupancy and urban zone are controlled for. The lower emissions of the construction material explain only around half of the difference, suggesting that wooden housing is linked to some additional sustainable consumption patterns. For example, the residents of wooden houses have lower emissions from housing energy and holiday travel than their counterparts. However, it is likely that the causal direction is from environmental consciousness to wooden housing and not vice versa.

Regarding investments in new housing, an investment in a new wooden house in an urban area has a strong reducing impact on a consumer's carbon footprint, while investments in other types of housing have a weaker or no reducing impact. Investments limit other consumption, which brings additional emission savings, called a negative rebound effect. Sometimes it is termed a desirable rebound effect, since it reduces emissions. Investment in a new wooden house seems to cause such a desirable rebound effect. In addition, the carbon spike of construction is lower for wooden than non-wooden houses.

Based on our findings and previous research, we can conclude that wooden construction has significant climate benefits, as long as it is not increased at the expense of forest carbon sinks. From a consumer's perspective wooden housing is a meaningful sustainable choice. Yet our findings also show that the carbon footprints are still dominated by motor fuels, air travel and fossil fuel-based housing energy. A rapid and just transition away from fossil fuels should be a primary climate policy target. Welfare states could do this through carbon pricing, income transfers and enhanced green investments [28], for example. Wooden construction is one type of green investment that would benefit from a higher carbon price in society.

Data availability statement

The data generated and/or analysed during the current study are not publicly available for legal/ethical reasons but are available from the corresponding author on reasonable request.

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