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The greenhouse gas and energy impacts of using wood instead of alternatives in residential construction in the United States

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ABSTRACT

Data developed by the Consortium for Research on Renewable Industrial Materials were used to estimate savings of greenhouse gas emissions and energy consumption associated with use of wood-based building materials in residential construction in the United States. Results indicate that houses with wood-based wall systems require 15–16% less total energy for non-heating/cooling purposes than thermally comparable houses employing alternative steel- or concrete-based building systems. Results for non-renewable energy consumption are essentially the same as those for total energy, reflecting the fact that most of the displaced energy is in fossil fuels. Over a 100-year period, net greenhouse gas emissions associated with wood-based houses are 20–50% lower than emissions associated with thermally comparable houses employing steel- or concrete-based building systems. Assuming 1.5 million single-family housing starts per year, the difference between wood and non-wood building systems represents about 9.6 Mt of CO_2 equivalents per year. The corresponding energy benefit associated with wood-based building materials is approximately 132 PJ $year^{-1}$. These estimates represent about 22% of embodied energy and 27% of embodied greenhouse gas emissions in the residential sector of the US economy. The results of the analysis are very sensitive to assumptions and uncertainties regarding the fate of forestland that is taken out of wood production due to reduced demand for wood, the continued production of co-products where demand for wood products is reduced, and the rate at which carbon accumulates in forests.

1. Introduction

In 2001, the US residential sector required approximately 18.6 EJ of energy and was responsible for emission of 1.155 Gt of carbon dioxide (CO_2) [1,2], representing 18% of national energy requirements and 20% of national CO_2 emissions [1–3]. Heating and cooling accounted for 41% of the primary energy requirements and 36% of the CO_2 emissions within the residential sector, representing, in both cases, about 7% of the corresponding national figures. While the importance of residential heating and cooling is well understood, a less obvious source of residential energy and emissions impacts is

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associated with the manufacture, transport, and recycling or disposal of materials used in construction, renovation, and maintenance. This report examines the significance of these other energy requirements and greenhouse gas (GHG) emissions and how they vary among different building materials.

2. Embodied energy and CO_2 emissions

The embodied energy and emissions of residential structures usually include those associated with obtaining raw materials, manufacturing building materials, transporting materials to construction sites, and building the structures. Estimates of embodied energy relative to operational energy (primarily for heating and cooling) vary over a wide range—from less than 5% of operational energy to 50% or more over the lifetime of a structure. A number of US-based studies have suggested that embodied energy and CO_2 emissions can be approximated by assuming that embodied values for homes in the US are one-tenth of the energy and emissions associated with heating and cooling [4–8]. Using this approximation (based on building lifetimes of 75–100 years) and the information above, it appears that the embodied energy in residential construction materials is between 0.5 and 1 EJ $year^{-1}$ and that the embodied CO_2 emissions are between 30 and 60 million tonnes (Mt) $year^{-1}$ (not including the effects of carbon sequestration).

3. Review of past studies

Because thermal performance is so influential in determining the energy requirements of structures (potentially overwhelming the embodied energy contribution), this examination focuses on studies of structures with comparable thermal performance. In the studies identified in this review that were designed to compare embodied energy in systems with comparable thermal performance, wood-based wall systems and buildings were almost always found to have lower embodied energy and CO_2 emissions than comparable building systems using concrete, steel, or brick [4,5,9–17]. In one study, the wood-based system contained more embodied total energy than the steel-based system, but embodied nonrenewable energy and CO_2 emissions for the wood-based system were lower than for steel-, brick-, or concrete-based systems [18].

In several cases, prior studies found that concrete-based wall systems had lifetime operational energy requirements and GHG emissions (or related life cycle indicators) comparable to or lower than those associated with wood frame walls [6–8,19]. However, because embodied energy and emissions were not reported and because the studies were not designed to compare structures with comparable thermal performance, their significance to comparisons of embodied energy and emissions is not known. These studies suggest, however, that in some situations concrete-based wall systems may provide benefits in operational energy and emissions that are difficult for wood-based systems to match.

In studies where concrete-based systems have been found to have lower operational energy and emissions, this has generally been attributed to thermal mass [6–8,19–22]. Studies at Oak Ridge National Laboratory have demonstrated that the importance of thermal mass depends on local climate, with most benefits occurring in places with large diurnal temperature changes that encompass the human comfort zone [22]. Two studies where the modeling was done with tools that allow comparisons of embodied energy, and in some cases embodied emissions, have been identified for structures with approximately comparable thermal performance, including considerations of thermal mass for concrete-based systems. Both studies found that embodied energy for the wood-based systems was lower than that for concrete-based systems, even over a 75- to 100-year building life [5,10]. Because these studies were based on conditions in Minnesota, Illinois, and Toronto, caution is warranted in extrapolating the results to regions where the benefits of thermal mass would be expected to be more significant.

The benefits of steel-based construction systems are highlighted in a number of reports. These studies usually focus on (a) the recyclability of steel studs; (b) the fact that embodied energy and CO_2 emissions are a small part of life cycle energy and emissions; (c) the lower lifetime maintenance requirements for steel; and (d) the land area (and implied ecological impacts) associated with wood-based systems [23–27]. In studies comparing embodied metrics for thermally comparable systems, however, wood-based systems are generally found to have lower embodied energy and CO_2 emissions than comparable steel-based systems [4,5,10,16–18].

In summary, studies of alternative building systems demonstrate the importance of residential heating and cooling to life cycle energy requirements and CO_2 emissions associated with residential structures. For systems with comparable heating and cooling requirements, however, wood-based building systems generally contain lower embodied energy and CO_2 emissions than steel-, concrete-, and brick-based systems.

4. Approach to estimating potential substitution effects in the US

Attempts have been made to estimate the potential impacts of substituting one type of building system for another in, for instance, Finland, New Zealand, the EU, and the world [28–30]. None of the studies identified in this review attempted such estimates for the US. The results to date of the Consortium for Research on Renewable Industrial Materials (CORRIM) program, however, provide much of the information needed to develop these estimates (see detailed information at www.corrim.org and summary reports in [4,16,17,31]).

5. Description of the CORRIM assessment

In 1996, CORRIM was formed by 15 research institutions as a non-profit entity that would undertake research on the use of wood as a renewable material. CORRIM work to date has produced life cycle inventories (LCIs) of environmental inputs and outputs from forest regeneration through product manufacturing, building construction, use, and maintenance for several different residential structures. Details on the study and its findings can be found in Refs. [4,16,17,31–33], as well as on the Internet at http://www.corrim.org/reports/.

To study the use of alternative building materials, typical residential designs were used for a wood frame design and a steel frame design comparison for the cold climate in Minneapolis, Minnesota (latitude: 44.96194; longitude: −93.26694), and a wood frame design and a concrete design comparison for the hot and humid climate in Atlanta, Georgia (latitude: 33.74889; longitude: −84.39056). The designs reflected local building codes with matched thermal properties, including building envelope designs.

The Minneapolis structure consisted of solid wood framing members except for the floor joists, which were composite I-joists. Other wood structural components consisted of oriented strand board (OSB) sheathing for roof, walls, and floor, and pre-engineered roof trusses for the roof system. As a non-wood alternative, steel floor joists and wall studs were substituted for wood I-joists and wall studs, with an extra layer of exterior insulation to meet code requirements.

The wood and concrete Atlanta structures were a slab-on-grade single-story design (common features included concrete slab floor and wood truss roof with OSB sheathing). The wood design incorporated wood wall studs, whereas the concrete design included a concrete block wall system with furred out wood stud walls.

6. Using CORRIM data to develop nationwide estimates

Several additional steps were required to develop nationwide estimates from the CORRIM studies. The most important of these are described here. The boundaries of the systems being compared in this analysis are described in Table 1.

6.1. *Modeling forest carbon over large areas and long times*

The CORRIM assessment follows a single plot of managed forest over the lifetime of a house. The analysis described herein, however, is based on calculations performed over a large land base of sustainably managed forest for 100 years so that it can be assumed that the forest carbon stocks are constant, for all practical purposes, as long as the forest remains managed. (The USDA Forest Service reports that carbon stocks on private timberland are increasing by more than 200 Mt carbon year^{-1}, so an assumption of constant carbon stocks probably understates the carbon benefits of the forest products industry value chain [34].)

6.2. *Modeling carbon in surplus forest*

The modeling of substitution effects requires an assessment of the fate of what has been termed “surplus forest” [13]. Surplus forest is that which is no longer required for wood production when non-wood building materials are substituted. Market forces tend to cause surplus forest to be converted to other uses, and these alternative uses often result in large losses of carbon from the land area.

For the estimates described in this report it is assumed that 20% of surplus forest is cleared to accommodate other uses (e.g., agriculture or other development), essentially amounting to a land use leakage of 20%. This rate is near the lower end of the range suggested by the work of Murray et al. [35,36]. The analysis assumes that the remaining 80% of surplus forest is allowed to grow to steady-state maturity and is never harvested or cut for other purposes. Although forest owners are more likely to alter management regimes to produce wood for markets that remain strong, it is beyond the scope of this study to model the range of options open to landowners when the demand for building products softens. The importance of this assumption, as demonstrated in the sensitivity analysis discussed below, suggests that careful attention to the likely fate of surplus forest is warranted in studies of the substitution effects of wood products.

Carbon accumulation in the forest is modeled using Forest Inventory and Analysis (FIA) data as compiled and summarized by the USDA Forest Service’s Carbon On-Line Estimator (COLE) [37]. The two regions included in the CORRIM study were emulated by filtering the COLE data. The Pacific Northwest (PNW) case was modeled by Douglas-fir and hemlock in publicly owned forests west of the Cascade Mountain Range in Oregon and Washington. The Southeast (SE) case was modeled by loblolly and slash pine in privately owned forests in Alabama, Arkansas, Florida, Georgia, Louisiana, Mississippi, North Carolina, Oklahoma, South Carolina, Texas, and Virginia.

6.3. *Modeling carbon in products in use*

Although the estimates in this report are based on CORRIM carbon data for products in use, the data are handled differently than in the CORRIM assessment. The nationwide analysis described herein assumes a constant annual output of products and a first-order decay equation with generally accepted product half-lives to estimate how much of the carbon in various annual product cohorts (i.e., groups of products of the same age) remains in use over time. This approach is patterned on that used by the US government to prepare the annual forest products carbon inventory in that it follows each year’s production over time based on time-in-use equations and accepted product half-lives [38]. The method is described in detail elsewhere [39].

6.4. *Modeling carbon sequestration in products in landfills*

An end-of-life module was added to the CORRIM assessment. Based on time-in-use information, it calculates and sums the amounts of carbon leaving the products-in-use pool annually for each cohort. In addition, some of the building material for new construction is assumed to be discarded at the construction site and managed in the same way as end-of-life waste.

Carbon sequestration in the landfill is estimated based on the approach used by the US government to develop the national inventory of harvested wood products carbon in landfills [38]. The method is described by the Intergovernmental Panel on Climate Change [39], and the specific parameter values are primarily from USEPA [40]. Carbon placed in landfills in discarded forest products is divided into

Table 1 – System boundaries of residential house construction methods

Boundaries	Wood frame wall system	Non-wood frame wall system (*impacts in italics*)	GHG impact?	Energy impact?
Temporal	100 years	100 years		
Spatial	Sustainably managed forestland of adequate size to continuously produce enough wood to build 1.5 million wood-framed houses per year	Same amount of land as required to produce wood to build 1.5 million wood-framed houses per year; because less wood is needed "surplus" forest is allowed to accumulate carbon	Yes	No
Processes included	Raw materials extraction, transport, and manufacture of building materials (wood products, concrete, mortar, nails, structural steel, rebar, etc.)	Raw materials extraction, transport, and manufacture of building materials (wood products (*less*), concrete (*more*), mortar (*more*), nails (*less*), structural steel (*more*), rebar (*more*), etc.)	Yes	Yes
	Transportation of building materials[a]	Transportation of building materials[a] (*more*)	Yes	Yes
	Construction of houses with comparable thermal performance using conventional designs[a]	Construction of houses with comparable thermal performance using conventional designs[a] (*variable*)	Yes	Yes
	Carbon sequestered in house (e.g., wood products used in construction)	Carbon sequestered in house (e.g., wood products used in construction) (*less*)	Yes	No
	Carbon sequestered in landfill (e.g., debris placed in landfill)	Carbon sequestered in landfill (e.g., debris placed in landfill) (*less*)	Yes	No
	Methane released from landfill	Methane released from landfill (*less*)	Yes	No
	Energy reclaimed from combustion of debris	Energy reclaimed from combustion of debris (*less*)	Yes	Yes
Processes excluded	Energy for heating and cooling; houses designed to have comparable heating and cooling requirements	Energy for heating and cooling; houses designed to have comparable heating and cooling requirements	No	No
	Maintenance; assumed to be comparable for houses	Maintenance; assumed to be comparable for houses	No	No

[a] Data from CORRIM [4,31].

"permanently" stored carbon and decomposable carbon based on information presented by NCASI (57% permanently stored, the remainder decomposable) [41]. The conversion of decomposable carbon into gas is estimated using a first-order decay relationship with a rate constant of 0.03 year^{-1}.

6.5. *Modeling methane emissions attributable to products in landfills*

The end-of-life analysis also estimates methane emissions from discarded wood-based building materials in landfills. The calculations make use of the landfill carbon sequestration calculations discussed above and USEPA information on typical landfill design and operation. Half of the gas generated in landfills is assumed to be methane.

At the beginning of the analysis period, 49% of the debris placed in landfills is assumed to go to landfills equipped with systems for collecting and destroying methane generated from decaying wood materials. This is consistent with current practice [40]. This percentage is assumed to increase linearly to 75% by the end of the analysis period. In landfills equipped with covers and gas collection systems, 75% of generated landfill gas is collected, while 10% of the uncollected landfill gas becomes oxidized to CO_2 in the landfill cap material. These assumptions are consistent with the default assumptions used by USEPA in its assessments of landfill gas releases [40].

6.6. *Assumptions regarding co-products*

When non-wood building materials are used and the production of wood-based building materials is reduced, it is assumed that the co-products associated with wood-based building materials will continue to be produced at some other location in the same quantities as before the production of wood-based building materials was reduced.

7. Results

GHG emissions and energy impacts were modeled over a 100-year period. The analysis incorporated a 100-year house half-life [42], with all construction and demolition debris landfilled. Tables 2 and 3 show the results for constructing 1.5 million houses per year, a rate representative of recent years [43]. Results are presented in terms of cumulative differences over a 100-year period. GHG emission differences (including methane emissions from landfills; 1 tonne of methane is equivalent to 21 tonne of CO_2) are presented in terms of CO_2 equivalents (CO_2 Eq.) in units of Mt. Sequestration differences

Table 2 – Minneapolis (PNW) design cumulative emission differences (Mt CO_2 Eq.) and cumulative net energy impacts (EJ) [after 100 years for 1.5 million housing starts per year (based on a 100-year house half-life)]

Parameter	Units	Wood frame	Steel frame	Difference[a] (steel–wood)
Wood content of house	% by mass[b]	15.1	7.4	−7.7
Embodied emissions	Mt CO_2 Eq.	5558	7025	1467
Product sequestration	Mt CO_2 Eq.	−2051	−1106	944
Forest sequestration[c]	Mt CO_2 Eq.	0	−1965	−1965
Landfill sequestration	Mt CO_2 Eq.	−831	−448	383
Landfill methane	Mt CO_2 Eq.	419	226	−193
Net emissions	Mt CO_2 Eq.	3095	3731	636
Net energy (total energy)	EJ	98	115	17.0
Net energy (non-renewable energy)	EJ	93	112	18.9

[a] Negative number indicates that emissions are less for steel frame case than for wood frame case.
[b] Lippke et al. [4].
[c] Assumes loss of 20% of surplus forest; near the lower end of the leakage range suggested by Murray et al. [35,36].

Table 3 – Atlanta (SE) design cumulative emission differences (Mt CO_2 Eq.) and cumulative net energy impacts (EJ) [after 100 years for 1.5 million housing starts per year (based on a 100-year house half-life)]

Parameter	Units	Wood wall	Concrete wall	Difference[a] (conc.–wood)
Wood content of house	% by mass[b]	10.1	7.8	−2.3
Embodied emissions	Mt CO_2 Eq.	3206	4200	995
Product sequestration	Mt CO_2 Eq.	−1623	−1338	285
Forest sequestration[c]	Mt CO_2 Eq.	0	−57	−57
Landfill sequestration	Mt CO_2 Eq.	−657	−542	116
Landfill methane	Mt CO_2 Eq.	332	273	−58
Net emissions	Mt CO_2 Eq.	1256	2538	1282
Net energy (total energy)	EJ	60	69	9.5
Net energy (non-renewable energy)	EJ	57	66	9.7

[a] Negative number indicates that emissions are less for concrete wall case than for wood wall case.
[b] Lippke et al. [4].
[c] Assumes loss of 20% of surplus forest; near the lower end of the leakage range suggested by Murray et al. [35,36].

are also expressed in terms of Mt CO_2 Eq. (1 tonne of carbon is equivalent to 3.67 tonne of CO_2 Eq.). Energy differences are expressed in units of exajoule (EJ).

8. Discussion

In considering the effects of substituting wood for non-wood, it is important to realize that the amount of wood in the Atlanta house is only increased from 7.8% to 10.1% of the total mass and the amount in the Minneapolis house is only increased from 7.4% to 15.1% of the total mass [4]. Thus, a relatively small fraction of the mass in a residential structure can represent a significant opportunity for improving the structure's embodied energy and GHGs.

The substitution effects examined here should be considered in the context of current practices for single-family housing construction. Wood-based materials have a large majority of the current market for structural support elements in exterior walls. In 2001, steel wall framing held only 2% of the wall framing market, while concrete represented about 9% of the market [44]. These figures indicate that the US already enjoys about 90% of the carbon and energy benefits (identified below) associated with using wood-based building materials in exterior wall systems.

8.1. *Embodied emissions*

The difference in embodied GHG emissions between construction techniques increases linearly over time as houses are constructed. Results indicate that non-wood houses are associated with greater embodied GHG emissions than wood frame houses. The GHG emissions difference is greater for the Minneapolis case due to the greater degree of substitution in the steel frame house than in the concrete wall house of the Atlanta case, and to the high embodied emissions associated with steel.

8.2. *Product sequestration*

More carbon is stored in houses built using wood-based construction techniques than in steel- or concrete-based techniques. Product sequestration results are influenced by the assumed house half-life, with longer half-lives resulting in more carbon stored in products in use. There is a greater difference in product sequestration between wood-based construction and non-wood systems in the Minneapolis case because there is more wood involved in the substitution for the steel frame (Minneapolis) house.

8.3. Forest sequestration

The forest sequestration difference between construction techniques is greater for the Minneapolis case (steel frame vs. wood frame) than for the Atlanta case (concrete wall vs. wood wall) due to the greater degree of alternative building material substitution in the Minneapolis case and the much greater carbon storage capacity of the PNW forests assumed to supply wood for construction of houses in Minneapolis. The PNW forests modeled in the analysis are some of the highest carbon capacity forests in the US, and therefore represent the upper end of the range of potential benefits associated with non-wood construction materials.

8.4. Landfill sequestration

As new houses are built or existing houses are renovated, expanded, maintained, or demolished, construction debris is deposited in landfills. The results in Tables 2 and 3 illustrate that wood-based houses are associated with a greater degree of carbon sequestration in landfills than houses built using non-wood materials. Furthermore, the difference in landfill sequestration between the different construction techniques is more pronounced in the Minneapolis case than in the Atlanta case due to the greater building material substitution in the Minneapolis case.

8.5. Landfill methane

Methane is generated as cellulosic materials in landfills (where conditions are typically anaerobic) degrade. The landfill methane emission estimates in Tables 2 and 3 indicate that the non-wood building material techniques are associated with lower landfill methane emissions than wood-based, conventionally built houses due to the greater amount of wood debris disposal from wood-based houses.

8.6. Net GHG emissions

Wood-based construction techniques are associated with lower net GHG emissions than the alternative material construction techniques. The cumulative net GHG emissions difference for the Atlanta design represents a reduction of approximately 50% in net emissions for the wood-based house compared with the concrete-based house. The net GHG emissions difference for the Minneapolis design represents a reduction of about 20% in net emissions for the wood-based system compared with the steel-based system. The benefits are less in the Minneapolis case primarily because of the assumptions regarding forest carbon sequestration. At the current rate of 1.5 million housing starts per year, the use of wood instead of concrete or steel is estimated to result in benefits (i.e., reductions) of 12.8 Mt (wood vs. concrete) and 6.4 Mt (wood vs. steel) of CO_2 year^{-1}, averaging 9.6 Mt year^{-1}. This represents 11–43% (averaging 27%) of the 30–60 Mt of embodied CO_2 emissions associated with the US residential sector.

8.7. Embodied energy

Embodied energy, computed as total embodied energy and as non-renewable embodied energy (total minus hydro and biomass), increases linearly as the number of houses increases. The difference in embodied energy between the wood and concrete wall houses (Atlanta designs) over the 100-year analysis period, based on 1.5 million housing starts per year, is 9.5 EJ (total energy) or 9.7 EJ (non-renewable energy). For the Minneapolis designs (wood vs. steel frame houses) the difference in embodied energy between the construction techniques is 17.0 EJ (total energy) or 18.9 EJ (non-renewable energy). These embodied energy differences correspond to an approximately 15% greater energy demand associated with the construction of concrete wall houses compared with that associated with wood wall houses (Atlanta designs) and about 16% more total energy (19% more non-renewable energy) required to construct steel frame houses than to construct wood frame houses in Minneapolis. These results are consistent with the results from Lippke et al. [4], which is to be expected because the energy impacts are associated primarily with differences in embodied energy and the data for embodied energy were from the CORRIM study [4].

Nationwide savings in total energy consumption are estimated to be 95 PJ year^{-1} (wood vs. concrete) and 170 PJ year^{-1} (wood vs. steel), averaging 132 PJ year^{-1}. These figures represent 10–34% (averaging 22%) of the 0.5–1.0 EJ year^{-1} of embodied total energy associated with the US residential sector. This total energy impact is approximately the same as the impact on non-renewable energy because almost all of the total energy benefits are associated with reduced use of non-renewable energy sources (i.e., fossil fuels).

9. Sensitivity analysis

Tables 4–7 present the results of a sensitivity analysis for the two scenarios investigated in this study, steel frame vs. wood frame houses (Minneapolis case) and concrete wall vs. wood wall houses (Atlanta case). Changing the period of analysis from 100 to 250 years increased the net GHG benefit of using wood-based construction materials primarily because the surplus forest carbon sequestration benefits associated with non-wood materials saturates after 150 years. The net energy benefit of wood-based construction increased linearly (by 150%) upon extending the analysis period.

Assumptions regarding the fate of surplus forest were found to introduce one of the largest sources of uncertainty. The fraction of surplus forestland lost to other uses was varied from the base case of 20% to 10% and 90%, encompassing the range of leakage indicated by Murray et al. [35,36]. Changing land use leakage from 20% to 10% resulted in a 48% decrease in the net GHG benefit of wood-based building materials for the Minneapolis case. Under a 90% leakage scenario the GHG benefit for wood-based building methods

Table 4 – GHG impacts sensitivity analysis results for the Minneapolis case (PNW, steel frame vs. wood frame houses)

Parameters evaluated (base value shown)	Variation in parameter (test value in parentheses)	Impact on result (%)[a]
Period of analysis—years (100)	+150% (250 years)	441
Land-use leakage—fraction (0.2)	−50% (0.1) +350% (0.9)	−48 309
Co-product leakage—fraction (1.0)	−25% (0.75)	−102
Rate of carbon accumulation in forest (615 tonne carbon ha^{-1} asymptote)	−25% (461 tonne carbon ha^{-1} asymptote) +25% (768 tonne carbon ha^{-1} asymptote)	90 −86
Landfill methane generation parameters	(50% permanent storage, 0.04 year^{-1} rate const.)	−16
(57% perm. storage, 0.03 year^{-1} rate const.)	(85% permanent storage, 0.02 year^{-1} rate const.)	36
Half-life of house—years (100)	−50% (50 years) +50% (150 years)	−22 9
Recovery and recycling of construction/ demolition debris—fraction (0.0)	(0.5)	−15
Energy recovery from non-recycled construction/demolition debris—fraction (0.0)	(0.25) (1.0)	0.4 1.4

[a] Results are expressed as net emissions difference between steel and wood frame houses over the analysis period; positive values represent higher emissions for the steel frame houses.

Table 5 – GHG impacts sensitivity analysis results for Atlanta case (SE, concrete wall vs. wood wall houses)

Parameters evaluated (base value shown)	Variation in parameter (test value in parentheses)	Impact on result (%)[a]
Period of analysis—years (100)	+150% (250 years)	133
Land-use leakage—fraction (0.2)	−50% (0.1) +350% (0.9)	−1.5 4.4
Co-product leakage—fraction (1.0)	−25% (0.75)	−0.3
Rate of carbon accumulation in forest (85.1 tonne carbon ha^{-1} asymptote)	−25% (63.9 tonne carbon ha^{-1} asymptote) +25% (106 tonne carbon ha^{-1} asymptote)	3.0 −3.0
Landfill methane generation parameters	(50% permanent storage, 0.04 year^{-1} rate const.)	−2.4
(57% perm. storage, 0.03 year^{-1} rate const.)	(85% permanent storage, 0.02 year^{-1} rate const.)	5.4
Half-life of house—years (100)	−50% (50 years) +50% (150 years)	−3.4 1.4
Recovery and recycling of construction/demolition debris—fraction (0.0)	(0.5)	−2.2
Energy recovery from non-recycled construction/demolition debris—fraction (0.0)	(0.25) (1.0)	0 0.2

[a] Results are expressed as net emissions difference between concrete and wood wall houses over the analysis period; positive values represent higher emissions for concrete wall houses.

tripled for the Minneapolis case. The effects of assumptions related to the surplus forest were minor for the Atlanta case.

In the sensitivity analysis, co-product leakage was changed from a baseline assumption of 100% to a value of 75%, meaning that instead of assuming that all co-products would continue to be produced when wood use declined, only 75% would be produced. The study did not consider the impacts associated with the production of other materials to meet the demand that had been satisfied by the displaced 25%. Ignoring these impacts understates the benefits of the wood-based building materials in this study. This change had a large effect on the GHG comparison for the Minneapolis case. This was again due to the high carbon storage potential of the surplus forest created when wood-based co-product production was reduced. There was almost no impact on the results for the Atlanta case.

The sensitivity analysis included evaluations of two additional characterizations of carbon accumulation in surplus forests for each of the regions in this study, increasing and decreasing maximum carbon storage by 25%. The effects were only significant for the Minneapolis case. Decreasing the maximum carbon storage almost doubled the net GHG benefit of wood-based construction techniques for the Minneapolis case. Increasing carbon storage virtually eliminated the net GHG benefit of the Minneapolis case, although over time the wood-based house would eventually regain the large advantage due to the saturation of forest carbon benefits, as described above.

Adjusting the landfill parameters had significant effects on only the Minneapolis case. Adjustments that decreased landfill carbon sequestration and increased methane emissions decreased net GHG benefits of wood-based building materials by 16%, while adjusting the parameters to increase landfill sequestration resulted in increased net GHG benefits for wood-based building materials of about 36%.

House half-life was adjusted by ±50% (to 50 and to 150 years) in the sensitivity analysis. Changing the half-life had a

Table 6 – Energy impacts sensitivity analysis results for the Minneapolis case (PNW, steel frame vs. wood frame houses)

Parameters evaluated (base value shown)	Variation in parameter (test value in parentheses)	Impact on result (%)[a]
Period of analysis—years (100)	+150% (250 years)	150
Energy recovery from non-recycled construction/demolition debris—fraction (0.0)	(0.25) (1.0)	6.0 24

[a] Results are expressed as net emissions difference between steel and wood frame houses over the analysis period; positive values represent higher emissions for steel frame houses.

Table 7 – Energy impacts sensitivity analysis results for the Atlanta case (SE, concrete wall vs. wood wall houses)

Parameters evaluated (base value shown)	Variation in parameter (test value in parentheses)	Impact on result (%)[a]
Period of analysis—years (100)	+150% (250 years)	150
Energy recovery from non-recycled construction/demolition debris—fraction (0.0)	(0.25) (1.0)	3.2 13

[a] Results are expressed as net emissions difference between concrete and wood wall houses over the analysis period; positive values represent higher emissions for concrete wall houses.

significant effect on net GHG benefits only for the Minneapolis case, where a shorter half-life reduced benefits by 22% and a longer half-life increased net benefits by 9%.

Based on McKeever's findings [45,46], the effect of increasing recovery and recycling of debris was investigated by assigning a rate of 50%. Although modest benefits were associated with recovery, the results must be used with caution because they do not include the probable reduced energy and emissions that would result from replacing virgin production with recycled materials, nor do they consider the potential for increased carbon sequestration in the forest due to use of recycled materials.

Energy recovery from construction and demolition debris is a feature of many of the European life cycle studies of building products. These studies have found that energy recovery provides significant life cycle energy benefits [9,13,15,47]. The impacts of recovering energy from debris were investigated in two scenarios: by assuming that 25% and 100% of debris were recovered. Although the GHG impacts were modest, the total net energy benefits of wood-based house construction increased by 24% for the Minneapolis case and by 13% for the Atlanta case when all construction and demolition debris was assumed to be recovered for energy production.

10. Summary and conclusions

Using data from CORRIM, life cycle energy requirements and greenhouse gas (GHG) emissions were compared for houses with comparable heating and cooling requirements but different construction materials. The differences were examined for a 100-year period. The results indicate that houses built with wood-based systems required about 15–16% less total energy for non-heating/cooling purposes than thermally comparable houses employing alternative steel- or concrete-based building systems. The results for non-renewable energy consumption were essentially the same as those for total energy, reflecting the fact that most of the displaced energy was in fossil fuels.

The GHG benefits of substituting wood for non-wood building materials are generally greater than the energy benefits. This study found that net GHG emissions associated with wood-based houses were 20–50% lower than those associated with thermally comparable houses employing steel- or concrete-based building systems. Only a small fraction of the building materials needed to be changed to accomplish these improvements. In the Atlanta example the additional wood used in the wood-based house represented only 2.3% of the mass of the house, while in the Minneapolis example the additional wood used in the wood-based house represented 7.7% of the mass.

Assuming the current rate of approximately 1.5 million housing starts a year, the difference between wood and non-wood building systems represents about 9.6 Mt CO_2 Eq. year^{-1}. The corresponding energy benefit associated with wood-based building materials is approximately 132 PJ year^{-1}. These figures represent approximately 22% of the embodied energy and 27% of the embodied GHG emissions in the residential sector of the US economy.

The GHG emissions profiles developed for the Atlanta and Minneapolis comparisons were very different. Embodied emissions for the Atlanta designs had far more effect on the overall results than those for the Minneapolis designs. Sequestration of carbon in forests was the most important factor for the Minneapolis designs because they relied on forests that were assumed capable of accumulating carbon to very high levels. Longer analysis periods diminished the relative importance of forest sequestration.

A sensitivity analysis revealed that the most important sources of uncertainty in this analysis were the fate of forestland taken out of wood production due to reduced demand for wood (land use leakage), production of co-products when the demand for primary wood products is reduced (co-product leakage), and assumptions about carbon accumulation in forests. Additionally, the sensitivity analysis demonstrated the importance of examining time horizons sufficiently long to distinguish between short-term and long-term effects.

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