WBGU
Wissenschaftlicher Beirat der Bundesregierung
Globale Umweltveränderungen

Materialien

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Can Use of Wood in Future Infrastructure Development Reduce Emissions of CO_2?

Expertise für das WBGU-Sondergutachten
„Entwicklung und Gerechtigkeit durch Transformation: Die vier großen I“

Berlin 2016

CAN USE OF WOOD IN FUTURE INFRASTRUCTURE DEVELOPMENT REDUCE EMISSIONS OF CO_2?

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July 19, 2016

Summary

The anticipated growth of urban population will require immense development of housing and other accompanying infrastructures. Production of currently wide-spread construction materials such as steel, cement, and aluminum is associated with high demands of energy as well as emissions of greenhouse gases (GHG). If the global population to increase to 9.3 billion and the developing countries are to build infrastructures similar to the ones in developed countries, then 350 Gt of carbon dioxide (CO2) will be emitted only from the production of construction materials needed to develop these infrastructures. Using wood materials in construction can reduce net CO2 emissions in several ways: less energy is needed to manufacture wood products compared with alternative materials; non-energy process emissions associated with the alternative materials can be avoided (e.g., CO2 emissions in the calcination reaction used in production of cement); carbon is stored in the wood infrastructures for a long time; and the byproducts of the wood material production can be used as biofuel to replace fossil fuels.

In this study, I estimate to what degree CO2 emissions from material production can be reduced, if wood is used to build infrastructures in the future. To calculate how much wood would be needed instead of steel, cement, and aluminum, I first assume the share of steel, cement, and aluminum for building housing out of the total material stock used for infrastructure development. Then, I estimate the wood mass required to replace these infrastructures. Finally, I calculate CO2 emissions from manufacturing the wood materials needed for construction and compare them to the respective CO2 amount emitted from production of steel, cement, and aluminum.

This study suggests that the use of natural materials, especially wood, can substantially reduce emissions of GHG associated with future manufacturing of construction materials required to accommodate needs of the growing world's population. Wooden buildings can also serve as sizable carbon storage with a long carbon residence time. However a substantial share of the world's forests would have to be harvested to meet the potential demand for wooden construction materials. It remains to be seen if it is possible on a sustainable basis. It is also questionable if full transition from steel and concrete construction materials to alternative materials is possible. New construction materials based on wood as well as other natural products like clay or biochar have to be explored in order to mitigate emissions of CO2 and global warming.

Introduction

Keeping global warming below 2° C requires substantial reduction of emissions of greenhouse gases primarily from burning fossil fuels, but also from land use change. How to reduce these emissions? A recent study suggest that if the global population to increase to 9.3 billion by 2050, then the emissions from development of infrastructures necessary to accommodate population growth will be 350 Gt CO2 equivalents (1 Gt = 10^9 t = 1 PgC) from manufacturing of needed materials only (Müller et al., 2013). These emissions correspond to about 35-60% of the remaining carbon budget available until 2050 if the average temperature increase is to be limited to 2° C and could compromise the 2° C target. In that study the infrastructure definition is very broad. It covers buildings, roads, piping, cars, machinery, containers, packaging materials, etc. Three key materials such as steel, cement, and aluminum are used as proxies for current infrastructures. 350 Gt of CO2 were emitted from materials used in development of infrastructure including all the abovementioned categories, assuming that the developing countries are to build infrastructures similar to the ones in developed countries. In-depth studies of individual material cycles suggest that most of the current stocks reside in the building and construction sector.

Aluminum stocks are negligible in rural societies, and then continue growing in postindustrial societies (Liu and Müller, 2013). The average fraction of aluminum used in construction is 24% globally (Cullen and Allwood, 2013). 80% of the global aluminum stocks reside in 15 countries with USA, China, Germany and Japan appearing at the top (Liu and Müller, 2013). Most of aluminum in these countries is stored in buildings & construction and transportation sectors with 40% and 27% respectively. The present level of aluminum stocks vary widely across countries. Industrialized countries have stocks 1-6 times higher than the world average. The wide range of aluminum stocks and their distribution between different products differs from estimations for steel in-use stocks, where difference among industrialized countries is relatively small and stock's growth has reached saturation (Pauliuk et al., 2013). In contrast, no sign of saturation in aluminum stock's growth in developed countries is observed (Liu and Müller, 2013).

Half of the world's annual production of steel is used in constructing buildings and infrastructure (Wang et al., 2007). In countries with long industrial history such as USA, the UK, or Germany the steel stock is accumulating slowly or reached a saturation point, which is 13±2 tons of steel per capita (Pauliuk et al., 2013). In mature steel stocks most of steel is stored in construction 75%. Transportation, machinery, and appliances hold substantially smaller fractions with 11%, 10%, and 4% respectively. For the construction sector it is not yet known, which types of structures use the largest aggregated tonnage of steel, not the predominant products that these structures are constructed from (Moynihan and Allwood, 2012). (Moynihan and Allwood, 2012) provide distribution of steel within a typical building, which is a three-story office block of braced-frame construction. Within a typical building most steel is found in the floor structure: 55-70%, regardless of whether the frame is made from steel sections or reinforced cement. The lower data points are for reinforced cement-framed systems, while the higher points are for steel frames systems. Substructure including foundation and/or basement contains 5-35% of steel. It contains more steel to resist soil and water loads and climate dependent. Non-structural steel is usually the smallest category. It can constitute however one third of the total amount of steel if a steel façade is used. Most of these construction elements have a potential to be replaced by wood, except perhaps the elements incorporated in a basement/foundation of building. These estimates are mostly based on data for Europe and USA and do not include estimates from large developing nations such as China and India. Recent modeling study suggest that CO2 emissions from steel production can be radically reduced in the future, but is less optimistic about the cement production (Van Ruijven et al., 2016).

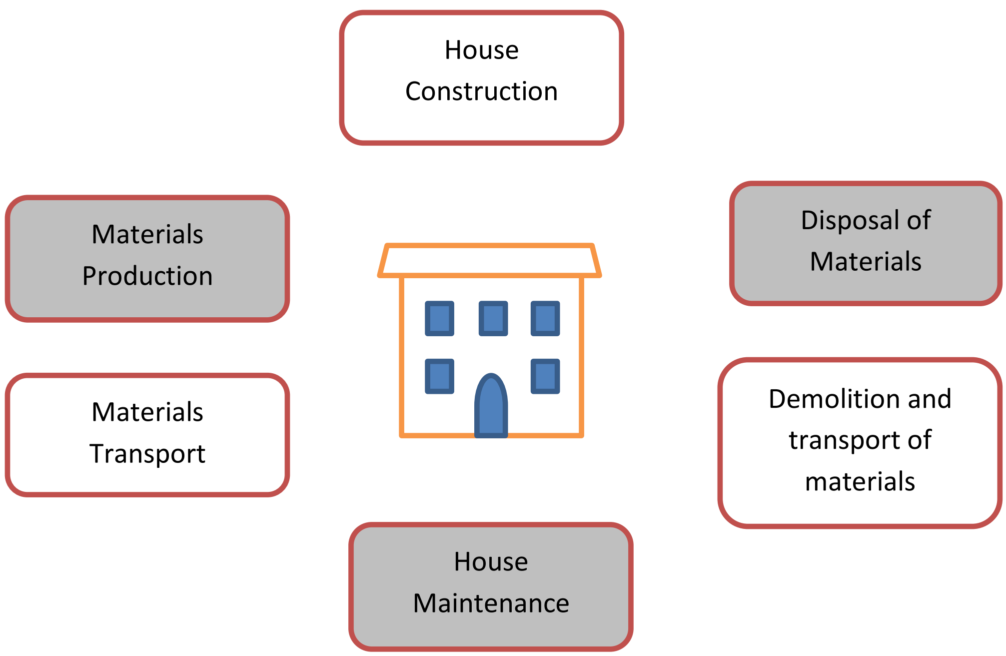

Figure 1. Major stages in a lifecycle of a house. Shaded boxes show where use of wooden material has a potential to reduce emissions of greenhouse gases. Emissions from material transport would be dependent on the distances between material source- material's manufacturing – house location.

Given that most materials with high emission intensity currently reside in construction and building sector, an option to build new settlements with materials, which manufacturing requires less energy and therefore less greenhouse gases are emitted, has to be explored. Using wood materials in construction can reduce net CO2 emissions in several ways: less energy is needed to manufacture wood products compared with alternative materials; non-energy process emissions associated with the alternative materials can be avoided (e.g., emissions of CO2 of the calcination reaction used in production of cement); and the byproducts of the wood material production can be used as biofuel to replace fossil fuels (Figure 1). Some studies also suggest that less energy is required for a wooden house keeping it cool in summer and warm in winter. A study of residential construction in the US found 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 cement-based building systems (Upton et al., 2008). Emission savings in material transport are only possible if the wooden building is constructed in a forested region and is built with local wooden materials. An additional benefit of a wooden building is that carbon can be stored in the infrastructures made of wood for a long time.

Churkina et al (2010) estimated that by the year 2000 carbon storage attributed to human settlements of the conterminous US was 18 Pg of carbon or 10% of its total land carbon storage. Based on this estimate, human settlements store more carbon than the US croplands, which store 14PgC± 7 (King et al., 2007) on the area of 1,718,531 km^2 *(Brown et al., 2005)*. 64% of this carbon was attributed to soil, 20% to vegetation, 11% to landfills, and 5% to buildings. Organic carbon is also stored in buildings in substantial amounts. This carbon is incorporated in the building's structure (including framing, flooring, roofing, and walls), furniture, books, and other organic materials. According to our estimates 87-91% of total carbon in buildings was stored in the structure of private houses, 3-7% - in commercial buildings, and 3-10 % - in furniture. The amount of carbon per unit of floor area depends on the purpose of a building (e.g., private houses have more carbon than commercial buildings) and on the building's location. The general trend is that the houses in the North have more wood per floor area than in the South (Wilson, 2006). The wood use per unit of floor area of a house is highly variable. In the conterminous US it varies by a factor of three on average (Keoleian et al., 2000; Meil et al., 2007; Wilson, 2006).

Several studies suggested that the greenhouse gas emissions from manufacturing of building materials were responsible for a very high proportion of the total greenhouse gas emissions of a home over its life time (Carre, 2011; Cha et al., 2011). The contribution of greenhouse gas emissions from production building material becomes even more important as regulatory requirements for minimum energy efficiency increase. Carre (2011) demonstrated that greenhouse gas emissions from building materials contribute 14-24% of total emissions of a 5-star home and 17-29% of a 6-star home in Melbourne, Australia. The Nationwide House Energy Rating Scheme in Australia uses star rating system (out of 10) to rate the energy efficiency of a home, based on its design. 10-star house complies with the highest energy efficiency standards. The contribution of emissions of greenhouse gases from the building materials increases to up to 50-51% of total emissions when steel framing was used in the temperate climates of Brisbane and Sydney, Australia, where the house was designed for 6-star energy efficiency. Although studies for Australia (Carre, 2011), Asia (Cha et al., 2011), Europe (Gustavsson and Sathre, 2006; Peuportier, 2001), and the US (Lippke et al., 2004) suggest that transition from steel-and-cement buildings to wooden ones brings substantial reductions in associated greenhouse gas emissions, global scale estimates of transition from conventional building materials to wooden ones have not been yet performed.

Here we investigate how transition to wooden construction of infrastructure can reduce emissions of CO2 equivalents associated with production of respective materials. Carbon dioxide equivalent is a measure used to compare the emissions from various greenhouse gases based upon their global warming potential. To calculate how much wood would be needed instead of steel, cement, and aluminum, we first assume the share of steel, cement, and aluminum for buildings out of the total material stock used for infrastructure development. Then, we estimate the wood mass required to replace these infrastructures. Finally, we calculate CO2 emission equivalents from manufacturing the wood materials needed for construction and compare them to the respective CO2 amount emitted from production of steel, cement, and aluminum.

Methods

The existing estimates of CO2 emissions from infrastructure development are based on the top-down estimates of CO2 emissions from production of steel, cement, and aluminum materials (Müller et al., 2013). The CO2 emissions are estimated for existing global infrastructure stocks in 2008 and then, projected for 2050 using per capita emissions from material production in industrialized countries. We would like to build some of future infrastructures, but not all of these with wood. Production of materials for infrastructures used for piping, transportation, industrial equipment, etc. is included in the abovementioned estimates, but cannot be replaced with wooden materials.

Limited data are currently available to perform these calculations at the global scale. Therefore, we upscale available estimates using several assumptions described below.

Assumptions

- The buildings build of aluminum, cement, and steel available by 2008 are still available in 2050. New materials were not needed during that period for renovation or rebuilding existing housing stock, because of building's disintegration, natural disasters, or wars.

- The shares of the steel and aluminum stocks, which are currently, used in construction in Annex I countries, and corresponding CO2 emissions are completely replaced by wood and respective CO2 emissions in the future.

- As in (Müller et al., 2013) all cement is assumed currently to be used for construction and can be replaced by wood. No cement is produced in the future and no corresponding CO2 emissions occur.

- New buildings to accommodate population growth from 2008 to 2050 will be constructed out of generic wooden materials. We did not account for different types of wood. We consider two types of wooden materials with contrasting energy requirements for manufacturing and respective CO2 emissions. These are plywood with high CO2 emissions and log with low CO2 emissions.

- The newly-built houses have maximum mass of wood per capita found in the literature. This maximum mass corresponds to the mass of wood in a log house. The houses made of plywood and of log have the same mass of wood per capita.

Estimations

Emissions from development of new infrastructures by 2050

To estimate how much CO2 will be emitted from future infrastructure development assuming that buildings are mostly built from wood (E_{2050}^{W}) we used the following equation:

$E_{2050}^{W} = (P_{2050} - P_{2008}) * (E_{ACS} - E_{ACS\text{-}C} - E_{W})$, where

P_{2050} = 9.31 billion – world's population in 2050 (UN, 2011),

P_{2008} = 6.76 billion – world's population in 2008 (UN, 2011),

E_{ACS} = 51 t CO_2 eq./capita - per capita total average emissions from production of aluminum, cement, and steel in Annex I countries (Müller et al., 2013),

$E_{ACS\text{-}C}$ – per capita total emissions from production of aluminum, cement, and steel currently used in construction,

E_W – per capita average CO_2 emissions associated with production of future buildings assuming mostly wooden materials.

We also re-calculate the emissions from future infrastructure development assuming future construction out of steel, cement, and aluminum (E_{2050}^{ACS}) using the same assumptions and method used in this study and data from Mueller et al. (2013):

$$E_{2050}^{ACS} = (P_{2050} - P_{2008}) * E_{ACS}$$

This method is different from the method used by Mueller et al. (2013), who did not clearly explained the assumptions used in their projections. They used the following equation:

$$E_{2050}^{ACS} = P_{2050} * E_{ACS} - E_{2008},$$ where

E_{2008} = 122 Gt CO_2 eq - emissions embodied in existing material stocks.

Emissions from production of aluminum, cement, and steel used in constructions

We used material stocks of Annex I countries in 2008 from Mueller et al. (2013) as a reference (Table 1) in these calculations. The average fraction of total aluminum products used in construction is 24% globally (Cullen and Allwood, 2013) and 40% in 15 countries with the largest aluminum stocks (Liu and Müller, 2013), which is split between buildings' structure, non-structural elements, and infrastructures. Published lists of major materials for wood framed houses do not contain aluminum (Gustavsson and Sathre, 2006). Therefore, we assumed that all aluminum currently used in construction in countries with the largest aluminum stocks (40% of current stock) could be replaced by wood. Approximately 50% of the global steel stock is used in construction (Wang et al., 2007). In industrialized countries buildings and construction sector is responsible for 75% (Pauliuk et al., 2013) of the total steel stock. Here we assume that 75% of the steel stock is used in construction.

Table 1. Material stocks of steel, cement, and aluminum in 2008, fractions of total stocks used in construction and respective references.

Material	Material stocks in Annex I countries [Gt] (Müller et al., 2013)			Fraction of the total material stock used in construction [%]	
	low	medium	high	global average	mature stock
Steel	18.6	23.6	27.2	50 (Wang et al., 2007)	75 (Pauliuk et al., 2013)
Cement	52.5	57	57.5	100 (Müller et al., 2013)	100 (Müller et al., 2013)
Aluminum	0.4	0.5	0.6	24 (Cullen and Allwood, 2013; Liu and Müller, 2013)	40 (Liu and Müller, 2013)

To calculate per capita total emissions from production of aluminum, cement, and steel for building and construction sector of the Annex I countries ($E_{ACS\text{-}C}$) we use the following equation:

$$E_{ACS\text{-}C} = \frac{M_s * f_s * k_s + M_c * f_c * k_c + M_a * f_a * k_a}{P_{2008}^{I}},$$ where

M_s, M_c, M_a – are the medium steel, cement, and aluminum material stocks respectively of the Annex I countries (Table 1),

f_s, f_c, f_a – the fractions of the steel, cement, and aluminum stocks respectively used in construction from Table 1 divided by 100,

k_s, k_c, k_a – the CO2 equivalent emission coefficients for steel, cement, and aluminum respectively as in Table 2,

P_{2008}^{I} = 1.35 billion - population of the Annex I countries in 2008.

Emissions from production of wooden construction materials

We estimate CO2 emissions to produce wooden construction materials assuming the coefficient typical for plywood and the coefficient typical for log (Table 2). These emission coefficients multiplied by the mass of dry wood in house per capita (see above) provide maximum and minimum CO2 amounts emitted with production of wooden materials used in a house.

To calculate per capita average CO2 emissions associated with production of future wooden buildings (E_W) we use the following equation:

$E_W = k_w * M_w^c$, where

k_w - the CO2 equivalent emission coefficients for plywood or log materials from Table 2,

M_w^c - the mass of dry wood in a house per capita.

We estimate mass of dry wood per capita in a house build of wood (M_w^c) using the maximum mass of wood per floor area found in literature was for a log house (Ruuska, 2013) and the average of floor area per person for EU 27 + Croatia & Serbia in 2008 including both residential (33.74 m2/capita) and service buildings (11.04 m2/capita) (Sebi et al., 2013). We use the following equation:

$M_w^c = M_w^f * A^f$, where

M_w^f = 524 kg/m2 - mass of wood per floor area,

A^f = 45 m2/capita - the average of floor area per person for EU 27 + Croatia & Serbia in 2008.

Table 2. Coefficients CO2 emission equivalents for steel, cement, aluminum, plywood, log, and corresponding references.

Material	Steel	Cement	Aluminum	Plywood	Log
Emission coefficients [t CO2 -eq./t]	2.94	0.8	13.67	1.05	0.12
Reference	(Müller et al., 2013)	(Müller et al., 2013)	(Müller et al., 2013)	(Ruuska, 2013)	(Ruuska, 2013)

Results & Discussion

Emissions from development of new infrastructures by 2050

Results of this study suggest that construction of buildings mostly of wood can substantially reduce the future CO_2 emissions from production of construction materials. We estimate that ~33 Gt of CO_2 equivalents would be emitted from infrastructure development if all new future buildings are constructed with logs (Figure 2). In case plywood is used for construction of the future wooden buildings, 89 Gt of CO_2 will be emitted from its production. These emissions would be respectively ~11 and ~ 4 times lower, than the total emissions from using conventional materials such as cement, aluminum, and steel estimated at 350 Gt of CO_2 equivalents by 2050 (Müller et al., 2013). Here, the estimates of CO_2 reduction indicate probably the highest CO_2 savings possible, because we assume that no cement is produced in the future and the manufacturing of aluminum and steel materials are reduced by respectively 40% and 75% relative to the current in-use stocks documented for the Annex I countries (Müller et al., 2013). Our total estimations are on the low side, because we assumed that there was no need for materials for renovation and for rebuilding of existing housing stock and consequently no associated emissions are included in these estimations.

Because here we use a slightly different method to project CO_2 emissions from production of future materials assuming construction of buildings is dominated by wooden structures, we calculate the total emissions from production of future conventional construction materials also using a method identical to the one used in this study. Then the total emissions from production of future steel, cement, and aluminum infrastructures assuming per capita emissions from material production in Annex I countries are 130 Gt of CO_2 equivalents (Figure 2), which is substantially lower than 350 Gt of CO_2 estimated by Mueller et al. (Müller et al., 2013). In this case the gains from future wooden constructions amount to ~4 and ~1.5 times for log and plywood construction respectively. More accurate scenarios for future development of construction sector, which would explicitly include emissions from production of materials for house renovation and replacement of demolished housing stock, would be beneficial to decide which estimate is more plausible.

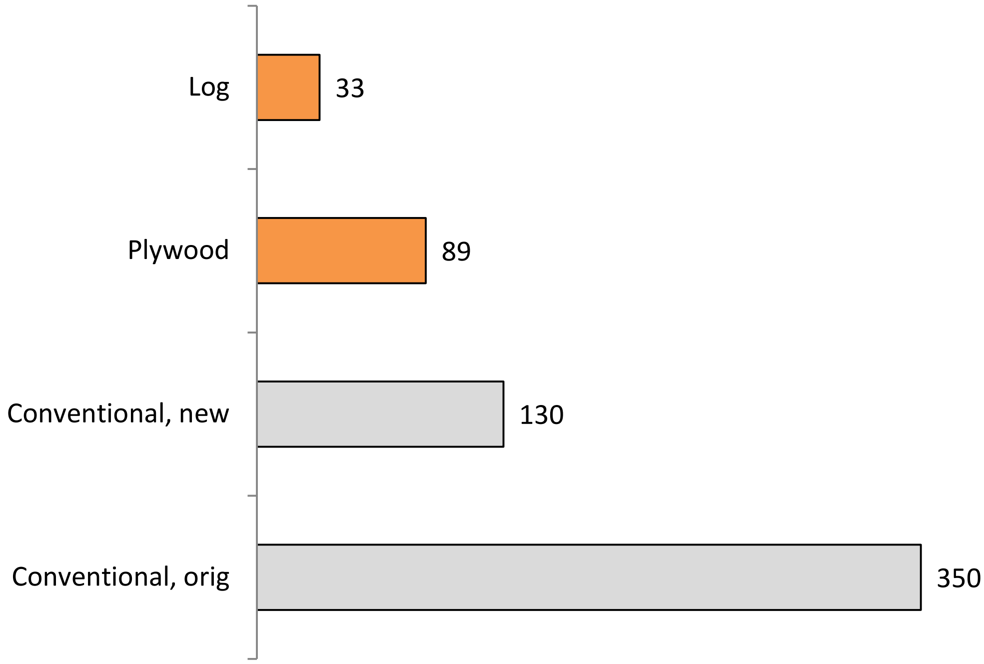

Figure 2. CO_2 emissions from material manufacturing (Gt) needed for the infrastructure development by 2050. Emissions from materials production of four different scenarios are considered with logs, plywood, conventional materials using the estimation method from this paper, and conventional materials using the original estimation method from Mueller et al. (Müller et al., 2013). Orange bars depict emissions from production of materials assuming most of future construction is dominated by wood. Grey bars refer to emissions from production of conventional construction materials such as aluminum, steel, and cement.

The emissions from production of wooden materials for construction by 2050 are much lower than from production of cement, aluminum, and steel. Here, we estimate that only 7 Gt of CO_2 equivalents would be emitted if the future buildings are built with logs (Table 3). The emissions are substantially higher (~63 Gt of CO_2 equivalents), if plywood is used instead, because of higher energy requirements for its production. These estimations were based on the assumptions that wood infrastructures can replace infrastructures out of cement, steel, and aluminum everywhere in the world. The feasibility of this replacement still has to be tested using at least technical, cost, and local climate considerations in different regions of the world. Some existing studies comparing wood and concrete framed houses report that a substantial fraction of materials used in the wood-framed house still contain cement and steel (Carre, 2011; Gustavsson and Sathre, 2006).

In this study we estimate that production of steel and aluminum for non-construction purposes by 2050 will result in the emissions of 26 Gt CO2 equivalents. This estimate is based on the assumption that the future stocks will amount to 60% for aluminum and 25% for steel of the ones currently in use in Annex I countries. These stocks would be distributed between transportation, machinery, as well as appliances and containers (Liu and Müller, 2013; Pauliuk et al., 2013).

In the case of log materials, emissions from their production would be less than a quarter of the total emissions from infrastructure development by 2050. More than three quarters of the total emissions would be emitted from production of steel and aluminum for transportation, machinery, packaging, etc. The share of emissions from production of plywood relative to the total emissions from infrastructure development is also greater. It amounts to 63% of the total emissions as compared to 26% emissions from production of steel and aluminum for non-construction purposes.

Table 3. Emissions from infrastructure development in 2050, assuming that 100% of cement, 40% of aluminum, and 75% of steel are replaced by wood. Here the total emissions depend on the type of wooden material used in construction. Substantially higher emissions are associated with production of plywood than with production of logs.

Wooden construction material	Total emissions	Emissions from production of wooden materials for construction		Emissions from production of steel and aluminum for non-construction purposes	
	[Gt]	[Gt]	[%]	[Gt]	[%]
Log	33	7	22	26	78
Plywood	89	63	71	26	29

Here we estimated savings from CO2 emissions from production of construction materials only. Existing studies of wooden houses over their lifetimes suggest that these savings increase during house use and maintenance as well as house demolition. In Australia, substituting wood products from well managed forests and plantations for more greenhouse gas (GHG) intensive building products in cladding, wall, roof and floor framing could reduce the GHG emissions of a typical residential house by up to 51% with the largest reductions gained from production of building materials (Carre, 2011). In Korea, for one 190 m2 house production of a wooden house would reduce emissions by 58 tCO2e mostly (90%) originating from the decrease in emissions embodied in construction materials (Cha et al., 2011). In Europe, the difference in life cycle emissions between wood and cement framed buildings was 77 % of CO2 per square meter of floor area (Gustavsson and Sathre, 2006).

Wood for infrastructure development: potentials and limitations

If we are to consider constructing new buildings out of wood, the questions arise if currently exist and if there will be sufficient wood available for this construction on a sustainable basis in the future. Another question is if the wooden buildings can serve as a substantial sink of carbon and for how long this sink can persist. In this study we estimate that the mass of wood which would be incorporated in the construction of the future buildings is 60 Gt. The total mass of wooden materials is ~ 15% higher, because of some material losses during construction (Ruuska, 2013). It means that the total mass of wooden materials required for this construction would be around 69 Gt. This number can be compared to the global production of roundwood or in other words unprocessed primary wood, which is a standard economic statistic annually collected by countries and reported to the Food and Agriculture Organization (FAO). Roundwood can become lumber, composites, pulp, fuel, plywood, or veneer for furniture and construction. Importantly, roundwood production is not exactly the same as timber harvest. It represents wood at an intermediate stage between tree harvest and wood products and is equal to timber harvest, minus harvest and transportation losses.

The global roundwood production in 2014 was 37000 million m^3 or 1.3-2.5 Gt depending on the assumption about the wood density (Table 4). It was divided roughly equally between wood fuel (1864 m^3) and industrial roundwood (1837 m^3). Even if we assume that all roundwood produced in 2014 could be used in construction, it would be only ~1.8-3,5 % of the total wood mass required for wood dominated construction to accommodate population growth by 2050 (Table 4). Substantially more wood per year would have to be harvested in the future in order to meet demand of the wood dominated construction. The total possible wood harvest is theoretically constrained by the forest wood reserves available globally.

The total global growing stock of the forest was 530 billion m^3 in 2015 (Köhl et al., 2015) or 185-350 Gt of wood depending on the assumed wood density of softwood (Canadian pine, 350 kg/m^3) or hardwood (birch, 670kg/m^3). Most of this stock is currently located in the tropical regions. Growing stock volume is the above-stump volume of living trees measured from the bark up to the treetops. We can consider the global growing stock as a proxy of forest reserves potentially available for harvest and future construction of wooden buildings. During harvest and transportation to the manufacturing facilities approximately 15-50% of wood is lost (Churkina and Running, 2000). If we assume that the total amount of harvested wood was 30% higher than the one required for construction of wooden buildings (69 Gt of wood), then we would have to harvest 90 Gt of wood. It implies that half to one quarter of the total growing stock (185-350 Gt) available in 2015 would have to be harvested for construction of the wooden buildings needed to accommodate the population growth by 2050. Here we assumed that all produced wood could be used for construction. In reality, it is not the case. Not all tree species are suitable for construction purposes. Moreover, tree species suitable for construction purposes would have to grow under certain conditions to produce wood of sufficient quality to be used for building log houses for example. Estimating a forest area required to grow these tree species is beyond the scope of this paper. A more detailed study similar to one initiated by WBGU for estimations of the global land use potential the bioenergy (Schubert et al., 2009) would have to be beneficial to account for these different factors.

Table 4. Production of roundwood in 2014 (FAO, 2016). The comparable wood masses are calculated using wood density of typical softwood (Canadian pine, 350 kg/m^3) and hardwood (birch, 670kg/m^3) species.

	Production in 2014 volume [million m^3]	Production in 2014 [Gt]		Proportion of wood required for future wooden construction [%]	
		softwood	hardwood	softwood	hardwood
Wood fuel	1864	0.65	1.25	n/a	n/a
Industrial roundwood	1837	0.65	1.25	0.9	1.7
Total roundwood	3700	1.3	2.5	1.8	3.5

Storage of carbon in the newly built wooden buildings would be ~30 Gt C assuming average carbon to wood biomass of 0.5 gC/g dry wood biomass. It is 4.5 times more than the amount of carbon stored in the buildings worldwide estimated recently (Churkina 2016). The amount of carbon stored in the future wooden construction would amount to ~5-7% percent of the total carbon storage in vegetation globally (450-650 PgC, (Ciais et al., 2013)). The residence time of carbon in wooden buildings is 12-80 years on average (Churkina, 2012) and in some cases well-preserved wooden buildings stand for 200-500 year or longer (e.g., wooden buildings in the Imperial Palace in

Beijing, China). By comparison the lifespan of a concrete building averages around 11 year with large deviations (1-100 years old) (Churkina, 2012).

Conclusions and Outlook

The current construction practices mostly rely on steel, cement, and aluminum and result in high emissions of CO2. Most of these emissions originate in manufacturing of building materials. The share of emissions from material manufacturing depends on house location (climate), building materials, and house efficiency. Data on current material stocks and variability of different materials (including natural materials) in building and construction sector in different countries and especially disaggregated data (sub-country) for material stocks would be beneficial for understanding the current situation. They should indicate the preferences for certain combinations of construction materials existing in different regions of the world and provide the basis for further investigations sustainable construction practices. Comparison of GHG emissions over a life cycle of houses located in different countries would be valuable to provide a full picture.

Existing studies suggest that full transition to construction without steel and cement could be problematic. These are however case studies from different countries often funded by companies producing certain type of construction material, which opinion maybe not bias free. A systematic survey of construction practices with a goal to determine if this transition is possible would have to be conducted.

This study suggests that the use of natural materials, especially wood, can substantially reduce emissions of GHG associated with future manufacturing of construction materials required to accommodate needs of the growing world's population. A more detailed study would be desirable to investigate how much wood suitable for construction would be available for such construction in the future on a sustainable basis and what types of wood would these be. Could, for instance, bamboo as a fast growing woody species solve the problem? This future study would have to take into account the global area, which is currently forested or available for afforestation, future rates forest growth, and their interactions with climate change. Also tradeoffs with other land uses such as biofuel production, agriculture, and urban sprawl would have to be accounted for. Various logging techniques and associated emissions of CO2 from litter left on the ground and from soil disturbed during forest harvest would have to be investigated as well.

In addition to the natural limitation of wood supply, promotion of wooden construction may face other challenges related to population density, country building regulations, and costs of wooden construction. Regulatory limitation on the use of wooden construction materials in densely populated areas is based on inflammability of wood and may pose an additional constrain on the use of wood for construction in certain countries.

Houses made of wooden materials have limitation on the height. Transition to wooden materials may imply that future settlements would have to grow more horizontally, not in vertically. It may be problematic in countries with high population pressure, low income, and high real estate prices. How tall can wooden houses become? The tallest experimental wooden buildings known today are ~ 6-7 stories high. The height limits for buildings made of natural materials have to be explored. The share of urban population and distribution of population in different climates was not accounted for in this study. In some climates wooden construction may be prohibitively expensive and emissions from material transportation could be horrendous.

An additional benefit of wooden construction is the enhancement of carbon storage on land. Wooden construction not only reduces the emissions of CO_2 from production of construction materials to the atmosphere, but also offers an opportunity to consume it and store carbon for a long time. Wooden houses can live and store carbon for 200-500 years in addition to the life span of a tree. To offset rising urban emissions of carbon, regional and national governments should consider how to protect or even to increase carbon storage of human-dominated landscapes. A more detailed investigation would be desirable to find out how much CO_2 can be sequestered in the urban areas and for how long.

Natural and renewable materials should be preferred for construction purposes. The choices of construction materials should include, but not limited to wood. Traditional houses in any culture were made out of natural and local materials. In the forested areas the traditional houses were made of wood (e.g., Russia, Scandinavian countries) or clay and wood (e.g., China and Japan). In dry areas (e.g., Greece, North Africa), the houses were made primarily out of clay and stone. Can practices used in construction of traditional houses and based on modern technology help to find more sustainable solution for accommodation of growing world's population?

Production of new construction materials from renewable materials should be explored. For example, HexChar is a new biochar-based building material, which is currently undergoing testing. It is made out of biochar and biodegradable binder. For HexChar production, biochar is made of wasted agricultural biomass, which was burned to a char by pyrolysis. At the end of its lifecycle, HexChar is shredded, and sequestered in the soil.

Tradeoffs between emissions of CO2 from production of conventional materials accounting for energy efficient processes and materials' recycling and from sustainable production of natural materials still have to be explored in details in the future studies. What would be the most optimal combination of construction materials for the future infrastructures, which would not compromise either human comfort or the climate of the Earth? What would be the optimal density and height of human settlements from both environmental and human perspectives? These important questions still have to be addressed.

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Externe Expertise für das WBGU-Sondergutachten
„Entwicklung und Gerechtigkeit durch Transformation: Die vier großen I"
Berlin: WBGU
ISBN 978-3-946830-00-9
Verfügbar im Internet unter
www.wbgu.de/sondergutachten2016/

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Titel: Can Use of Wood in Future Infrastructure Development Reduce Emissions of CO_2?
Berlin, 2016

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