Prefabricated Polystyrene-Plywood Structural Insulated Panels v. Straw Bale Structural Insulated Panels

A Life Cycle Assessment of the Global Warming Potential of Alternative Building Materials in South Los Angeles, California

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Abstract: This comparative Life Cycle Assessment (LCA) provides an analysis of the global warming potential associated with constructing the exterior wall assembly of a single-story duplex using straw bale structural insulated panels and standard plywood-polystyrene structural insulated panels in the South Central/Watts area of Los Angeles. Assessing the carbon dioxide (CO2), methane (CH4) and nitrous oxide (N2O) emissions from creating the necessary material for each panel (post-resource extraction), transportation of each material to the site of panel assembly along with construction of the panels themselves revealed that the straw bale SIP is favorable when compared to the conventional SIP, due to the lesser amount of emissions and solid waste it produces. It was also found that the straw bale SIP could be improved by lessening transportation distance or utilizing a more fuel-efficient method of travel in order to decrease the large amount of emissions related to diesel fuel usage.

Keywords: SIP, EPS, sustainable, construction, straw bale

INTRODUCTION

Definition and Motivation of the Problem

Buildings and their construction together account for 36% of global energy use and 39% of energy-related carbon dioxide emissions annually, contributing to changes in local, regional, or global surface temperatures and a cascade of effects on the ecosystem and in effect human health (UN 2017). According to the World Resources Institute, "although all buildings must be net-zero carbon by 2050 to meet the goals of the Paris Agreement, not even 1% of buildings are considered net-zero carbon today" (2019). More specifically, Los Angeles, California is part of C40, a network of cities committed to addressing climate change, and is pursuing net-zero carbon in all new buildings by 2030 and all buildings by 2050 (C40.org). According to the California Air Resources Board (2020), the building sector is the second-largest source of greenhouse gas emissions in the state and therefore offers immense potential to reduce its environmental impact via sustainable construction, operation, and renovation of new and existing buildings.

Key Technologies

Buildings for human habitation must provide shelter and generally have to be heated or cooled (Ashby 2012 p. 333). The focus of this research is on the building envelope of residential homes, a critical assembly of wall components that serves as structural siding, weather resistant barrier and continuous cavity insulation. Rather than assess the environmental impacts associated with more traditional stick-built homes, this analysis compares two types of Structural Insulated Panels. Structural Insulated Panels (SIP's) — after having been introduced in 1935 by Forest Products Laboratory in Madison, Wisconsin — have been of high research interest due to their potential to construct in an affordable and fast pace manner with minimal environmental impact (Panjehpour, Abang Ali, and Lei Voo 2013, p. 2). These panels are a prefabricated building component that can be used for wall, roof and floor structures and are composed of a low density core, often polystyrene foam, placed between two structural facings, often oriented strand board or plywood. SIP's, however, can be created from a wide variety of materials. Straw bales have historically been used in construction processes. Patents for load bearing strawbale building systems were first granted in the late 1800's (Eisenberg and Hammer 2014, p. 24). Significant developments in the technique have combined these traditional materials with modern methods of construction, such as prefabrication (Wall et. al, 2012, p. 377). Prefabricated structural insulated panels have been constructed using straw as the low density core and a combined wire mesh and plaster as the structural facings.

Life-Cycle Framework

While building efficiency is important to assess, this analysis prioritizes the investigation of the up front embodied emissions inherent in the harvesting, manufacturing and transporting involved in constructing alternative types of building envelopes. Due to the characteristics of structural insulated panels, there are reduced opportunities for thermal bridges and other types of air leakage (Krarti and Hildreth 2007). As operational energy efficiency increases, the impact of embodied carbon emissions in buildings will become increasingly significant. Considering the high impact potential of insulation for the amount of energy buildings use (energy efficiency), research into the emissions from material manufacturing, construction and transportation processes of these building envelopes is of high priority. More specifically, whether the materials that are most conventionally utilized to create panels that reduce air leakage and improve energy efficiency, polystyrene foam and plywood, have a significant environmental impact in comparison to SIP's made of alternate forms — straw bale — is the goal of this study. This analysis looks at the life cycles of these panels from cradle — being the location/facility where each material needed for each panel is manufactured — to gate — being post panel assembly prior to on site house construction.

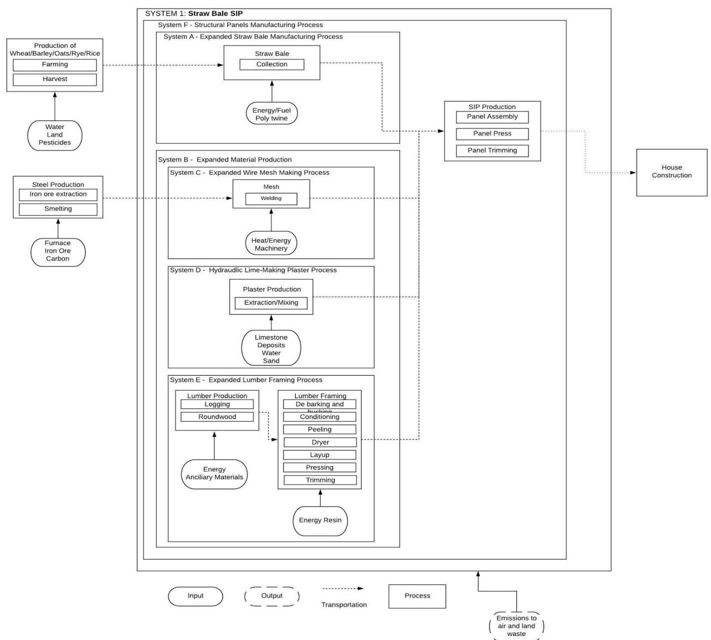
Current literature

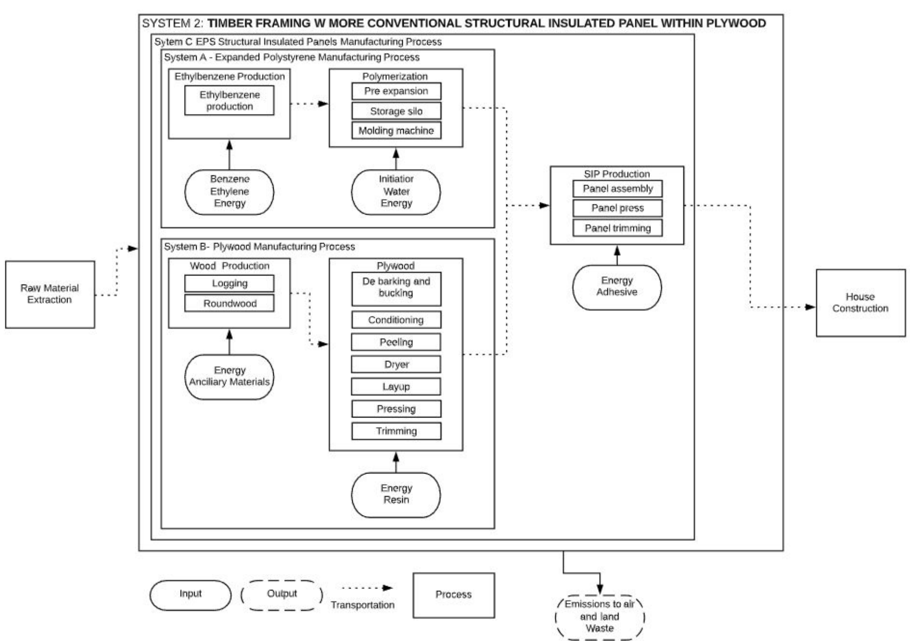
Current literature on SIPs comes from a variety of sources. SIP's are the only non-concrete based enclosure (roof, walls & floors) product accepted to meet Title 24 thermal enclosure requirements, offering minimal air leakage, not exceeding 0.04 cfm/ft^2 (California Energy Commission, Section 3.5.8.1). In addition, studies have revealed reduced installation and labor time, with Mullens and Mohammed (2006) indicating that SIPs saved about two-thirds of the site framing labor for walls and roofs, with similar cycle time savings. SIP manufacturers provide a lot of educational material to help inform potential customers on the building process and benefits of SIPs. Section R610 of the Los Angeles Residential Code details specifications required for constructing with SIP's within the Southern California region, and Appendix S specifically outlines requirements for building with strawbale. The U.S. Green Building Council (USGBC) awards points for LEED certification for the use of straw bales in new and or existing construction and several articles have been published on LEED certified straw bale projects.

System Boundary and Limitations

The system boundaries for both SIP's being compared include the manipulation of the main raw materials to create each required SIP component, the gates of transporting these respective materials from their source to a chosen SIP Manufacturing facility in Newport Beach, CA and the assembly of these materials to construct the panels themselves. We assumed that a single production facility would manufacture the EPS and Straw Bale SIPs. Straw bale SIP production requires minimal setup and specialty tools, and there are several manufacturers that produce multiple SIP variants. Our study truncates the creation of the raw materials themselves as well as the transportation to the construction site in South Los Angeles and on-site assembly of the home. Not only was there a lack of availability of some of this granular data, but since SIP's pull from a small amount of totals for these resource extraction processes, a dilution effect was noted. Further, the on-site assembly of the home was excluded due to similarities in these processes. The foundation, splines, screws, studs and joints used to attach panels and roof assembly, electrical chases, doors and/or windows, and labor time to assemble was excluded due to lack of substantial differences between each SIP system.

The system boundary is identical for both panels. This analysis included the manufacturing processes for the different inputs, but excluded the processes related to resource extraction such as the growing of straw, the extraction and smelting of iron ore, the extraction of limestone and other products to make the plaster, as well as the growing of wood for lumber. Production processes regarding the transformation of these materials were included, such as steel into mesh, straw into bales, forwood into framing and clay concentrate soil, sharp aggregate and fiber into plaster. These processes included material inputs along with the total energy utilized in the process. For the case of System 2, exclusions pertained to raw material production, such as the oil refinery to extract the chemicals needed to create the polystyrene, as well as the inputs related to growing wood. However, the materials, energy and water required for production of the main panel components from these raw materials was included, such as the production of the monomer styrene, which is required during polymerization, and wood logging, which is required for plywood production.



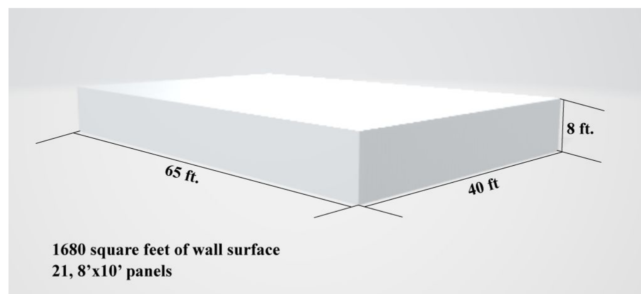


Purpose: This study seeks to answer whether straw bale is a suitable construction material that would help Los Angeles reach its climate goals, whether the transportation of straw bale to assembly sites in Los Angeles actually outweighs any potential emissions reductions, and whether straw bale could potentially replace the commonly used expanded polystyrene foam in construction.

METHODOLOGY

This research provides a comprehensive analysis of the potential environmental impact reductions associated with constructing a single-story duplex with straw bale structural insulated panels. Utilizing a Life Cycle Analysis (LCA) methodology, the study compares the relative environmental impacts in terms of the global warming potential of constructing a single story multi-family home with 1680 square feet of wall surface using a straw bale structural insulated panel exterior wall assembly versus a standard plywood-polystyrene structural insulated panel exterior wall assembly within the South Central/Watts area of Los Angeles.

In residential SIP construction today, 8’ x 9’ or 8’ x 10’ panels are very commonly used to achieve 9’-or 10’-tall walls, and SIP panels cannot exceed 11 ft 7in according to CA Residential Code R301.3. For these reasons, the panel size for both types was chosen to be 8x10 sq ft. As of March 2020, 2,500 sq.ft is the minimum area per dwelling unit (22.52.270) of multiple residential homes. Therefore, the model single story residential home for this analysis is 2,600 square feet, with 1,680 square feet of wall area, given a panel height of 8 ft. Windows and doors are assumed to be identical in both scenarios, therefore, such systems were excluded from calculations based on the assumption that the results would not be significantly affected. Considering materials are partially conditioned by the local climate, according to Energy Star, a program run by the U.S. Department of Energy that promotes energy efficiency, California’s recommended R-value for construction is R25. California has additional residential regulations for the construction of SIP homes given the climate and seismic region. While high wind speeds are not a primary concern, with the annual average hovering at around 1.9 miles per hour, the wall assembly needs to support gravity (vertical loads) and resist, axial, shear, and both in-plane lateral and out of plane flexural loads. SIP panels are acceptable to be used as shear walls in all seismic design categories (Simon et al. 2017). Based on this initial data, the number of panels needed was estimated (21 panels) along with the material needed for each panel. Each panel was broken down into subsystems to determine the materials, water, energy inputs and air emissions, water emissions, and solid waste outputs from their manufacturing processes.



Further, the South Los Angeles area was chosen as the construction site. According to a UCLA study that looked at records for new multifamily development that opened in the city of LA between 2014 and 2016, new multifamily construction is more common in (but not exclusive to) the denser or more central parts of the city, such as South LA and Hollywood (Bachrach, Monkkonen, and Lens 2017). Fifty-nine of the 104 new developments in the sample were duplexes, mostly concentrated in South LA. The site of SIP assembly was chosen to be JD Fox in Newport Beach, an SIP manufacturer in Southern California. These locations along with locations that manufacture the materials needed for SIP assembly were chosen to determine spatially explicit environmental impacts of transportation for each product system as well.

Functional unit: Wall assembly covering 1680 square feet [21 8x10' SIP's] providing an R value of 25 and able to have the shear strength to withstand the climate and seismic loads in the South LA/Watts area of Los Angeles, CA.

Reference Flows:

Straw Bale SIP Assembly	7421.26 kg straw bales, 74.13 kg steel wire mesh, 17569 kg clay plaster, 95.59kg framing *The plaster reinforced with wire mesh that encases the bales in strawbale walls provides flexural and shear strength necessary to withstand powerful seismic loading. The wall assembly is able to provide an R value of 27.9, exceeding the R-25 value.
Conventional SIP Assembly	61.29 kg of Expanded Polystyrene, 0.188 cubic meters of plywood, 18 kg of venner *Structural elements provide the flexural and shear strength necessary to withstand powerful seismic loading. The wall assembly is able to provide an R value of 25.

SYSTEM 1. Straw Bale Structural Insulated Panel (SIP)

Sub-System A: Straw Bale Production

Standard dimensions for small straw bales are 14x36x18 inches. If these bales are oriented flat, there can be a total of 22.86 bales in a 8'x10' panel, with a thickness of 18 inches. This thickness would result in an R-value of 27.9, given each inch provides an R value of 1.55, which exceeds 25 (AS108.1). According to CA Residential Code, straw bales for construction must have a dry density of not less than 104 kg/cubic meter (AS103.5). Assuming this metric is met, each bale would weigh about 15.46 kg, resulting in 7421.26 kg of straw bales for all 21 SIP's. If each acre of land devoted to rice production also produces 3 tons (2721.55 kg) of rice straw, then 2.73 acres of land would be required to bale 7421.26 kg of straw. Straw is the dried stems of grain parts not including the grain head and may come from wheat, oat, barley rye and rice (Harries and Bhavna 2019, p. 131). A 2016 study of rice production in CA's Sacramento Valley by the CA Rice Commission indicated that three to four tons of rice straw remain standing in the field per acre. The system boundary for this analysis does not include the inputs and outputs associated with the growing of the rice crop. The emissions associated with the process of obtaining the straw bale material from the field to the SIP assembly site is calculated.

Substantial volumes of data about California's rice cultivation system, soils, and climate were investigated by the Environmental Defense Fund and UC system to validate and improve the DeNitrification-DeComposition (DNDC) biogeochemical process model for the rice production system in the state, which created a more precise prediction of carbon and nitrogen behavior linked to various management practices (2010). Virtual field trials were then able to create an accurate understanding of the impact of management changes on GHG emissions and carbon storage. The winter flooding with straw removal scenario was chosen for the emissions values in this study.

It is important to note that a small percentage of straw is baled and sold — less than 10% as of 2015 since the costs of removing, storing, and transferring straw are too high to enable the economic viability of other known uses (CA Rice Commission 2016, p. 6). The most common current management practice for rice production systems utilizes continuous flooding during the rice growing season with crop residue (straw) soil incorporation followed by winter flooding to enhance its decomposition. Based on current practices, approximately 60% of growers use winter flooding with residue incorporation. Assuming this would be the fate of the straw if it were not baled, the emissions from this process of reincorporation into the soil with winter flooding are taken into account and credited via LCA's avoided-burden approach. Net emissions of baling 7421.26 kg of straw is calculated as -1610.7kgCO2eq.

These net emissions exclude fossil fuel use during baling operations. In order to calculate these emissions, it was determined that it takes about 8.25 miles to plow one acre, given a furrow width of 12 in, or 22.52 miles to plow 2.73 acres (Moore 2009). Average tractor mileage was assumed to be 6 mpg (Garthwaite 2011). While the tractor would require a total of 3.75 gallons of diesel, a 20 kW generator to power the rectangular baler would require 4.28 gallons, given it uses 1.6 gallons per hour, and it takes an hour to bale one acre (FAO). Carbon emissions from diesel fuel and CH4 and N20 emissions from agricultural equipment were calculated using EPA's Emissions Factors for Greenhouse Gas Inventories (2014), resulting in a total of 85.38kgCO2eq.

The transportation of the straw bales to SIP assembly was calculated by finding the closest farm to Southern California that produces building-quality straw bales. RiceStrawMarket.org, an interactive marketplace for buyers and sellers of California rice straw that seeks to enhance opportunities for exchange, allowed a refined search of construction quality bales. Farms were mapped on GoogleEarth to determine the shortest distance source. A single axle class 7 truck can legally haul 7,421.26 kg and averages at about 6.5mpg. This was incorporated with the distance from Lowery's Hay Services Inc to the SIP Manufacturer in Newport Beach (267 miles) and EPA emissions factor tables to calculate 419.39 kg CO2e emissions associated with transport.

Sub-System B: Wire Mesh Production

Wire mesh is used as reinforcement material for structural assemblies. It is produced in sheets by welding ribbed steel wires at right angles and creating gaps that are either square or rectangular. The specifications of this mesh were determined by a study evaluating the seismic performance of various types of steel mesh (Ackerson and Williams 2017). The strongest wall in the assessment was made of 18" wide rice straw bales encased in 14-gauge 2" x 2" electro-galvanized welded steel wire mesh (p. 40). In addition, CA's Residential Code specifies that galvanized welded wire mesh is allowed for use with all plasters (AS106.13). These specifications were chosen for this assembly in order to determine the total weight of mesh needing to be transported to SIP assembly. The manufacture of the mesh involves wire drawing, straightening, cutting, welding and electroplating (galvanizing) which requires electrical energy, filler material, lubricant, electrode coating, shielding gas and compressed air. Due to the lack of available data on CO2, CH4 and SO4 emissions during these processes, a study on the life cycle of this reinforcement mesh that utilizes data from steel manufacturers and wholesalers in Norway was used (Fet and Jenssen 2015). In taking from this source, values associated with the manufacturing phase of the wire mesh (including emissions from cutting, bending, storage, material and energy consumption) were utilized while emissions associated with raw materials and transportation were excluded, coming to a total of 50.08kgCO2eq. The transportation emissions for this analysis of SIP's was determined by calculating the total weight of mesh required for the entire wall assembly (74.3 kg), the distance between mesh manufacturer Grating Pacific, Inc in Los Alamitos, CA to SIP assembly in Newport Beach (21 miles), and the CO2, N2O and CH4 factors associated with light-duty trucks as indicated by the EPA to produce a total of 7.5kgCO2eq.

Sub-System C: Clay Plaster Production

Clay plaster was chosen as the material of choice for the interior and exterior wall coating. Clay plaster is a coating that relies on clay as the primary binder, usually from a high clay content soil or bagged as dry pure clay. Clay plaster is typically composed of clay, sharp aggregate (silt or sand), fiber, and water. Due to the large amount of clay needed for an entire home, the material is typically sourced directly from a manufacturer or quarries that specialize in clay mixes. Aggregate can generally be obtained from typical construction supply chains, and is ideally similar to concrete sand or stucco sand per ASTM C33 grading limits. The fiber content for straw bale SIPs is usually composed of chopped straw. Leftover straw from bale construction can be used as the source of fiber and can be processed by a chipper/shredder.

Appendix S of the International Residential Code (2018) calls for a minimum thickness of 1 inch for plaster skins on straw bale SIPs, with 1.5 inch thickness being common. Assuming this thickness across our chosen panel size (8'x10'), a volume of 0.566336 m^3 (836 kg) is needed to complete both sides of the panel. The EPA estimates that 8% of plaster material is wasted during construction (US Environmental Protection Agency 2020, 16), giving a total of 0.61164288 m^3 of material needed per panel. The carbon footprint for clay plaster is relatively low, most of the emissions are related to the excavation and transportation of the soil and is estimated to be 0.0052 $kgCO_2e/kg$ (Magwood 2016, 23). Using these numbers, the impact for the use of clay plaster on our straw bale SIPs is 4.69 $kgCO_2e$ per panel and 98.59 $kgCO_2e$ per home.

Sub-System D: Wood Framing Production

Softwood lumber is required for the framing of the straw bale SIPs. The frame consists of a base plate, side plates, and an optional top plate for load bearing walls (or for connecting panels). Environmental impacts can be low to high depending on the forestry practices of the lumber supplier. Care should be taken to verify that sustainable harvesting and production is used by lumber producers as opposed to unregulated clear cutting in order to ascertain the degree of impact.

Framing plates for the top and bottom must cover the length of the panel and the depth of the straw bale insulation. These plates often consist of 2x4 wood sandwiched by ½” thick wood panels on the top and bottom for each plate assembly (Magwood 2016, p. 44). Side plates must also use 2x4s for the required depth of the panel (Magwood 2016, p. 56). For each S-SIP, the estimated amount of lumber needed is 0.204 m^3 per panel. The North American Product Category Rule (PCR) estimates a GWP of 93 $kgCO_2e$ per m^3 of planned softwood lumber (Puetmann, Oneil, and Bergman 2013, p. 22). Using the North American PCR estimate and assuming a volume of 0.204 m^3 of lumber per 8x10’ panel, 19.11 $kgCO_2e$ per panel is generated for a total of 401.48 $kgCO_2e$ per home.

Sub-System E: Panel Assembly

The construction process of putting these materials together is quite straightforward. The frame is laid horizontally, wire mesh is attached to the sides of the frame and back bracing, plaster is layered above the mesh, bales receive a coating of plaster before being inserted into the framing (plaster against plaster), bales are knocked tightly against one another and a final layer of plaster is worked onto the bales and leveled. This process involves simple tools and minimal energy. For these reasons, emissions associated with assembly were assumed to be 0.

System 2. Expanded Polystyrene (EPS) Structural Insulated Panel (SIP)

An Expanded Polystyrene (EPS) structural insulated panel uses a foam core of EPS between two layers of structural board to create a construction material. The structural board can be plywood, cement, magnesium oxide board (MgO) or oriented strand board (OSB). The most common and most cost effective EPS structural insulated panel is the one with plywood as outer skin. Expanded Polystyrene panels come in different sizes depending on the required R value; an R-value of 3.85 is given per inch of EPS, giving a total of 6.5 in thickness for the required 25 R-value. With a panel size of 8x10 sq ft, the total volume needed is 61.29 kg of EPS.

Sub-System A: Expanded Polystyrene Production

Expanded Polystyrene (EPS) is made from expandable polystyrene, which is a rigid cellular plastic containing an expansion agent. EPS main components are obtained from oil but less than 0.1% of the derivatives of oil are used for EPS, which is why oil production and extraction were excluded from the system boundaries (Behr, Arno). Air represents 98% of Expanded Polystyrene, which is a poor heat conductor and results in a low thermal conductivity, making it perfect as insulation material for construction.

Polystyrene is a hydrocarbon polymer made from the styrene monomer; the production of styrene is by a catalytic alkylation of benzene with ethylene through aluminum chloride. It is important to note that 50% of the world’s benzene production is used for the styrene production and 99% of ethylbenzene use is as a component of styrene (Behr,Arno) making the CO2 emissions of ethylbenzene production solely for the production of styrene. After styrene is produced, expanded polystyrene is made through a suspension process by addid a blowing agent, usually pentane, to form droplets of polystyrene. The droplets are then subjected to steam heating that causes them to expand by 40 to 90 times and produce the cellular form.

Estimates for material, energy and water required to produce 1kg of EPS were sourced from the Eco-profiles of the European Plastic Industry on Expandable Polystyrene. Transportation from this document was excluded as transportation for the main inputs were calculated for locations in California. It was estimated that 5.48 MJ of energy and 10664 tons of water were required to produce 61.29 kg of EPS. 105 kg of CO2e were estimated, with 76% from energy production and use.

Regarding the transportation of the polystyrene to its ultimate destination for panel assembly, it traveled a total of 9.4 miles with a travel time of 13 minutes, using 1.45 gallons of diesel. This produced 14.77 kg of CO_2, 0.000048 kg of CH_4, and 0.00004512 kg of N20.

Sub-System B: Plywood Production

The chosen material for the structural board was a ½" inch width plywood, giving a total volume of 0.1889 cubic m based on the panel length and width.. The system boundary excluded raw material extraction for plywood, such as forestry operations to plant and extract trees; however, wood logging was included. After the logging the wood, logs are cut and debarked before going into a conditioning process, where hot water and steam are required. Logs are peeled to produce veneer, which is then dried using thermal energy before resin is applied for the layup and pressing processes. Finally, the plywood panels are trimmed to the appropriate dimensions before packaging and shipping.

Input and output estimates- found in the Data Section- were sourced from a Life Cycle Assessment of Softwood Plywood Production in the US Southeast by WoodLife Environmental Consultants, LLC and the University of Tennessee, where data was collected from softwood plywood producers for the 2012 year. The majority of CO_2 emissions were generated from the energy required for veneer drying and steam production for drying, giving a total of 77 kg of CO2e for 0.1889 cubic m of plywood.

In order for the plywood to reach its destination at the assembly center, it needed to travel 4.6 miles with a travel time of 13 minutes, which used 0.71 gallons of diesel. This produces 7.23 kg of CO_2, 0.000023 kg of CH_4, and 0.000022 kg of N20.

Sub-System C: Panel Assembly

Panel assembly is performed by a pressing manufacturing process that requires energy and adhesive as inputs. Limited data was found for the specific EPS panel assembly; therefore, a general pressed panel process from the U.S. Life Cycle Inventory (USLCI) Database was used. The CO_2 emissions from this process come from the energy required to press and trim the panels, resulting in a total of 5.08 kg of CO2e per panel.

DATA MODELS AND ANALYSIS

Microsoft Excel was utilized in order to collect data and perform calculations.The data model used was a list of inputs and outputs per unit of material that then was used to calculate the total quantities using initial panel information. Emissions were listed in terms of CO2, CO, CH4, N2O, SO2 that then were translated into kgCO2e using conversion factors. Tableau Software was used to plot graphs and analyze results visually.

Dataset for System 1

Panel information	Qty	Unit
Rvalue	25	
Bale Thickness	18	in
Total Bale Volume (per panel)	120.00	cubic ft
Bale Height	14.00	inches
Bale Length	36.00	inches
Single Bale Volume	5.25	cubic ft
# Bales/panel	22.86	
Single Bale Mass	15.46	kg
Total Bale Mass (house)	7421.26	kg
Bale Density	104.00	kg/cubic meter
Wire Mesh Material	3.53	kg per panel
Wire Mesh Material (house)	74.13	kg

*not including packaging, not including procedures to form the raw materials.

		Input				Output										
						Air Emissions					kg CO2eq	Solid Waste				
					for 1680 sq ft of panels	Emmision	Qty	Unit	Qty	Unit		Solid Waste	Qty	Unit	Qty	Unit
Straw Bale Harvest	Material					Soil Carbon Gains	1.1193	t CO2eq	1119.3	kg CO2eq	1119.3					
						N2O	0.819	t CO2eq	3.090566038	kg N2O	819					
						CH4	6.3063	t CO2eq	225.225	kg CH4	6306.3					
						Net GHS's (sum CH$, N2O, soil C)	8.2446	t CO2eq	8244.6	kg CO2eq	8244.6					
		Avoided : Most common alternative = incorporate straw into soil with winter flooding (f)				**Avoided**										
						Soil Carbon Gains	-0.9555	t CO2eq	-955.5	kg CO2eq	-955.5					
						N2O	0.7098	t CO2eq	2.678490566	kg N2O	709.8					
						CH4	8.19	t CO2eq	292.5	kg CH4	8190					
						Net GHS's (sum CH$, N2O, soil C)	7.917	t CO2eq	7917	kg CO2eq	7917					
						NET										
						Soil Carbon Gains	0.1638	t CO2eq	163.8	kg CO2eq	163.8					
		Straw	15.4	kg / bale	7421.26 kg	N20	0.1092	t CO2eq	0.412075472	kg N2O	109.2					
						CH4	-1.8837	t CO2eq	-67.275	kg CH4	-1883.7					
						Net GHS's (sum CH$, N20, soil C)	0.3276	t CO2eq	327.6	kg CO2eq						
	Energy	Diesel for tractor	3.75	gallons	3.75 diesel	CO2	82.91881333	kg	82.91881333	kg CO2eq	82.918813					
		Electricity to bale	20	kW	4.368 gallons di	CH4	32.4288	g	0.0324288	kg Ch4	0.9080064					
		Total diesel			8.12 gallons di	N2O	5.8552	g	0.0058552	kg N2O	1.551628					
		Avoided														
	Transportation [from farm to SIP assembly]	Diesel for truck	41.08	gallons	41.08 gallons di	CO2	419.3953846	kg	419.3953846	kg CO2eq	419.39538					
						CH4	1.2816	g	0.0012816	kg Ch4	0.0358848					
						N2O	1.3617	g	0.0013617	kg N2O	0.3608505					
Creation of Wire Mesh	Material	Steel	1230	kg		kg CO2-eqv	0.000304000000	kg	0.022535520000	kg CO2eq	2.25E-02	Hazardous Waste	6.41E-09	kg	4.75E-07	kg
		Wire Drawing Lubricant				kg CFC11-eqv	0.000000000007	kg	0.000000000500	kg		Non hazardous waste	1.61E-03	kg	1.19E-01	kg
		Zinc Solution (for electro-galvanizing)				kg Ethylene-eqv	0.000000081200	kg	0.000006019356	kg		Radioactive waste	4.03E-07	kg	2.99E-05	kg
						kg SO2-eqv	0.000000587000	kg	0.000043514310	kg						
						kg PO4 -3 -eqv.	0.000000147000	kg	0.000010897110	kg						
	Energy		1.5	kWh / kg	111.195 kWh	kg CO2	49.93289093	kg	49.93289093	kg	49.932891					
	Transportation [from mesh manuf. To SIP assembly]	Diesel for truck	0.7241379	gallons	0.724137931 gallons	CO2	7.393448276	kg	7.393448276	kg CO2eq	7.3934483					
						CH4	0.504	g	0.000504	kg Ch4	0.014112					
						N2O	0.399	g	0.000399	kg N2O	0.105735					
Clay Plaster	Material	Clay/High Clay con	203.88	kg	4281.48	CO2, CH4, N2O	5.2988	kgCO2e	111.2748	kg CO2eq	111.2748	Solid Waste	81.5	kg	1711.5	kg
		Sharp Aggregate	203.88	kg	4281.48											
		Fiber	203.88	kg	4281.48											
	Water Consumption		226.53	L	4757.13											
	Transportation [from plaster manuf. to SIP assembly]	Diesel for truck	10.6154	gallons		CO2	108.3830769	kg	108.3830769	kg CO2e	108.38308					
						CH4	0.0003519	kg	0.0098532	kg CO2e	0.0098532					
						N2O	0.0003312	kg	0.087768	kg CO2e	0.087768					
Framing Lumber	Material	Roundwood	0.203881	m3	4.281501 m3	CO2	19.11789	kg	401.47569	kg CO2eq	401.47569		2.695	kg	56.595	56.6
		Bark	0.13644	m3	2.86524 m3											
	Energy	Electricity	0.964357	kWh	20.2515 kWh											
		Diesel and gasoline	0.159027	L	3.339567 L											
		Gasoline	0.029766	L	0.625086 L											
	Water Consumption	Water	33.64	L	706.44 L											
	Transportation [from lumber source to SIP assembly]	Diesel for truck	0.71	gallons		CO2	9.2	kg	9.2	kg CO2e	9.2					
						CH4	0.00002346	kg	0.00065688	kg CO2e	0.0006569					
						N2O	0.00002208	kg	0.0058512	kg CO2e	0.0058512					
Panel Assembly	Materials	Measuring/Marking Tools														
		Miter/Circular Saw														
		Bale Moisture Meter														
		Grinder														
		String Line Trimmer														
		Impact Driver														

Dataset for System 2

Panel information

	Qty	Unit
Rvalue	3.85	per in
Rvalue needed	25	
Polysterene Thickness	6.5	in
Polysterene Volume	43.29	cubic ft
Polysterene Material	61291.81	g
Plywood Thickness	0.5	in
Plywood Volume	6.666664	cubic ft
Plywood Volume	0.188778591	cubic m

		Input					Output Air emissions					kg CO2eq	Output Solid Waste				
			Qty	Unit	Total	Unit		Qty	Unit	Total	Unit		Solid Waste	Qty	Unit	Total	Unit
Resource Extraction	Material	Ethylene	0.293	kg	17.95850033	kg	CO2	0.261	kg	15.997	kg	15.99716241	Solid waste	0.00208	kg	0.1272	kg
		Benzene	0.783	kg	47.99148723	kg	CO	0.00027	kg	0.0165	kg	0.025981598					
							N2O	0.0001	kg	0.0061	kg	1.624232965					
	Energy	Electricity, at grid	0.1636	kWh	10.02734012	kWh											
		Electricity, at plant	0.0002205	kWh	0.013514844	kWh											
		Natural gas	0.4267	m3	26.15321533	m3											
Polymerization	Material	Air	440000	mg	26.9683964	kg	CO	500	mg	0.0306	kg	0.048114071	Solid waste	703.345	kg	43109	kg
		Bauxite	700	mg	0.042904267	kg	CO2	190000	mg	11.645	kg	11.6454439					
		Bentonite	83	mg	0.00508722	kg	SO2	510	mg	0.0313	kg	0.013753882					
		Biomass	11000	mg	0.67420991	kg	CH4	2400	mg	0.1471	kg	4.118809632					
		Cu	190	mg	0.011645444	kg											
		Fe	350	mg	0.021452134	kg											
		Limestone	390	mg	0.023903806	kg											
		N2	410000	mg	25.1296421	kg											
		O2	6200	mg	0.380009222	kg											
		S	210	mg	0.01287128	kg											
		Sand	650	mg	0.039839677	kg											
		Sodium Chloride	2300	mg	0.140971163	kg											
	Energy	Electricity	7.27	MJ	0.445591459	MJ	CO	3400	mg	0.2084	kg	0.327175682	Solid waste	41.82	kg	2563.2	kg
		Oil fuels	46.28	MJ	2.836584967	MJ	CO2	620000	mg	38.001	kg	38.0009222					
		Other	35.88	MJ	2.199150143	MJ	SO2	6600	mg	0.4045	kg	0.177991416					
							CH4	29610	mg	1.8149	kg	50.81581383					
	Water Consumption	Water	174000000	mg	10664774.94	kg											
	Transportation						CO2	14.76523	kg	14.765	kg CO2e	14.76523077					
		Diesel per truck	1.44615385	gallons			CH4	4.79E-05	kg	0.0013	kg CO2e	0.00134232					
							N2O	4.51E-05	kg	0.012	kg CO2e	0.0119568					
Resource Extraction	Material	Pine	95.86	% for p	6.39066411	cubic	CO	0.104036	kg	0.0196	kg	0.030834497					
		Yellow popula	4.14	% for p	0.27599989	cubit	CO2	12.12394	kg	2.2887	kg	2.288740312					
							SO2	0.0266	kg	0.005	kg	0.002209465					
							N2O	0.0207	kg	0.0039	kg	1.035544962					
	Energy	Diesel and gasoline	3.44	L			CH4	0.0242	kg	0.0046	kg	0.127916373					
		Lubricans	0.054	L													
		Electricity	0.455	kWh													
Plywood Manufacturing	Material	Roundwood	1230	kg	232.1976671	kg	CO	0.99559	kg	0.1879	kg	0.295075342	Solid Waste	0.03934	kg	0.0074	kg
		Bark	107	kg	20.19930925	kg	CO2	489.177	kg	92.346	kg	92.34614489					
		Phenol-formaldehyde	14.7	kg	2.77504529	kg	SO2	1.44	kg	0.2718	kg	0.119610115					
		Extender and fillers	2.6	kg	0.490824337	kg	N2O	0.791	kg	0.1493	kg	39.57082438					
		Catlyst	0.167	kg	0.031526025	kg	CH4	0.599	kg	0.1131	kg	3.166194531					
		Soda ash	0.458	kg	0.086460595	kg											
		Venner	9.64	kg	1.819825619	kg											
		Venner (green)	3.39	kg	0.639959424	kg											
	Energy	Electricity	158	kWh	29.8270174	kWh											
		Hogged fuel (produce	147	kg	27.7504529	kg											
		Hogged fuel (purchas	17.5	kg	3.303625345	kg											
		Wood waste	47.1	kg	8.891471643	kg											
		Natural gas	28	m3	5.285800552	m3											
		Liquid Petroleum gas	2.14	L	0.403986185	L											
		Gasoline	858	L	161.9720312	L											
		Diesel	1.23	L	0.232197667	L											
	Water	Water	407	L	76.8328866	L											
	Transportation						CO2	7.225538	kg	7.2255	kg CO2e	7.225538462					
		Diesel per truck	0.70769231	gallons			CH4	2.35E-05	kg	0.0007	kg CO2e	0.00065688					
							N2O	2.21E-05	kg	0.0059	kg CO2e	0.0058512					
Panel Assembly	Material	Polyvinyl Acetate	0.058399	kg	1.226379	kg											
		Urea formaldehyde re	0.114	kg	2.394	kg											
		Venner	0.8977	kg	18.8517	kg											
	Energy	Diesel	0.000588	L	0.012348	L	CO2	0.2423	kg	5.0883	kg	5.0883					
		Gasoline	0.00014399	L	0.00302379	L											
		Electricity	0.341	kWh	7.161	kWh											
		Heat	1.09	MJ	22.89	MJ											
		Natural gas	7.43E-07	L	0.000015603	L											
	Transportation						CO2	65.97231	kg	65.972	kg CO2e	65.97230769					
		Diesel per truck	6.46153846	gallons			CH4	0.000214	kg	0.006	kg CO2e	0.0059976					
							N2O	0.000202	kg	0.0534	kg CO2e	0.053424					

Results and Analysis

The total CO2e emissions were calculated for each panel, broken down into system, subsystem and process with the use of Excel and then plotted using Tableau. Figure 1 shows a total of -416kg CO2e for Straw Bale Panels and 285kg CO2e for EPS Panels.

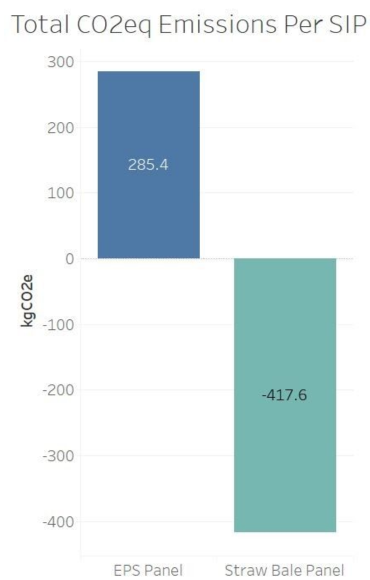


Figure 1

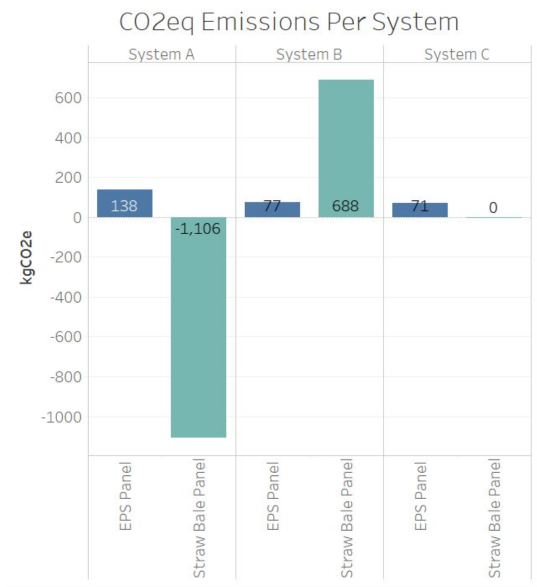
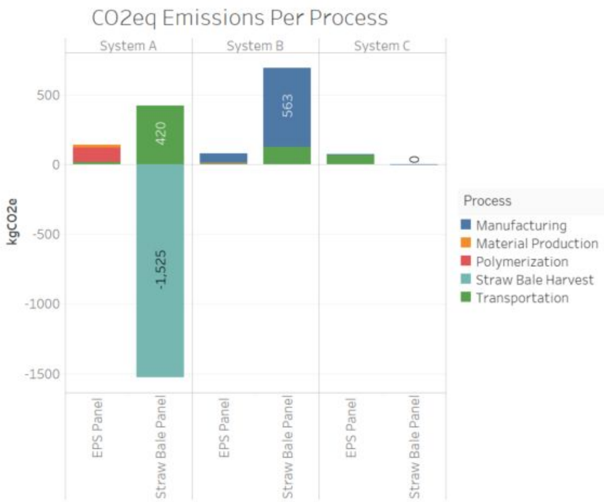


Figure 2

To understand the source of emissions and do further analysis, the panels were broken down into systems. System A pertains to the low density material of the SIP, for the conventional SIP, this would include processes involved in the EPS foam and for the straw bale SIP, this would include processes involving the straw bales. System B refers to the processes involved in the structural elements of each panel. For the conventional SIP, this includes the plywood, and for the straw bale SIP, this includes the wire mesh, clay plaster and framing. System C refers to panel assembly. It can be observed on Figure 2 that the emissions for EPS panels are almost equally distributed across each system; however, Straw Bale panels show a negative value of 1106kgCO2e emissions due to its embodied energy on system A, a total of 688kgCO2e for system B and no emissions from system C.



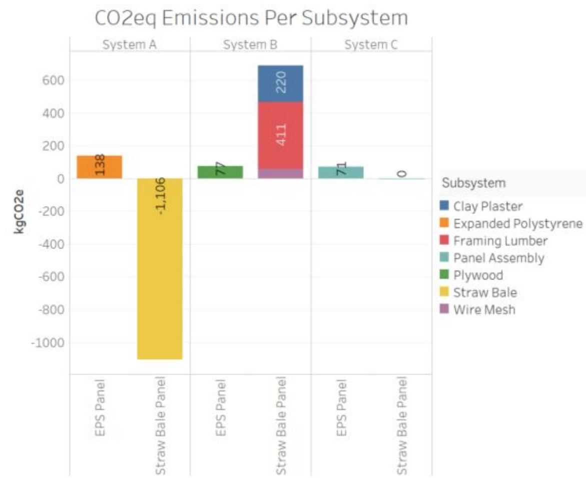


Figure 3 Figure 4

Furthermore, each system was divided by total kgCO2e per process and subsystem, Figure 3 and 4. It can be observed that transportation and manufacturing processes are the main sources of positive kgCO2e for Straw Bale panels, while Polymerization is the main source of kgCO2e for Expanded Polystyrene Panels. In terms of subsystems, while framing lumber and clay plaster have greater kgCO2e compared to the ones from subsystems for EPS Panels, the impacts were greatly lessened by the negative kgCO2e from Straw Bale Harvesting.

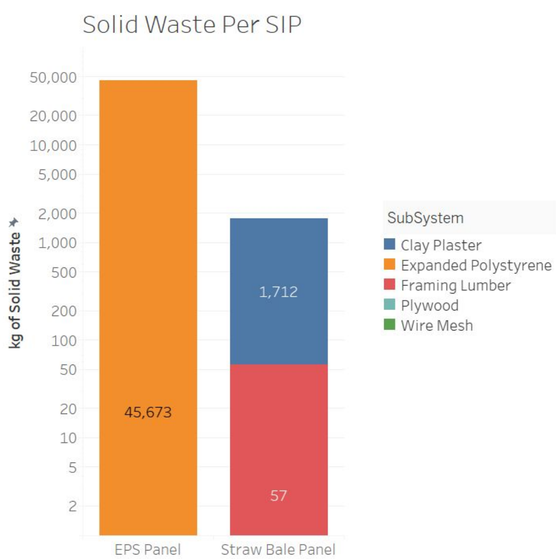


Figure 5

Figure 5 shows the total kg of Solid Waste per Panel, broken down into Subsystems. It is important to note that the y-axis is in logarithmic form. EPS panels produce a total of ~46 tons of solid waste, mainly from plastics and chemical sources while Straw Bale panels only produce ~1 ton of solid waste, generated from clay plaster and framing lumber processes. Waste from steel wire mesh manufacturing was excluded from this analysis due to lack of data, and results may vary significantly if included.

Data Quality

Water consumption and solid waste data was found for some processes, but proved difficult to determine given the specificity of each material. Some data sources referred to results observed in other States within the U.S. while others referred to other countries, such as the data on steel wire mesh from Norway. Technological advancements in the latter years which improve overall performance and therefore reduce kgCO2e might affect the data sourced from documents not recently published. Information regarding vendor location was not selected arbitrarily, rather, it was selected based on the location of the building site. Assumptions can be found within the "Methodology" section.

Sensitivity Analysis

Given that emissions from transportation were the main source of kgCO2e for Straw Bale panels, a comparison for both Panels in terms of changes in transportation was performed, which is presented in Figure 6. The selected vendors for EPS materials were within less than 10 miles from the construction site. Meanwhile, straw bale transportation from the manufacturer to the building site was around 267 miles, making this subsystem the main source of kgCO2e for Straw Bale Panel.

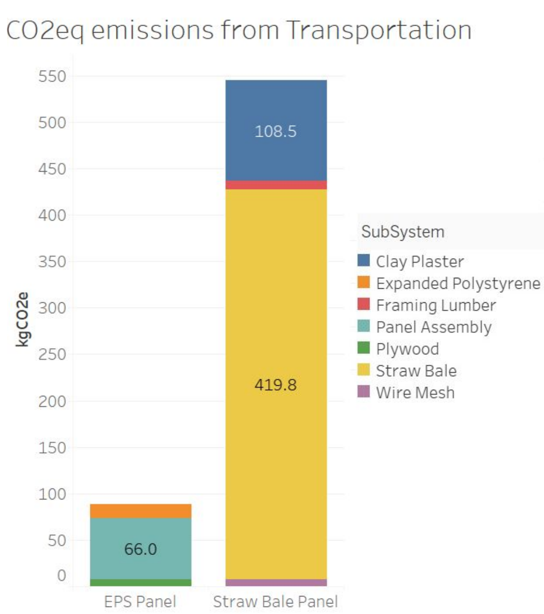


Figure 6

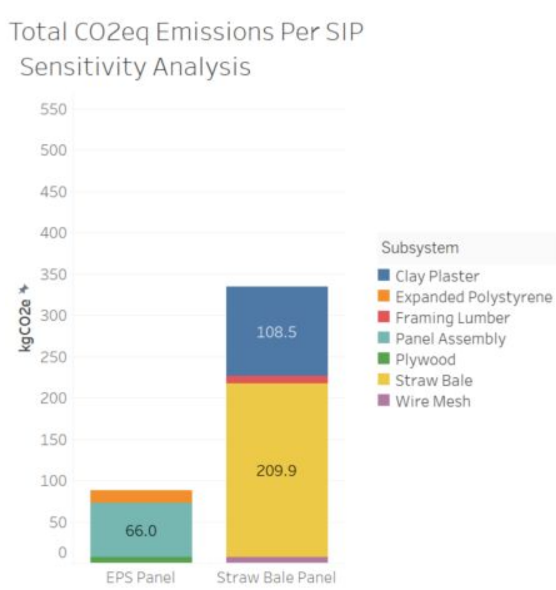


Figure 7

A sensitivity analysis was performed in order to observe the difference in kgCO2e for a shorter distance between Straw Bale Manufacturer and building site. Figure 7 shows the emissions for a vendor located at half the distance presented for System 2. It can be observed that kgCO2e emissions for transportation are still greater for Straw Bale panels than the ones for EPS panels.

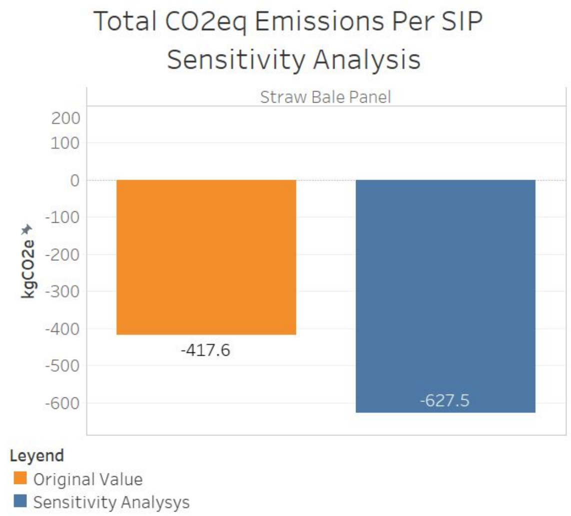


Figure 8

However, in order to maximize negative CO2 emissions for Straw Bale panels, the distance between Straw Bale manufacturing and building sites should be reduced; Figure 8 shows a 50% increase in negative CO2 emissions when the distance from Straw Bale manufacturer to building site was reduced by half, giving a total of -627 kgCO2e.

CONCLUSION

From the data obtained and the analysis conducted, it has been found that during the beginning stages of the systems, the CO2eq emissions for the conventional SIP are much higher than that of the straw bale SIP, given that the straw bale SIP actually has a negative 694kgCO2e in System A. It should be noted that removal of the rice straw actually shifts rice fields from a small net sink of carbon to a new source. However, the net GHG reduction is the result of decreased methane emissions (which has a higher global warming potential from baling) as opposed to reincorporating the straw back into the field. Despite this, these negative numbers do change in the progression of the panel manufacturing process. In Systems B and C, the Straw Bale SIP's kgCO2e increases in the Framing Lumber, Wire Mesh, and Plaster categories. While these are higher than that of the conventional SIP, the negative kgCO2e from straw bale harvesting offsets these increases and in combination with the lesser amount of waste produced, the Straw Bale SIP is favored. However, the main negative aspect regarding the Straw Bale SIP is the issue of transportation. The transportation of the straw bale to the assembly facility makes up the largest part of the Transportation kgCO2e comparison both for the straw bale and conventional SIPs. From this analysis, the Straw Bale SIP is confirmed to have a smaller impact on the amount of waste produced and emissions of greenhouse gases to the atmosphere. The key area of improvement for the Straw Bale SIP would be that of decreasing the transportation distance to the assembly facility, or utilizing a more fuel-efficient method of transport in order to reduce kgCO2e emissions.

FUTURE RESEARCH

One of the most common limitations experienced was that of having a lack of data. If it would be possible to obtain this data, the scope would be able to be increased to include the extraction processes, packaging, building processes, and a greater catalogue of the emissions and waste generated at each step of the process. This would also allow for a more detailed description of each step. Greater accessibility to public data regarding these processes is also necessary in order to allow for these assessments to be completed without paying for software.

L.A. County is one of the largest and fastest-growing metropolitan regions in the US and the population is expected to increase by 1.2-3.2 million people by 2060 (Burillo et al. 2018, p.2). Given this population increase and potential future heat waves described by climate change projections in LA County, there is potential for an increase in peak demand and risk of electric power outages in the county to 2060. According to a Report for California's Fourth Climate Change Assessment (2018), multi-family (shared wall) housing units were estimated to reduce peak demand by up to 50% per capita relative to single-family detached housing. In time, there will be a need to assess the capability of new multi family residential structures to be carbon sinks.

Additionally, there is a great potential in other areas of the world to benefit from the use of straw bale SIPs. One such area is the capital of India -- New Delhi. Northern India is known for its farming of rice and wheat, where rice is grown from "May to October," and then wheat right after from "November to March." Growing the rice produces millions of tonnes of straw, and due to the quick turnaround time between the rise and wheat seasons, the straw is most often burned in the same location of its growth. Contrary to California, which established regulations to phase out straw burning in the 1990's, burning is a common practice in India. With each acre producing about 2.5 tonnes of straw, the amount of emissions being sent into the atmosphere is extremely high. Burning the straw sends about a tonne of gases into the atmosphere, including carbon dioxide and carbon monoxide. There have been efforts made to utilize this excess straw in other forms, and being that rice in these areas is often grown in small areas it can make it impossible to "till the straw deep into the soil prior to planting wheat" (Berry and Sagi 2017).

Given this situation, New Delhi is a prime contender for the new Straw Bale SIPs. New Delhi has had a great reduction in the amount of individuals living in its rural areas-- from 2001 to 2011, decreasing by more than half. This area is experiencing rapid urbanization, with the area of farmland being used decreasing from 52,816 to 34,750 hectares between the years of 2000 and 2016 due to urbanization and "shift in occupational pattern" (Singh 2018). Due to this rapid development and surplus of straw, as much of this farmland is beginning to be bought to build houses, there is an opportunity to utilize the Straw Bale SIPs in their construction in order to lower waste and time spent constructing the houses.

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