Environmental impact and indoor quality assessment of Pinoleville Pomo Nation demonstration home:

An implementation of life cycle assessment and culturally-inspired design

By

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ABSTRACT

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Among the many environmental and social challenges present today, the development of sustainable communities poses much potential for a harmonious future. The Pinoleville Pomo Tribal Nation is actively working towards sustainability, partially through the design and development of energy-efficient, culturally-centered homes. This work assessed the environmental impact and indoor environmental quality of the recently occupied demonstration home in order to advise modifications for this and future homes. To address environmental impacts, a cradle-to-grave life cycle assessment was performed using TRACI 2.1 impact assessment methodology. Results indicated that 66% of the total impacts come from the use and maintenance during the home's life, but this is heavily susceptible to the actual grid electricity consumption rate. Within the building's structure and systems, most of the environmental burden can be attributed to steel, primarily in the roof. To address indoor environmental quality, culturally-inspired sensors were designed and implemented to actively measure indoor air temperature, relative humidity, and illuminance. Preliminary testing revealed more than desirable diurnal temperature fluctuations and healthy humidity levels. A thermal comfort analysis showed acceptable levels in all tested spaces except the back office, which tended towards cool. Design alternations, feedback to occupants, and future studies are suggested based on results.

ACKNOWLEDGEMENTS

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1. INTRODUCTION

With increasing population and affluence and decreasing resource supplies, there is a global challenge to discover what sustainable living means. Sustainability takes on many definitions and forms, the most common of which, provided by the Brundtland Commission of the United Nations, states that "sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs" [1]. This involves addressing environmental, economic, and social needs.

Among environmental concerns relating to energy and material consumption, the building sector contributes a significant majority. In the United States in 2008, 40% of the total site energy is consumed by buildings, of which 22% is residential and 18% is commercial. Within residential energy consumption, the top contributors are space heating (28.1%), space cooling (14.3%), water heating (14.1%), and lighting (10.9%) [2]. Material consumption in the United States is growing at an astonishing rate, and construction materials (crushed stone, sand, and natural aggregates) largely dominate overall consumption by mass [3]. Worldwide, the construction industry is estimated to use approximately 40-50% of the total mass of materials consumed [4]. The effects of these high material and energy consumption rates are realized locally and globally in various ways, including climate change, smog formation, eutrophication, and human toxicity, to name a few. While a necessary first step is understanding what is consumed and how much, identifying how those consumption patterns affect the natural environment is invaluable to decision makers. To accomplish this, life cycle assessment (LCA) is a popular and comprehensive tool that enforces researchers to consider environmental impacts throughout the entire life cycle of a product or system.

In addition to reducing energy consumption and overall environmental impact, the health and comfort of the indoor environment should also be considered. In the United States, people spend over 85% of their lives indoors on average [5], which means that indoor environmental quality (IEQ) has significant impact on our health and wellbeing. In fact, indoor air pollutants in air tight buildings are known to be two to five times higher than outdoor levels, and this can be more than 100 times higher on occasion [6]. IEQ encompasses many factors, including lighting (intensity, color, consistency), indoor air quality (IAQ), and thermal comfort. Thermal comfort, while heavily dependent on an individual's body shape and preferences, is largely influenced by six factors: air temperature, relative humidity, mean radiant temperature, air velocity, occupant clothing, and occupant activity.

Developing sustainable communities has generally been perceived as a way to address health and environmental concerns as well as economic and cultural prosperity. Founded in 2007, the Community Assessment of Renewable Energy and Sustainability (CARES) group at the University of California, Berkeley aims to "enable end users to make informed decisions about sustainability and renewable energy technologies by giving them agency during the design, development, and implementation of sustainability best practices and renewable energy technologies" [7]. The CARES methodology can be represented as a cycle of assessing, advising, implementing, living, and re-assessing. While the community are experts in their needs and culture, CARES provides external expertise in engineering, environmental science, architecture, and sustainability in order to help communities achieve their goals. Since March 2008, CARES has partnered with the Pinoleville Pomo Nation (PPN) to co-design sustainable communities through housing that embodies cultural values and traditions. The Pinoleville Pomo Nation is a federally recognized Native American tribe in Northern California, actively pursuing tribal sustainability. Alongside CARES, the PPN designed and constructed two demonstration homes, one of which has now been occupied since January 2015.

In order to complete the CARES cycle and determine how well the homes perform in actuality, it is important to re-assess the homes from various perspectives. While there is an overall goal of reducing energy use and environmental impact, these reductions ought to not come at the expense of compromised IEQ and user satisfaction. The objective of this project is to perform a preliminary assessment of the environmental impact and indoor environmental quality of the PPN's demonstration home in order to advise modifications for improving performance of the current and future homes. These assessments will be achieved through LCA and the design and implementation of culturally-inspired sensors.

2. BACKGROUND

2.1 Geography and Climate

The demonstration home is located on the PPN Reservation, Pinoleville Rancheria, on the outskirts of Ukiah, California, which is approximately 100 miles north of the San Francisco Bay Area. Specifically, Pinoleville Rancheria is situated on the south side of Ackerman Creek, where the creek exits a steep canyon before entering the Ukiah Valley [8]. The climate generally is cool and mild in winter but snows lightly some years, and the summers are comfortable. There are diurnal variances over 11°C (20°F) all year, and it is often windy in the afternoon [9]. In fact, the Pomo people called the area "ya-mo bida", which is Pomo for "wind hole creek" [10]. General climatic and geographic data are summarized below in Table 1.

Table 1: Geographic and climatic data for Ukiah, California

Parameter	Value	Data source
Altitude (m)	195	[11]
Latitude (DEC)	39.15	[11]
Longitude (DEC)	-123.21	[11]
Annual precipitation (mm)	939	[12]
Annual heating degree days (°C-day)*	1713	[13]
Annual cooling degree days (°C-day)*	468	[13]

* Average (1971-2000) annual heating and cooling degree days to a base temperature of 18°C (65°F), which represents a commonly used base [14].

Situated in California Climate Zone 2 and Mendocino County, Ukiah has a temperate and coastal climate where the weather is "influenced by the ocean approximately 85% of the time and by inland air 15% of the time" [8]. Daily temperature and relative humidity (average and range) from 2014 can be seen below in Figure 1. Over the course of 2014, the average outdoor temperature was 17°C, while the maximum and minimum recorded were 42°C and -5°C, respectively. For relative humidity in 2014, the average was 60%, while the maximum and minimum recorded were 100% and 4%, respectively (Figure 1).

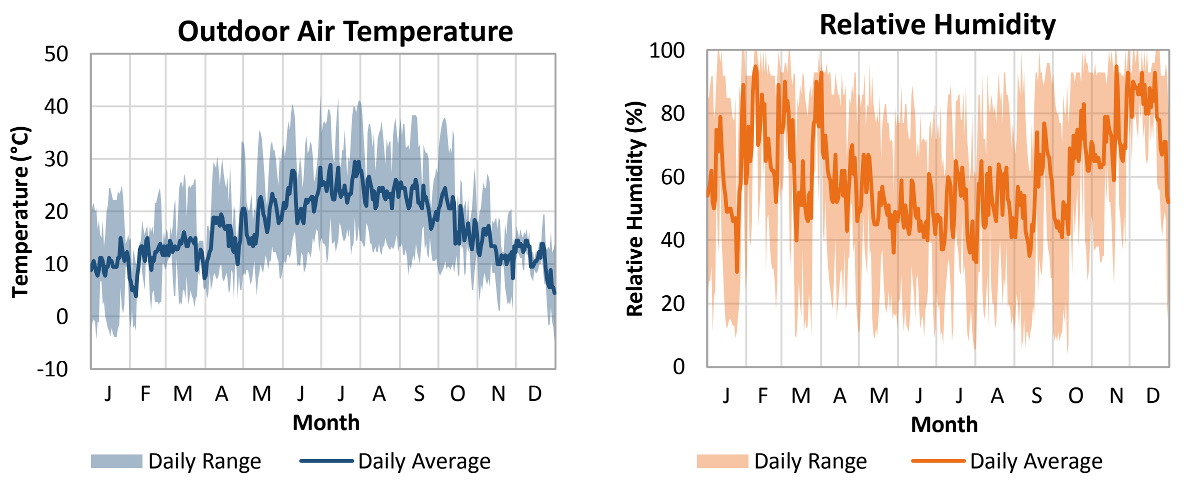

Figure 1: Daily average and range for outdoor air temperature (left) and relative humidity (right) in Ukiah, CA in 2014. Data source: [15]

2.2 The Pinoleville Pomo Nation and Demonstration Home

The Pinoleville Pomo Nation (PPN) is a federally recognized Native American Tribe in Northern California. There are approximately 300 citizens in the tribal nation, most of which live off the reservation in cities such as Santa Rosa or Sonoma and are seeking to return to their ancestral land. The PPN have a strong drive for sustainability and identify their vision as:

> *"We see our community being healthy spiritually, physically, emotionally and mentally. We will be independent and self-sufficient through economic development. Self-governance will be carried out through leadership focused on cultural and traditional values, taking actions needed to bring our people into balance. We see ourselves passing on the knowledge and wisdom of our ancestors to future generations, and encouraging understanding with communities outside of our own."* [16]

Traditionally, the PPN were known for their basket weaving, traded goods among other regional tribes, and moved between the coast and inland region depending on the season, gathering whatever was needed and available at the time. Their roots go back to the lush Potter Valley, where there were several villages and camps, varying from five to nearly one hundred houses, that all spoke Northern Pomo. Village leaders, or Captains, were selected based on their abilities or power, and alliances between villages formed through mutual ceremonies and marriage [16].

Housing structures varied depending on the season and their need. In the summer, minimal brush shelters were sufficient, while winter shelters, or "tca", were built out of willow trees, thick grasses, and tules into a hemispherical shape. Large roundhouses were built in each village for meetings, some of which could house several hundred people for dance or ceremony [16]. Acorns were the most notable staple food, and this was supplemented by abalone, pepperwood nuts, buckeyes, and other small game, to name a few. Ceremonies have always been an important part of life; these include giving thanks for a good harvest, honoring religious beliefs, celebrating a new phase in someone's life, and welcoming visitors [16].

With the arrival of Europeans beginning in the early 1800's, the Pomo people were driven from their lands and traditional ways of life with much devastation and deceit. In 1878, a group of Potter Valley Pomos purchased land just north of Ukiah, called “ke-buk ke-bul”, which later came to be known as Pinoleville. Unfortunately, the Ukiah townspeople complained about the “ceremonial cremation and loud wailing, which, in the traditional way, went on for days when there was a death” [16]. In 1893, the Pinoleville and other Northern Pomo captains traded their land for 100 acres between Ackerman Creek and Orr Spring Road, where the PPN now currently reside.

From 2008-2010, UC Berkeley and the PPN partnered to co-design and co-build sustainable homes that are culturally-centric (Figure 2). These homes feature natural construction materials, geothermal heating and cooling, rainwater catchment, photovoltaic (PV) panels, and solar thermal panels for hot water heating. General facts and figures about the home are summarized in Table 2 below, while further specifications are included in Section 3.3. Culturally-inspired features include rounded corners to reflect traditional architecture, a lowered gathering center, natural wood pillars to signify cardinal directions, and natural materials (abalone shells, stone, earth, etc.) built into the structure. Through this partnership and design workshops, a tailored framework for PPN sustainability was developed that includes: cultural sovereignty, tribal sovereignty, economic self-sufficiency, and environmental harmony [17].

Figure 2: Pinoleville Pomo Nation demonstration home from a North-West facing view

Table 2: Facts and figures for Pinoleville Pomo Nation demonstration home

Building parameter	**Value**
Location	Ukiah, CA
Year of completion	2014
Unit cost	\$2580/m^2, \$475,000/unit [17]
Useful life	60 years
Gross floor area	180 m^2
Structure:	Single story
	2x4 wood frame
	Straw-bale insulation
	Earth plaster
	Corrugated metal roof
Energy sources:	Photovoltaic*
	Solar thermal*
	Geothermal heat pumps
	Electricity grid
Operating grid energy (estimate)	100 kWh/m^2/year
Operating water	140,000 kg H_2O/year

* Planned installation in April 2015

2.3 Literature Review

With near universal recognition of the pressing environmental challenges ahead, efforts to reduce our environmental burden and fossil fuel consumption in the built environment have been undertaken all across the globe. From implementing cutting edge technology to revisiting traditional construction methods, there are many ways people are working towards realizing green buildings, which are often highly depend on the local conditions and needs. For example, in the warm and humid climate of Cuba, "traditional design strategies… recommend the use of light buildings well protected against sun and rainfall [that are] unable to store heat in their envelope" [18]; meanwhile in the Netherlands, passive homes that "give high priority to the performance of the thermal envelope" through high-grade insulation, thermal bridge-free construction, and air tightness have shown much promise in saving energy [19]. In Sana'a, Yemen, Al-Sallal [20] examined the balance between environmental and socio-cultural requirements in traditional and modern architecture in order to derive sustainable design guidelines. On the other hand, groups in Italy have integrated photovoltaic panels into intelligent window systems, explored natural materials, and built roof gardens into buildings [21].

In order to realize sustainable buildings, it is equally necessary to assess the building's actual performance as it is to integrate sustainable features into the design. This is particularly important with buildings since the designer, occupant, owner, and contractor are often different people. Once occupied, many buildings go through a commissioning process to identify gaps between how the building is functioning and as how it was designed. This may include testing the health and comfort of the indoor environment [22], energy and water consumption [20], and/or thermal performance [19]. Life cycle assessment (LCA) is a commonly used tool to evaluate buildings as it recognizes the building's effects not only during use but also during other phases such as manufacturing and demolition.

There have been many efforts to evaluate residential buildings through LCA, but it is often difficult to compare studies because of variations in scope and methodology. Several groups have evaluated the energy of buildings and/or the global warming potential [19,23-31]. Others have decided to focus life cycle mass of materials [24], water consumption [32], and select emissions [24,33]. While all of these impact types are important considerations, individually they do not provide a comprehensive assessment of a building. Additionally, the scope of studies often varied. Some were defined from cradle-to-grave [23-24,33-35], but others only focused on the pre-use phase only (cradle-to-gate) [36], or excluded transportation and end-of-life phases [25,29]. Similarly, some only focused on common structural materials [4,24,37-39], finishing and technical equipment [33], or fenestrations [40]. An overview of building LCAs can be found in Ghattas et al. [41], where the effect of lifetime and floor area in residential building LCAs are highlighted.

A few comprehensive LCAs of residential buildings are notable for comparison to this study. Keoleian et al. [23] performed a cradle-to-grave LCA on a standard 228 m^2 single-family home and compared the life cycle energy and cost to an equivalent energy-efficient home. Results indicated that the use phase accounts for 91% of the total life cycle energy of the standard home, while an overall reduction of 60% in life cycle energy was achieved through the energy-efficient home. The pre-use phase accounted for 26% of the life cycle energy in the energy-efficient home [23]. The study concluded that the payback period for energy-efficient homes needs to decrease from around 50 years to eight years or less in order for the market to grow [23]. With the goal of refining the US residential building life time, Aktas and Bilec [42] performed a cradle-to-grave LCA on a medium sized home in the United States using the databases in SimaPro v7.1 and TRACI 2 v3.01 impact assessment methodology. Demolition and waste transportation were found to be 0.1-1% of the life cycle energy and therefore were neglected during this study. Results indicated that the average US building lifetime is 61 years and a dominance of use-phase energy to overall impacts in standard homes, while “the relative importance of interior renovation” increases as buildings become more efficient [42].

Residential buildings consume energy and resources in order to meet their occupants needs, which include providing shelter, comfort, privacy, community, and a healthy environment. While green buildings aim to minimize the burden they place on the environment, they must also meet the needs of their occupants. The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) developed the 55 Standard by which the built environment should be evaluated [43]. To assess thermal comfort, the static model (PMV/PPD) involves calculating the predicted mean vote (PMV), the predicted percentage of dissatisfied (PPD), and the percentage of points outside of the comfort zone. For PMV, the ASHRAE-55 standard recommends that the average PMV stay between -0.5 and 0.5, which signifies neutral thermal comfort [43]. The PMV is given on a scale from -3 (cold) to +3 (hot). The predicted percentage of dissatisfied (PPD) directly relates to PMV, and the ASHRAE-55 standard recommends a PPD less than 10% for acceptable comfort. While average PMV and PPD signify the average thermal state, the percentage of points outside of the comfort zone indicates the range of comfort experienced. For this, the ASHRAE-55 standard recommends that less than 5% of points fall outside of the comfort zone; however this 5% is specified for commercial buildings, not residential [44]. Each of these metrics will be examined when assessing the thermal comfort of the demonstration home.

3. ENVIRONMENTAL LIFE CYCLE ASSESSMENT

3.1 Approach and Methodology

A preliminary LCA of the demonstration home was undertaken in order to determine where improvements can be made to the current home and future constructions. Since the family first moved into the house in January 2015, only three months of use and maintenance data is available. This limits the confidence of the assessment, since assumptions need to be made about a year's worth of consumption and use patterns from a short time frame in late winter/early spring. However, starting analyses early help with the goal of reassessing the home for continual improvement.

This analysis followed the LCA guidelines set forth by ISO 14040:2006 through the process of goal and scope definition, inventory analysis, impact assessment, and interpretation [45]. The impact assessment was performed in Sustainable Minds [46], an easy-to-use cloud-based software that intends to make it convenient for companies to integrate "life cycle thinking and LCA into their product development process" [47]. Since this is a preliminary assessment of the home, this software package was suitable because of its availability and simplified interface.

Sustainable Minds applies the TRACI 2.1 impact assessment methodology, which characterizes environmental damage over a 100 year time horizon in terms of the following impact categories: acidification, ecotoxicity, eutrophication, global warming, ozone depletion, fossil fuel depletion, carcinogenics, non carcinogenics, respiratory effects, and smog formation [48-49]. The Tool for the Reduction and Assessment of Chemical and other environmental Impacts (TRACI) was created by the United States Environmental Protection Agency (EPA) in order to provide a comprehensive impact methodology based on U.S. conditions [48]. Normalization and weighting factors are applied to midpoint values in order to compute a single score represented in terms of "points". It is important to note that these Life Cycle Impact Assessment (LCIA) "results are relative and do not necessarily predict impacts on each respective category's end points, thresholds' exceedance, safety and health risks" [49].

3.2 Problem Definition and Scope

The goal of the LCA was to quantify environmental impacts of the demonstration home throughout its life cycle and identify hotspots within the building materials and life cycle stages. A scope 3 cradle-to-grave LCA of the demonstration home was undertaken with an assumed useful life of 60 years based on national averages for single-family residential homes [42], as can be seen below in Figure 3. This scope is defined as considering environmental impacts from raw material extraction through use and eventual disposal or recycling at end-of-life, and it includes impacts from the upstream and downstream supply chains. The demonstration home was also assessed from cradle-to-gate in order to identify the materials and aspects of the home that contribute the highest environmental impacts. For a building, relevant life cycle stages include harvesting raw materials, manufacturing, transportation, site work, construction, use, maintenance, and demolition. While all of these phases were included in the analysis, the data quality varied among phases.

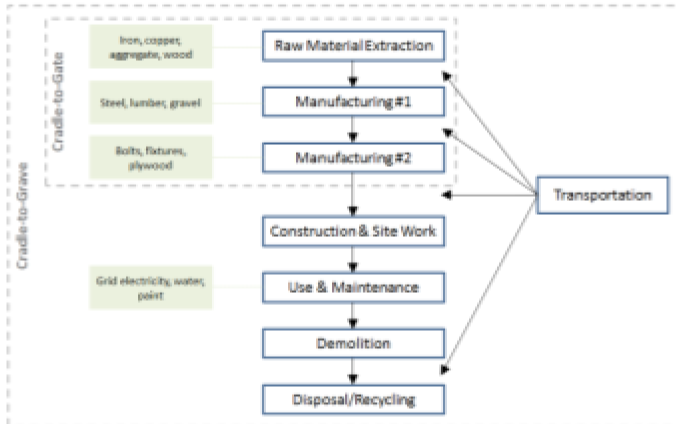

Figure 3: Simplified system diagram of demonstration home life cycle assessment with examples for select stages

A general listing of the included and excluded systems are summarized in Table 3 below. The analysis included the home's main structure, water systems, electrical systems, and mechanical systems, while appliances and other interior elements were excluded. The general scope definition was to include all systems that are permanently attached or fundamental to the building's design and exclude those that can be removed or moved.

Table 3: List of materials and systems that were included and excluded in the life cycle assessment

Life cycle phase	**Included**	**Excluded**
Pre-use (raw material extraction, manufacturing, construction)	Building structure, insulation, fenestrations, roofing, foundation, geothermal heat pump system, PV panels, solar thermal panels, pumps, water heaters, electrical wiring, water storage tanks, plumbing, fans, duct work	Appliances, furniture, countertops, cabinetry, light bulbs, utility hookup (excavation of mains, wiring, meters), worker transportation to/from construction site
Use	Grid electricity, water consumption	User transportation, landscaping, food, personal goods, cleaning products, entertainment equipment, municipal services
Maintenance	Earth plaster (biannual application), cement plaster, internal and external paint	Appliance replacement, HardiePanel siding, inside walls and doors, electrical maintenance, floor staining/waxing, replacement windows, PV maintenance, geothermal maintenance
End-of-life (demolition, disposal/recycling)	Building structure, plumbing systems, electrical systems, HVAC systems	Foundation

The functional unit for the assessment was defined as one 180 m^2 single-family residential building with a 60 year useful life. All impact results are provided with respect to this functional unit. While the home design indicated that water would be supplied entirely by rainwater and groundwater sources [50], upon construction the groundwater proved to be inaccessible. As a result, water is currently being trucked in whenever the storage tank nears depletion.

3.3 Inventory Analysis

All material and mass contributions for the demonstration home were estimated based on design documents, bid documents, and site inspections. Table 4 below summarizes the primary inventory data for the top 20 materials by mass. Since not all materials were available directly in the Sustainable Minds database, proxy materials were selected when necessary. Based on available data, it was estimated that the house contains a total of 290,000 kilograms of material spanning 48 unique material types, and an additional 49,000 kilograms of material are added through maintenance during its useful life.

Table 4: Top 20 materials used in the demonstration home by mass of finished product from cradle-to-gate

No.	**Material**	**Mass of material** *(kg)*	*(% of total)*
1	Concrete	160000	56
2	Gravel	59000	21
3	Sand	22000	7.7
4	Lumber (Douglass Fir)	13000	4.5
5	Steel	8300	2.9
6	Corn straw	7100	2.5
7	Gypsum	6500	2.3
8	Clay	2600	0.91
9	Fiberglass	1200	0.42
10	PVC*	1100	0.38
11	Walnut	870	0.30
12	Plywood	740	0.26
13	LDPE*	730	0.25
14	Ceramic	660	0.23
15	Water-based paint	590	0.21
16	Felt #15	324	0.11
17	PV Panels*	320	0.11
18	PP*	300	0.10
19	Copper	250	0.087
20	Glass	230	0.080

* PVC = polyvinylchloride, LDPE = low density polyethylene, PV = photovoltaic, PP = polypropylene

Grid electricity and water consumption were estimated based on design specifications and consumption patterns for the first three months of occupation. Grid electricity was modeled as U.S. 120 volt average electricity mix. While water currently is being trucked in when the storage tank requires refilling, water consumption was modeled as tap water at the user, which is based on Switzerland data and includes the "infrastructure and energy use for water treatment and transportation to the end user" [46]. Since there is much uncertainty in electricity consumption and its high impact potential, sensitivity analyses were performed around this quantity. As a base case, grid energy consumption throughout the demonstration's home life was assumed to be 100 kWh/m^2/year (552,000 kWh/functional unit), based on electricity consumption trends from the first three months of occupation. For sensitivity analyses, two additional electricity consumption scenarios will be modeled; one that follows the rate of grid electricity consumption as specified in the design documents [50] (1.4 kWh/m^2/year; 15,100 kWh/functional unit), and a second that follows the rate of an "energy-efficient home" from a study by Keoleian et al. [23] (156 kWh/m^2/year; 1,160,000 kWh/functional unit).

Transportation from manufacturing sites to the construction site was modeled for the included building materials. For trucking, transportation was modeled as "Transport, combination truck, average fuel mix", the data for which comes from the U.S. Life Cycle Inventory (LCI) database [46]. This inventory data assumes 100% diesel fuel and assumes industry standards in the United States for truck fill percentage and empty return trips. It was assumed that concrete, aggregates, and other natural materials were sourced locally, as is typical, while metal and plastic products were manufactured in China and shipped to Oakland via an oceanic freighter. Since transportation normally does not contribute significantly to overall impacts, these estimates were deemed satisfactory.

Estimates for environmental impacts associated with the construction and demolition phases were made based on previous literature studies. Since these phases typically were found to contribute small percentages to overall impacts [18,23,42], it was assumed that these rough estimates should not significantly influence the results. For end-of-life, it was assumed that building materials were either recycled and landfilled, depending on typical recycling rates and ability to disassemble materials, and that the foundation remains intact for future use.

3.4 Impact Assessment

Environmental impacts were broken down by midpoint categories before evaluating single score points. Midpoint impacts by life cycle stage are summarized below in Table 5. Use and maintenance represented the most impactful life cycle stage in all midpoint categories except non-carcinogenics and ozone depletion, in which manufacturing was the most damaging. Manufacturing represented the second highest in all other impact categories.

Table 5: TRACI 2.1 midpoint impacts of the demonstration home from cradle-to-grave by life cycle stage

Life cycle stage	**Impact category**									
	Acidification (kg SO_2 eq)	Ecotoxicity (kg CTU_e)	Eutrophication (kg N eq)	Global warming (kg CO_2 eq)	Ozone depletion (kg CFC-11 eq)	Fossil fuel depletion (MJ surplus)	Carcinogenics (CTU_h)	Non carcinogenics (CTU_h)	Respiratory effects (kg PM2.5 eq)	Smog (kg O_3 eq)
Manufacturing	5.7E+2	8.5E+4	3.4E+1	1.5E+5	4.2E-2	1.0E+5	3.7E-3	2.8E-2	8.0E+1	8.2E+3
Transportation	3.3E+1	1.5E+3	1.5E+0	1.9E+3	2.1E-4	3.2E+3	1.6E-5	1.2E-4	1.9E+0	5.2E+2
Construction	6.1E+0	4.3E+2	4.8E-1	1.1E+3	1.9E-4	1.9E+3	1.5E-5	8.1E-5	5.9E-1	1.3E+2
Use & Maintenance	3.3E+3	1.7E+5	7.3E+1	4.7E+5	2.2E-2	2.8E+5	6.8E-3	1.8E-2	2.0E+2	2.3E+4
Demolition	4.2E+0	3.0E+2	3.3E-1	8.0E+2	1.3E-4	1.3E+3	1.0E-5	5.7E-5	4.1E-1	9.0E+1
Disposal/ Recycling	2.5E+0	1.1E+2	3.5E+0	1.3E+3	9.7E-5	9.1E+2	4.5E-6	2.2E-5	2.5E-1	6.1E+1

The breakdown of TRACI single-score impacts by life cycle stage can be seen in Figure 4 below. In this case, the use and maintenance stage represents approximately 66% of the total impacts, while the embodied impacts from raw material extraction and manufacturing represent 33%. This modeled scenario assumes an energy use intensity of 100 kWh/m^2/year, which is the expected grid consumption rate based on the first three months of occupancy. All remaining life cycle phases contribute less than 1% to the overall environmental impact of the demonstration home throughout its life cycle.

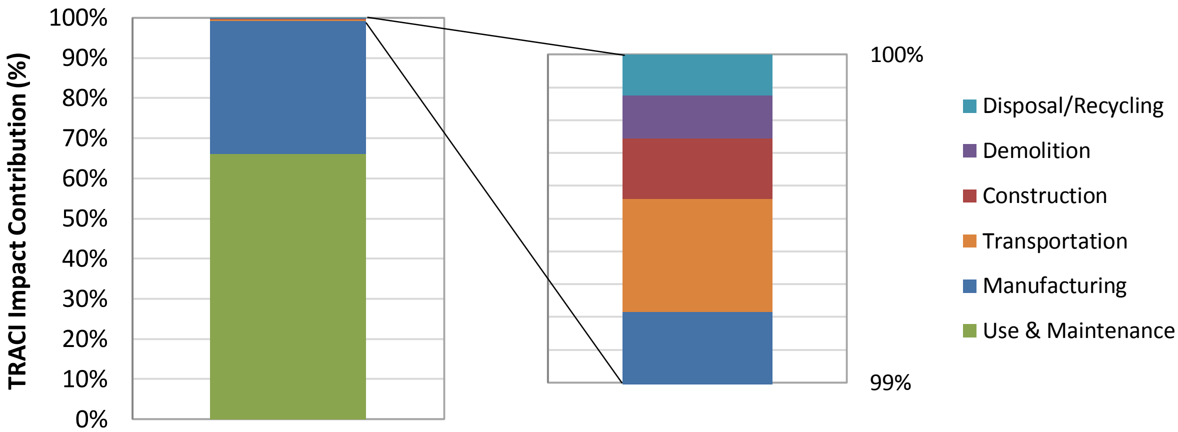

Figure 4: Cradle-to-grave environmental impacts per functional unit, assuming energy consumption consistent with first three occupied months

The breakdown of TRACI single-score impacts by impact category can be seen in Figure 5 below. Contrary to Table 5, these endpoint results have been normalized and weighted to represent impacts in terms of points. While there is more uncertainty in endpoints than in midpoints, endpoints allow comparisons to be made across impact categories and decisions to be made about the home's overall ecological footprint. Carcinogenics represent the largest contributor, followed by global warming. Fossil fuel depletion and non-carcinogenics are the next largest impacts, and ecotoxicity is the fifth largest contributor. As with midpoint results, most of these impacts come from the use and maintenance stage.

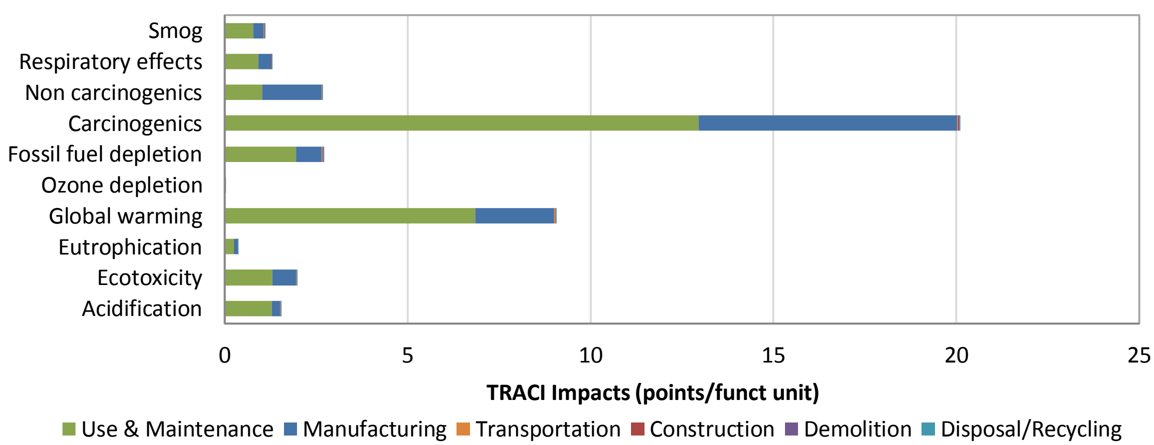

Figure 5: Cradle-to-grave environmental impacts of demonstration home by midpoint category, assuming available occupied trends for energy consumption

Examining the results from cradle-to-gate (from raw material extraction through the manufacturing phases) allows the distribution of material contribution to the home's impacts to be realized (Figure 6). Steel represented approximately 58% of the total environmental impact from cradle-to-gate. This is followed by the concrete foundation, which is responsible for 23% of the manufacturing impacts. By using corn straw bale in the home's insulation and plaster, more environmental benefit occurred than harm, as indicated by the "negative" contribution (-7.0% of total from cradle-to-gate).

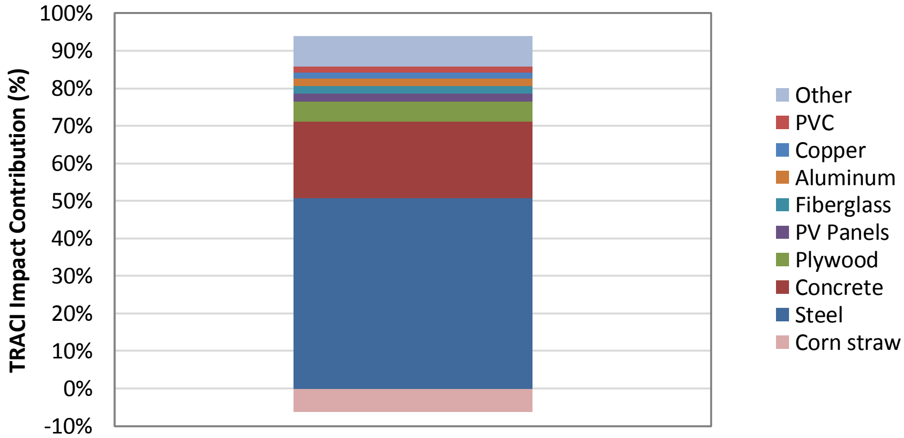

Figure 6: Cradle-to-gate impacts of demonstration home by material type. Materials representing less than 2% of the overall impact are included in other.

For a sensitivity analysis, two additional energy consumption scenarios were modeled. The results comparing the overall environmental impacts of the base case scenario (100 $kWh/m^2/year$) with two additional estimates are presented in Figure 7 below. Across these three cases, only the amount of grid energy consumed during the demonstration home's useful life was changed. The two alternative scenarios depict very different stories when it comes to the magnitude of environmental impacts and the distribution of where the highest impact contributors lie. An energy use intensity of 1.4 $kWh/m^2/year$ was specified in the design documents [50]; this case has less than half of the impact compared to the base scenario. In this design case, the embodied impacts from raw material extraction and manufacturing represent approximately 94% of the total, while 4.0% comes from use and maintenance of the home. The second sensitivity analysis, which assumes a grid electricity consumption rate of 156 $kWh/m^2/year$ based on previous studies, nearly doubles the overall impact compared to the base scenario. Here, the use and maintenance stage represents approximately 80% of the total impacts. Complete utility bills from the first year of occupancy will provide necessary insight into which of these scenarios is closest to the actual story.

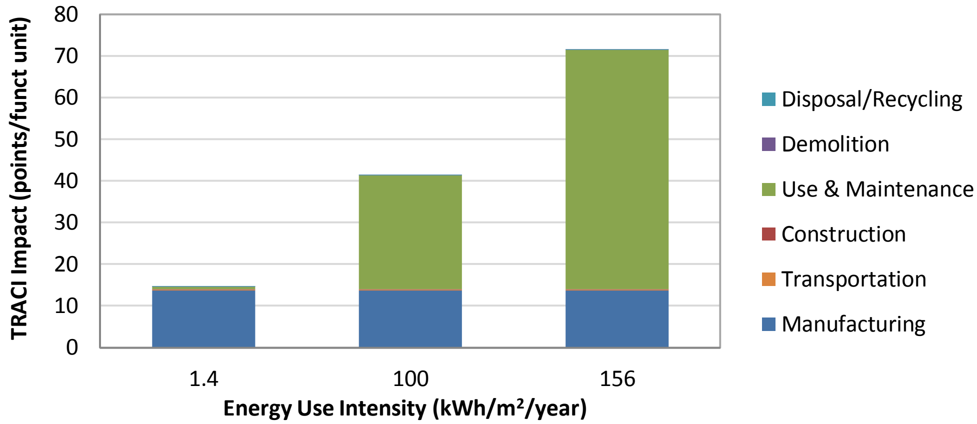

Figure 7: Cradle-to-grave environmental impacts of demonstration home with energy consumption rate as designed (1.4 kWh/m²/year), based on trends from first three occupied month (100 kWh/m²/year; the reference case), and based on an "energy-efficient" home's rate (156 kWh/m²/year) [23].

3.5 Interpretation

This LCA indicated that the use and maintenance phase of the home, particularly the grid energy consumption, is most responsible for the negative environmental impacts; however this may not be the case depending on actual performance. Most of the environmental impacts were realized as carcinogenics and global warming. Out of all the materials in the building's structure and systems, steel was responsible for the majority of the impacts. This can mostly be attributed to the mass and processing required for the corrugated steel roof. The corn straw bale in the plaster and insulation contributed a "negative" impact score, indicating that it is providing more benefit than harm by using it. This is likely the case since it is normally considered as waste.

Previous literature generally reinforces the results found here. As found by Keoleian et al. [23] and Aktas and Bilec [42], the electricity consumption during use dominated impacts. The distribution of impacts within the building's materials is more difficult to compare since it is highly dependent on the particular structure, and the buildings studied in previous LCAs did not feature steel roofs. However, it is understandable that steel contributes significantly to the environmental impacts, due to the volume in which it is present, its density, and heavy processes required to mine the raw materials and process into steel. Straw bale has been received in both positive and negative ways as a building material. Miller and Ip [4] pointed out that straw bale, while being used for centuries, have often been replaced by modern materials because they are "quicker and often require less skill to erect". Meanwhile, others indicated that straw bale optimally provides high insulation and load bearing properties while being a natural and cheap material. Future work should work to determine if the benefits of straw bale found here outweigh any losses in its ability to insulate buildings from their external environment.

As a preliminary assessment, there are several limitations to data quality that should be considered. Data uncertainty can arise in LCA for many reasons, including the acquisition method, independence of data suppliers, representativeness, temporal correlation, geographical correlation, and further technological correlation [51]. While independence of data suppliers, representativeness, and temporal correlation were strong, the data was lacking in acquisition method (rough estimates were made based on documents and site visits), geographical correlation (global and national data were used), and further technological correlation (data was from materials and processes under study, but not specific to actual suppliers). The Sustainable

Minds database is highly limited compared to others, such as ecoinvent or GaBi, and future studies should use some of these larger databases as well.

Several limitations to this study should be considered beyond data quality. First, estimates for energy use, water consumption, and maintenance practices were made based on short term data, and these may not represent actual trends and yearly trends. Second, the U.S. grid electricity mix was modeled, and the actual electricity mix used likely differs. Future models should model California's electricity mix rather than the national average for more accurate results. Lastly, simplifications for materials estimates had to be made due time constraints and the complexity of the home and included systems. Passer et al. [33] showed that technical building equipment can contribute significantly to environmental impact, and this study made rough estimates for these components. Additionally, the steel in the home was modeled as 25% secondary, which may or may not be close to what was actually used in the building's roof, equipment, rebar, etc. Future investigations should revisit the mass flows of all relevant materials to better model the residential building.

Based on this work, the following recommendations are advised in order to improve this home's environmental performance and future homes.

(1) Continue to work towards reducing energy consumption, by for example, unplugging appliances, using energy-efficient appliances, and turning off lights
(2) Investigate natural roofing materials, such as ceramic tiles or wood shingles
(3) Ensure straw bale insulation is well packed and tight around wood frame to avoid thermal-bridging and undesirable heat transfer
(4) Close blinds and windows when you want to keep heat in, and rely on natural ventilation to clear the air and cool the rooms when it's too hot

LCA provides much benefit as a design tool that can help inform improvements for the use phase of buildings and future designs. Energy consumption tends to dominate, but embodied impacts in buildings materials play a significant role. In order to identify where efforts should be directed to make the most difference and to understand the effect our decisions have on the environment, it is important to take a comprehensive approach in the assessments made.

4. INDOOR ENVIRONMENTAL QUALITY

4.1 Sensor Design and Development

The objective was to create product or service to monitor the quality of the indoor environment. While there are various products on the market that measure IEQ parameters, it was important to address the needs of the tribal citizens. Before implementation, we underwent several iterations of the design thinking process (understanding the context, developing frameworks/insights, generating ideas, exploring solutions, and re-evaluating the context) in hopes of producing a solution that adequately meets the tribe's needs.

User needs were determined through interviews with tribal citizens and office employees (7 in total), observations, and tertiary sources (including interview transcripts, published literature, and summarizes of workshop events). Through this process, the top five needs were identified as:

(1) Empowering PPN cultural values and traditions
(2) Communicating information about home status (energy, comfort, etc.) with others, particularly the PPN Council
(3) Understanding how comfort levels change between rooms
(4) Furthering a deep understanding of environmental harmony
(5) Promoting higher education and green jobs for youth

Over 100 concepts were generated, and the top ideas were selected for prototyping and further testing. These concepts included community events, job trainings, trade-in programs, home monitoring platforms, community data displays, micro grid designs, phone applications, video games, data visualization methods, and shared energy kits. After user feedback, a wireless sensor network (WSN) featuring culturally-inspired sensors was selected for further prototyping and refinement.

The 3D printed sensor casing (Figure 8) is modeled after an abalone, which is a staple food in traditional PPN culture and the shell often used for jewelry and decorations. The sensor units are powered by a small PV cell with assistance from an auxiliary battery when light levels are low. Each sensor includes a TelosB mote, which was developed by UC Berkeley and is "an open-source platform designed to enable cutting-edge experimentation for the research community" [52]. To accommodate the casing and power management system, the TelosB motes were modified as necessary.

Figure 8: Abalone wireless sensor fully assembled (left) and showing internal circuitry (right)

The WSN operates in a star configuration with a central base station computer (Figure 9). Each abalone sensor unit collects relative humidity, temperature, and illuminance, which it then sends to the base station every minute. Along with the TelosB, a power management board featuring a Cymbet CBC-3150 chip was designed and built to regulate power. In addition to the illuminance sensor that records light level for monitoring purposes, there is a second photodiode on the abalone shell that signifies whether there is sufficient light to power the mote from the PV cell. The Simple Measurement and Actuation Profile (sMAP) is a protocol that allows time-series data to conveniently be captured, transmitted, stored, and presented from a wide variety of sensors [53]. This as well as the website/phone app allow the data to be accessed by the family, members of the tribal council, and researchers.

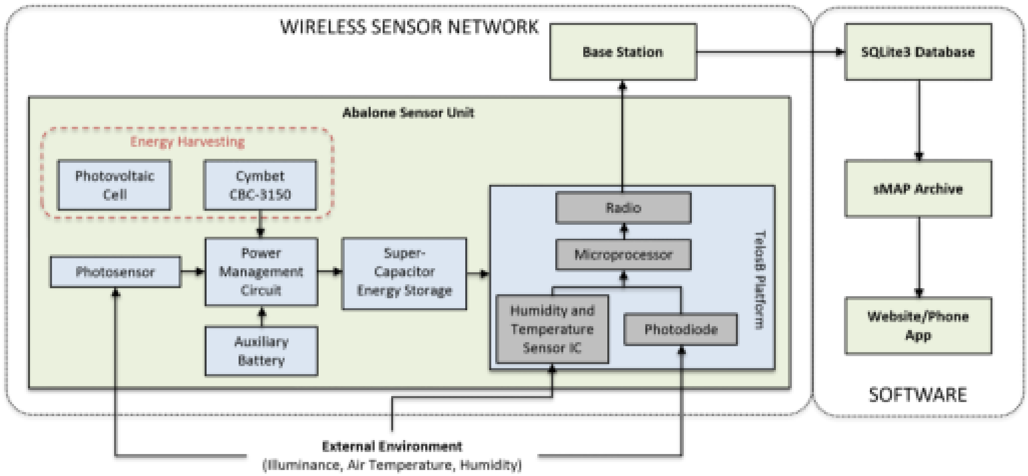

Figure 9: System diagram of wireless sensor network and communication protocol

After storing data on the base station computer, it then is designed to display real-time data and recommendations on the private website and phone application. The recommendations can be used to improve the indoor environment (health and comfort) and, if possible, to reduce energy consumption. While this was the intention throughout the design phase, the home's wireless internet was not yet set up when the sensors were first deployed. As a result, this first iteration of testing did not send data to the database and website/phone application, but only stored data locally on the base station computer. Future deployments will include these later data visualizations steps as designed.

4.2 Implementation

Sensors were deployed at various locations throughout the home for two-week periods while unoccupied (October 24-November 7, 2014) and occupied (March 6-20, 2015). Along with the abalone sensors, six HOBO U12-012 interval data loggers (Figure 10, left) were also deployed in order to validate the abalone sensors and adjust calibration if needed. In addition to air temperature, relative humidity, and illuminance, the HOBO sensors were also set to collect mean radiant temperature (MRT) through an external temperature probe with a radiation-averaging sphere (Figure 10, right). Through this, thermal comfort could effectively be calculated if assumptions were made for air speed, occupant activity, and occupant clothing. Approximate locations for each of the sensor units during the unoccupied and occupied measurements can be seen below in Figure 11. The abalone and HOBO sensors were set to record measurements every one and five minutes, respectively.

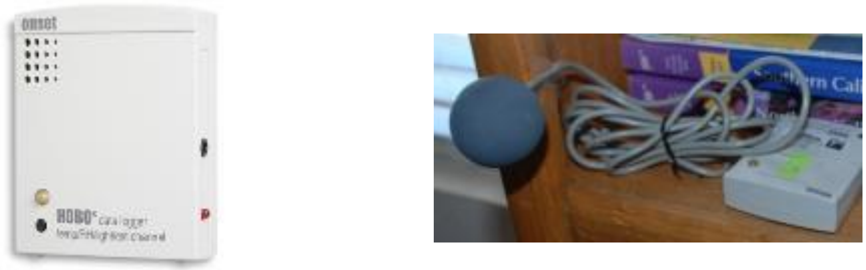

Figure 10: Image of HOBO U12 Temperature/Relative Humidity/Light/External Data Logger by Onset alone [54] (left) and with external mean radiant temperature probe (right)

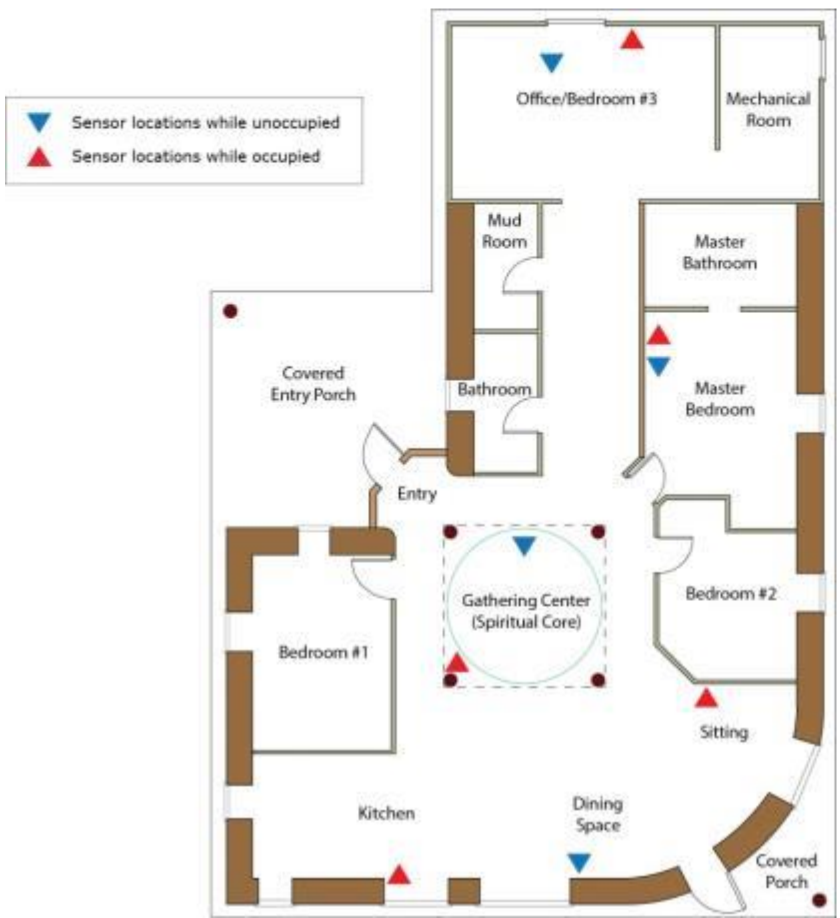

Figure 11: Approximate sensing locations during unoccupied and occupied measurement periods in Ukiah Demonstration Home

The objective for the data collections were to test the accuracy of the abalone sensors and assess the indoor environmental quality (light and thermal comfort) of the demonstration home. For a baseline comparison, local outdoor weather conditions were taken from the Ukiah Airport station [15]. To assess the light and thermal comfort, data were compared against standards set forth in the ASHRAE-55 Standard [43] and input into the Thermal Comfort Tool developed by the Center for the Built Environment (CBE) at UC Berkeley [55].

4.3 *Results and Discussion*

During the unoccupied data collection (October 24-November 7, 2014), the average temperature, relative humidity, and illuminance of the home was 17.3°C, 55.7%, and 56.5 lux, respectively. The average daily range for indoor air temperature, relative humidity, and illuminance was 5.7°C, 8.6%, and 251 lux, respectively. During the occupied data collection (March 6-20, 2014), the average temperature, relative humidity, and illuminance of the home was 20.7°C, 49.5%, and 50.1 lux, respectively. The average daily range for indoor air temperature, relative humidity, and illuminance was 6.1°C, 10.0%, and 230 lux, respectively. The abalone shell temperature and humidity measurements were on average within 1% of the HOBO measurements; however illuminance readings varied significantly. This largely can be attributed to the change in angle between the HOBO and abalone light sensors; the HOBO light sensor is oriented vertically while the abalone light sensor is tilted at an angle.

The abalone data in general was more inconsistent in measurements. During the unoccupied data collection, the sensors repeatedly stopped recording data from around 8 P.M. to 9 A.M. each day, presumably because power to the home and/or base station computer was being turned off during these hours. This problem did not occur during the occupied data collection. All of the illuminance sensors encountered problems when exposed to direct sunlight, which is expected for these types of diodes. Finally, the abalone sensor that was placed farthest from the base station computer missed more transmissions compared to the other sensors, indicating that the distance required for the radio communication was a problem.

While the unoccupied data collection was beneficial for baseline testing and validating the abalone sensor network, it does not provide significant benefit when assessing indoor environmental quality. Since no power was being provided to the home while unoccupied, the indoor environment reasonably fell outside of the comfort zone the majority of the time. The occupied data collection, however, is useful for a short-term evaluation of the thermal and light comfort in the home. Over the two week data collection in March, the indoor air temperature and relative humidity stayed within a healthy range over time and between rooms (Table 6). The illuminance on the other hand varied between rooms more significantly (Table 6). The hottest and coldest rooms had a difference of 5.5°C on average; the most and least humid had a difference of 11.3% relative humidity, and the brightest and dimmest had a difference of 81 lux on average. However, it is important to note that for illuminance, the light provided is only useful while the room is occupied, and differences in illuminance across rooms may just signify differences in the time of day and duration that each room is being used.

Table 6: Daily averages, highs, and lows measured from the sensors at various locations, averaged over the 13 complete days of occupied data. Outdoor data taken over same days from a local weather station [15].

Location	**Kitchen**	**Dining Space**	**Gathering Center**	**Master Bedroom**	**Office/ Bedroom #3**	**Outdoor**
			Air temperature (°C)			
Daily average	20.7	21.0	21.3	21.1	19.5	15.8
Daily high	23.3	24.8	24.9	23.0	22.7	24.3
Daily low	17.8	17.5	17.8	19.3	16.1	7.01
			Relative humidity (%)			
Daily average	48.1	47.6	47.8	51.3	54.1	58.9
Daily high	51.5	53.4	52.9	56.3	59.8	87.4
Daily low	44.3	41.4	43.0	47.8	47.5	30.3
			Illuminance (lux)			
Daily average	78.0	41.5	95.4	14.4	20.9	-
Daily high	488	190	378	73.6	62.8	-
Daily low	3.90	11.8	11.8	6.33	10.0	-

Throughout occupied data collection, the gathering center was on average the hottest and the office/bedroom #3 was the coldest (Figure 12). The indoor air temperature of all other rooms resided between these two extremes. The temperature generally follows the outside temperature's trend; the indoor temperature hugs the upper bounds of the outdoor temperature, and fluctuates with much less modulation. During the data collection, the indoor temperature in the home had a minimum and maximum of 15°C to 28°C, which is more than desirable. These temperature fluctuations were also noticeable by the current occupants, and they were on average adjusting the thermostat one or two times each day. As specified in the designs, the house contains windows in the cupola above the gathering center that are supposed to open and close depending on temperature; however currently, these windows are not operable and are always closed. Retaining function in these windows could allow air and heat to escape when needed, causing the daily temperature fluctuations to decrease.

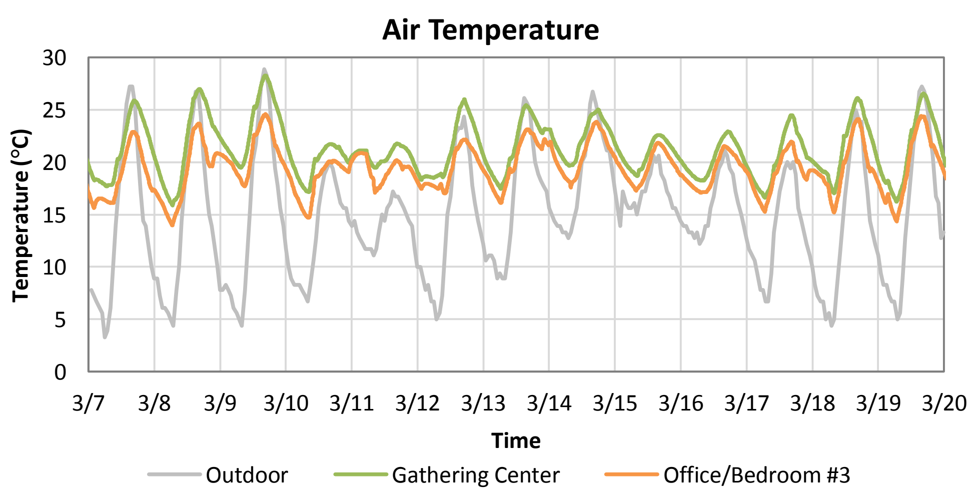

Figure 12: Indoor air temperature trends from sensor locations that demonstrated the highest and lowest average temperature recordings during the occupied data collection. Outdoor air temperature taken from local Ukiah weather station [15].

Throughout occupied data collection, the office/bedroom #3 was the most humid on average and the dining space was the least humid (Figure 13). The relative humidity of all other rooms resided between these two extremes. For the health of the occupants, it is advised that relative humidity stay between 40 and 60% [56]. Outside of this range, the risk for respiratory problems due to, mold, mites, fungi, and allergens increases. As can be seen in Figure 13, all rooms largely stayed within these limits during the data collection. The relative humidity generally follows the outside humidity's trend, except with much less modulation.

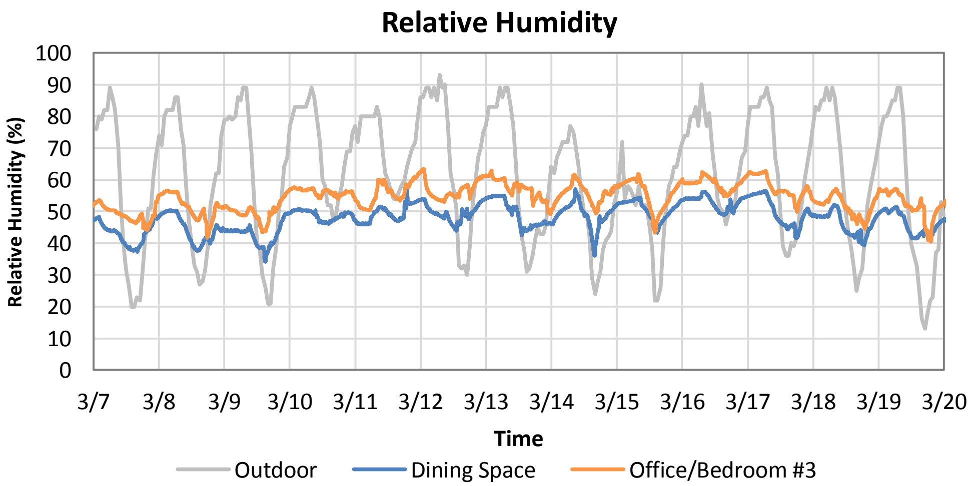

Figure 13: Relative humidity trends from sensor locations that demonstrated the highest and lowest average humidity recordings during the occupied data collection. Outdoor air temperature taken from local Ukiah weather station [15].

Throughout the occupied data collection, the gathering center was on average the brightest and the master bedroom was the dimmest (Figure 14). The illuminance of all other rooms resided between these two extremes. The high illuminance in the gathering center can be attributed mostly to daylight, since the sensor was directed away from artificial lights. While rooms like the master bedroom don't receive much light, this is acceptable since the occupants spend very little time in their bedroom during the day. However, what constitutes acceptable light levels is highly disputed and rather subjective. For office work, it's generally understood that illuminance should stay average around 500 lux [57], but recommended levels change depending on the task. Also, the human tolerance range at any light level is approximately 50% [58], indicating that some variance will not be detected. Despite all this, it is not possible to make conclusions about illuminance based on the data available; occupancy information is required in order to determine if light levels are acceptable or not.

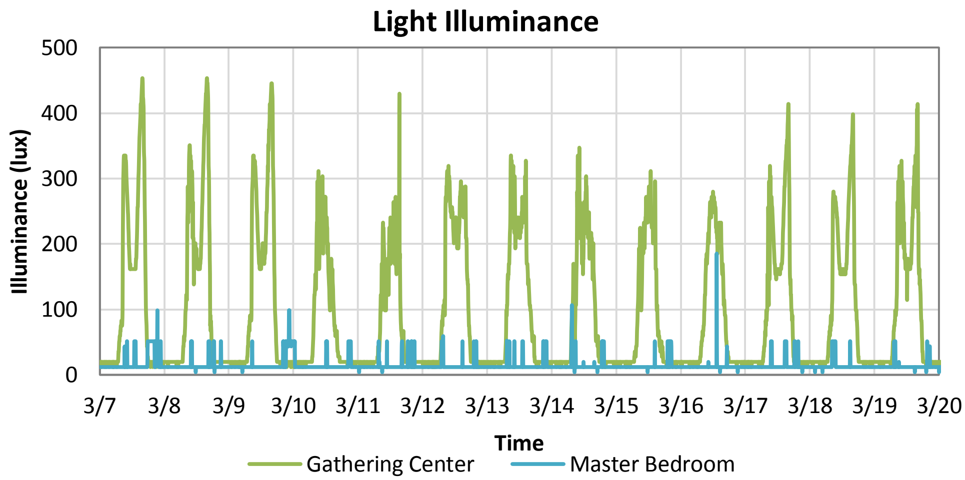

Figure 14: Illuminance trends from sensor locations that demonstrated the highest and lowest average illuminance recordings during the occupied data collection.

In order to assess thermal comfort, it is important to look at all six involved factors (air temperature, mean radiant temperature, humidity, air velocity, occupant clothing, and occupant activity) at the same time, since they are interrelated. The occupied data was divided between daytime and nighttime, and the daytime was analyzed in the CBE Thermal Comfort Tool [55]. Air speed, metabolic rate (occupant activity), and clothing insulation (occupant clothing) were assumed to be 0.15 m/s, 1 clo, and 1.1 met, respectively. Night time comfort was not included since adequate values for clothing insulation under blankets was not found.

Results from the thermal comfort evaluation are summarized in Table 7. During the occupied data collection, the mean radiant temperature sensors in the kitchen and gathering center malfunctioned and therefore these locations were not included in the comfort assessment. The average PMV remained within acceptable standards for the dining space and master bedroom, but the lower (cooler) bound of -0.5 was exceeded slightly for the office/bedroom #3. This is the same for the PPD, where the office/bedroom exceeded the 10% threshold, but the other spaces remained within acceptable limits. The recommended threshold of 5% for the percentage of points outside of comfort zone was exceeded in all spaces by a significant margin. This indicates that the comfort level of the house is fluctuating more than desirable. These points outside of the comfort zone fall on both the cold and hot ends of the spectrum.

Table 7: Thermal comfort results during daytime (7 A.M. – 7 P.M.) of occupied data collection

Sensor location	**Average predicted mean vote (PMV)**	**Predicted percentage of dissatisfied (PPD) (%)**	**Points outside of comfort zone (%)**
Dining space	-0.10	5.2	50
Master bedroom	-0.28	5.0	41
Office/bedroom #3	-0.53	10.9	56

The demonstration home on average maintains a healthy and comfortable environment, but there is room for improvement. In general, the illuminance was low in many spaces, the relative humidity was in a safe and comfortable zone, and thermally the home was comfortable but tended towards cool. During the two weeks of occupied data, the indoor air temperature fluctuated 6°C each day on average, which is slightly more than desirable. However the mean temperature generally stayed within the comfort range. The office/bedroom #3 was the coldest and most humid out of all the spaces, which makes sense since the exterior wall construction is different than the rest of the house.

Temperature, humidity, and illuminance provide valuable information, but it would be beneficial to quantify some other factors as well. For one, assumptions had to be made about occupancy. Occupancy sensing would help inform how well the space is being utilized and if the various spaces are meeting comfort requirements while occupied. As with lighting, turning off lights while not in a room is highly recommended to save energy. Occupancy sensors coupled with the illuminance sensors would inform whether or not lighting is being provided when there are people present or not present. Secondly, an average air velocity of 0.15 m/s was assumed throughout the entire home. Air movement greatly affects thermal comfort and it is very likely that the air does not move consistently across all spaces. It is recommended that future studies examine the air speed rates throughout the home as well in order to better understand thermal comfort.

Through implementation, the abalone sensors effectively recorded temperature and relative humidity most of the time, but problems occurred with the illuminance sensor and transmission distance. The star network configuration proved to be problematic in a home environment because of the long transmission distances required and interference from walls and other objects. Future versions should utilize a mesh or combined network configuration instead in order to increase the communication range and reliability.

In terms of the technology used, there is much room for improvement with the remote sensors and base station. The wireless sensors were developed based on an existing platform featuring TelosB motes and Cymbet CBC-3150 power management modules. While these products are convenient and effective for research and development, they are also expensive and have many integrated capabilities that are not necessary for our application. For future versions, it is recommended that the wireless sensors utilize cheaper, less capable hardware that is more specifically tailored to the application. For example, a tailored printed circuit board could be built to include the central processing unit, radio transmitter, power management circuit, and environment sensors. This would not only decrease production cost and power consumption, but also decrease the amount of material required for casing.

Furthermore, the current set up requires a small central computer to act as the "base station", collecting and uploading data to the server and website/phone application. This unnecessarily wastes energy since the computer must remain on at all times and only a tiny fraction of its processing power is being utilized. Future versions should investigate purpose-built base stations or integrate with smart phones. Some examples could be using open source platforms such as Arduino or Samsung's SmartThings. Regardless, the base station should be configured to receive, log, and process data from the wireless sensors before transmitting information to the server and website/phone application.

Based on this work, the following recommendations are advised in order to improve the indoor environment. First, opening blinds and allowing daylight to enter the house will assist both with increasing light levels and allowing the sun to warm the space, particularly when it is needed in the mornings. Second, the upper windows in the cupola of the gathering center currently cannot be opened; these were designed to automatically open/close depending on temperature, but the controllers and motors are no longer available for purchase. Finding a way to operate these windows either manually or automatically will allow excess heat to leave the space and provide healthy fresh air. Third, adjust the thermostat for heating/cooling before the house becomes too cold/hot in order to account for the latency in the geothermal heat pumps. Allowing the geothermal heat pumps to start heating/cooling the home early will help decrease the daily variations in indoor temperature. Similarly, if there is thermal bridging in the exterior walls, heat will undesirably be transferring through the walls. This may be contributing to the more-than-desirable daily temperature fluctuations that are currently present. Future investigations could include examining the insulation and thermal performance of the building's structure in more detail with, for example, infrared cameras. Lastly, open windows/doors in the early afternoon to increase air flow and expel unwanted heat. These change will hopefully help keep the home more comfortable each day and help stabilize the system.

5. CONCLUSION

This project sought to assess the environmental impact and indoor environmental quality of the PPN's demonstration home in order to advise modifications for improving performance of the current and future homes. This was accomplished through a cradle-to-grave life cycle assessment and the design and implementation of culturally-inspired in-home sensors. While the uncertainty of these assessments are increased due to the short time frame available, they regardless provide beneficial information for the current status and the potential for design improvements.

For the life cycle assessment, energy consumption during use is a principle consideration and should continue to be a high priority for the occupants and future homes. The demonstration home's design indicated a significantly lower energy use intensity than current occupied trends reveal, and the reasons for this should continue to be investigated. The embodied impacts in the home's structure and systems represent an important consideration for environmental impact, especially if grid electricity consumption is low. Steel represented 33% of the impacts from manufacturing, while the straw bale contributed -7%, indicating it should continue to be used as a building material.

For indoor environmental quality, the home was comfortable on average, but experienced more-than-desirable fluctuations. This was indicated in both the temperature data and percentage of points outside the comfort zone in the thermal comfort analysis. On average, the hottest and coldest rooms had a difference of 5.5°C; the most and least humid had a difference of 11.3% relative humidity, and the brightest and dimmest had a difference of 81 lux. For thermal comfort, all rooms were within the acceptable range except for the office/bedroom #3, which just barely exceeded the threshold on the cold side.

While this investigation started the re-assessment process of the demonstration home, additional study should be undertaken before drawing conclusions. First, a years-worth of data ought to be included in order to account for annual variances in energy consumption. Energy estimates were made here based on the available three months of data (January-March), and while this is a useful starting point, it does not reflect yearly consumption patterns. Additionally, the thermal comfort analysis would benefit by testing the home at other times of year as well to account for seasonal variation. Second, occupancy sensing should be included in order to understand how the space is being utilized and if the home is providing comfort only when necessary. Third, the next generation of abalone sensors should be developed to improve reliability in a home environment and more precisely meet the hardware needs for IEQ sensing. Lastly, in this project the environmental impact and indoor environmental quality were examined in parallel but not integrated. As previously discussed, there is an interrelation between consuming energy and providing a healthy and comfortable living space. Future work should tie these two sides together more closely by studying the effect material and energy decisions have on the indoor environment and vice versa.

As the Pinoleville Pomo Nation continues to work towards sustainability in their community, they also must continue to revisit their design decisions and assess the actual performance of their homes. This preliminary assessment demonstrated where improvements can be made in the current home and future generations of homes, as well as highlighted some of the successes of the current demonstration home. Life cycle assessment can be used for incredibly complex projects requiring many years of work, but it can also effectively assist designers in understanding the comprehensive picture of environmental impacts. Furthermore, a discussion of environmental impacts should not occur without understanding the effect on the end users. In homes, indoor environmental quality is an important part of this. By taking a comprehensive approach, we can begin to understand the relationships between ourselves and our environment and strive for a harmonious balance.

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