

Article

# Sustainable Residential Building Considerations for Rural Areas: A Case Study

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Received: 4 April 2020; Accepted: 12 May 2020; Published: 15 May 2020



**Abstract:** Intelligent use of rural residential land and sustainable construction is inexorably linked to cost; however, options exist that are eco-friendly and have a positive return on investment. In 2011, a research residence was built to evaluate various land-use and sustainable components. This Texas house has subsequently been used for both residential and research purposes. The purpose of this case study was to evaluate break-even construction considerations, to assess environmental impacts, and to evaluate qualitatively efficacy of sustainable options incorporated in the research residence. Some of the specific components discussed are home site placement (directional positioning); materiel acquisition (transportation); wood product minimization; rainwater harvesting; wastewater management; grid-tied solar array power; electric car charging via a solar array; geothermal heating and cooling; insulation selection; windows, fixtures, and appliance selection; and on-demand electric water heaters for guest areas. This study seeks to identify the impact of proper land use and sustainable techniques on the environment and return-on-investment in rural areas. Break-even and 15-year Net Present Value (NPV) analysis at 3% and 5% cost of capital were used to evaluate traditional construction, partially sustainable construction, and fully sustainable construction options for the case study house, which was built sustainably. The additional cost of sustainable construction is estimated at \$54,329. At 3%, the analysis suggests a 15-year NPV of \$334,355 (traditional) versus \$250,339 million (sustainable) for a difference of \$84K. At 5% cost of capital, that difference falls to \$63K. The total estimated annual difference in carbon emissions is 4.326 million g/CO<sub>2</sub>e for this research residence. The results indicate that good choices for quick return-on-investment in rural construction would be the use of engineered lumber, Icynene foam, and Energy Star windows and doors. Medium-term options include photovoltaic systems (PVS) capable of powering the home and an electric car. Sustainable construction options should positively affect the environment and the pocketbook. Regulations and code should require adoption of short-range, break-even sustainable solutions in residential construction.

**Keywords:** rural residential construction; rainwater harvesting; solar; spray foam; finger-jointed studs

## 1. Introduction

Sustainable rural land use requires environmentally sound residential construction [1]. Residential (and commercial) construction options affect the water supply [2], water demand [3,4], electricity demand [5–8], the use of land lumber and other materials [9,10], as well as the entire ecosystem [11]. Improper use of land can accelerate global warming [12,13], have impacts on human health (particularly in regards to disease) [14], lead to eutrophication/acidification of water [15,16], and cause smog formation in urban areas [17,18]. Perhaps unsurprisingly, land-use impacts are most affected by the use of wood products [19]. Sustainable construction begins with planning.

### 1.1. Planning and Transportation Considerations

When planning for sustainable residential construction, site placement is important to consider predominant winds and facing for solar capture [20,21]. Pre-planning of construction should include a significant sustainability analysis, and techniques such as simulation are helpful to this process [22,23]. Also important is minimizing the transportation costs (a construction waste), which include consciously purchasing materials that are located closer to the construction site [24]. Waste produced during the construction should be minimized and recycled where possible, and a construction waste management plan should include subcontractor incentives [25]. Since lumber waste is the largest contributor to detrimental land-use effects [19], the use of engineered lumber (as well as other resources) are possible solutions [26,27]. The planning for waste management must begin in the design cycle [28].

### 1.2. Global Warming Potential

Another consideration in pre-planning of residential construction is reducing the impacts on Global Warming Potential (GWP) balanced by a tight residential envelope to reduce requirements for heating and cooling energy. As an example, Icynene foam insulation currently has the lowest possible GWP of 1.0 [29] and provides a tight house envelope, which is a winning combination. Fenestration considerations (e.g., the installation of Energy Star windows and doors) are important to maintain the building envelope according to human and environmental considerations [30]. A residence's thermal mass is vital to achieve reductions in energy demand [31].

### 1.3. Electricity

Energy demands of residences must be considered prior to construction as well. Photovoltaic systems (PVS), wind energy, and nuclear-power grid energy reduce the carbon footprint of the residence when compared to traditional fossil fuel and sequestration plants. The difference is estimated to be from 78 to 110 gCO<sub>2</sub>eq kWh<sup>-1</sup> to 3.5 to 12 gCO<sub>2</sub>eq kWh<sup>-1</sup> [32]. The use of solar water heaters or tankless electric water heaters powered by a PVS are two of many options that may reduce both cost and kWh demand [33]. Further, electric cars charged by PVS that are sized properly for residential and transportation demands may reduce environmental impacts, as will the proper choice of Heating Ventilation and Air Conditioning (HVAC) [9,34].

Some new residential construction has attempted to reduce the demand for grid electricity and slow global warming by Net-Zero (or even Net-Positive) construction, which involves the design of facilities that either consume no net energy (demand less than supply) or that produce more energy than consumption [35,36]. Net-Zero construction may even power user transportation, further reducing the impact of the built environment [37,38]. Net-Zero homes coupled with proper water management and residential construction techniques may mitigate many of the environmental effects associated with residential construction [9].

### 1.4. Water and Wastewater

Water life-cycle considerations are vital when constructing houses in rural areas, particularly in rule-of-capture states that allow for exploitation of common-use groundwater [39]. The source of water should be responsibly considered (e.g., well water, rainwater harvesting, or municipal water connections, assuming they exist). Well contamination in rural communities is a significant consideration [40–42], and municipal water connections may be unavailable. Rainwater harvesting is then an option, which reduces the overall supply requirements for each gallon demanded when compared to groundwater and which has other beneficial properties including softness [43–45]. Environmentally responsible use of any water source must consider the use of low-flow fixtures. Use of these fixtures resulted in a 22% reduction in average annual household usage from 1999 to 2016 [46]. Further, xeriscaping reduces water requirements, can contribute to the success of construction projects, and should be part of best practices in arid and semiarid regions particularly [47]. Part of the water

life cycle requires disposal of black water. In rural areas, no municipal sewage system may exist, so the options are aerobic or anaerobic sewer systems. While aerobic systems break down waste more quickly than anaerobic systems, they are more expensive from both acquisition and maintenance perspectives [48].

### 1.5. Purpose and Research Questions

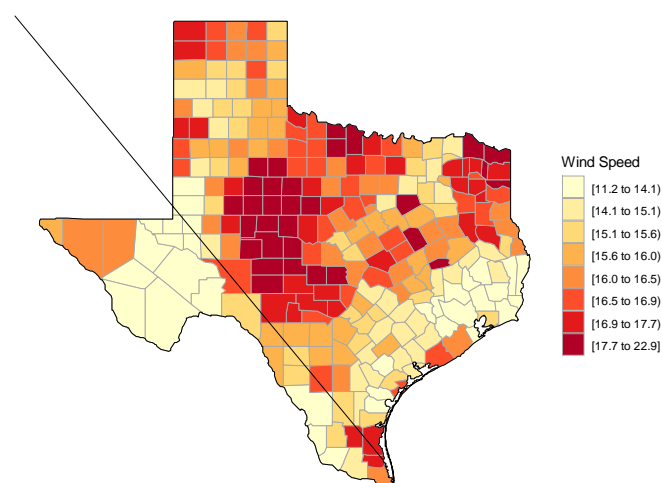
This case study analyzes best-practice construction design for both the environment and the consumer based on a rural residence designed in 2011 for research purposes. This residence was the highest-rated house ever certified by the National Association of Home Builders (NAHB) at the time it was built [37]. NAHB sets standards for rating construction based on energy efficiency, water conservation, resource conservation, indoor environmental quality, site design, and homeowner education [49]. The actual standards are available here: [50]. Both construction successes and failures are analyzed with commentary from both the environmental and consumer perspective.

The primary research question addresses which sustainable construction options in this case study would also achieve breakeven (and when) if built today, as well as how sustainable these interventions are in terms of environmental impact. A secondary component of the study investigates the Net Present Value (NPV) of two different construction options that were available for building the research residence: traditional and sustainable. The time horizon investigated was 15 years. Comparing these three building decisions helps inform the value of green construction. Further, qualitative assessments of the sustainable interventions are provided.

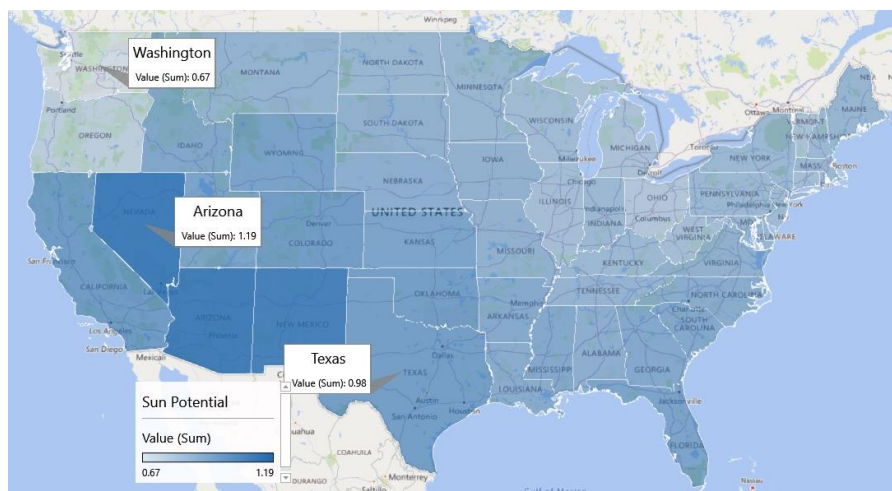
### 1.6. Significance

The study's significance is that it investigates which sustainable options may result in a reasonable break-even period and whether planning of proper land use and application of sustainable construction may produce a return-on-investment while minimizing environmental effects. While this case study is not generalizable, the equations provided to compare both cost and environmental considerations may be applied to any other case, making the study useful. Further, the experiential component of the study spans nearly a decade of lived experience. No literature exists from a researcher in this area who has lived the results of the sustainable experimentation, which makes this study unique.

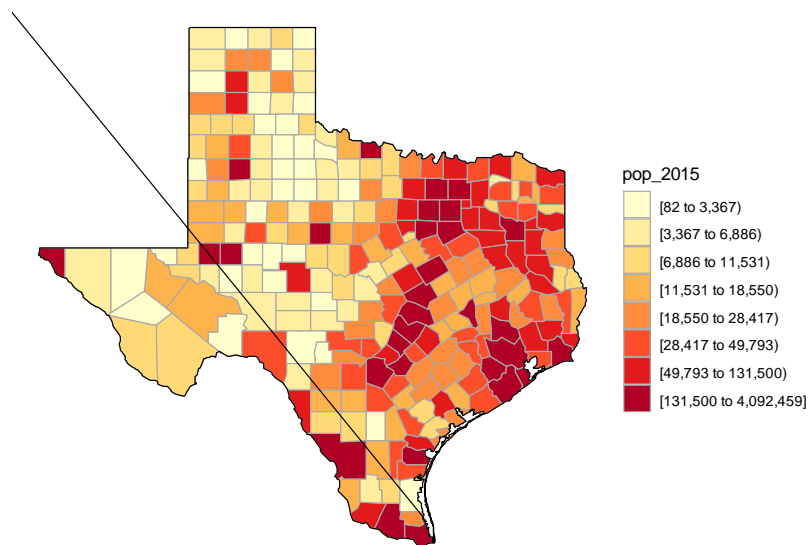
The study is also significant to increasing use of renewable sources in Texas. The use of solar or wind power solutions becomes increasingly relevant to rural Texans [51], and the state had over 28,871 MW of installed wind capacity at the end of 2019 [52]. Figure 1 shows that, in many areas of rural Texas (identified in Figure 2), the average wind speed would support wind turbine construction. Figure 3 illustrates the solar production potential by state



**Figure 1.** Choropleth map of wind speed by county in Texas.



**Figure 2.** Choropleth of state solar production potential.



**Figure 3.** Distribution of Population Intensity in Texas.

### 1.7. Generalizability

While this is a case study, the majority of Texas is actually rural (Census Bureau data, [53]), so the techniques discussed are widely applicable within the state (see Figure 3, mapped in R Statistical Software [54] using the software library “choroplethr” [55]). Further, there is evidence that both new housing as well as renovations and modifications are needed in the rural areas of Texas [56], so this case study is made more important in that it provides some best-practice considerations. The rural areas in Texas often face enormous electrical transmission and distribution rates, sometimes twice the state average [57].

The study proceeds as follows. First, a discussion of Net Present Value (NPV) and break-even analysis is explicated in Section 2. Following this section, Section 3 evaluates the elements of construction included in the sustainable house, which is the subject of the study. After a discussion of these elements, analysis of various constructions based on the study residence are evaluated in terms of both break-even timing and NPV. Finally, ideas and insights are provided in the discussion and conclusion, Sections 4 and 5, respectively.

## 2. Materials and Methods

In this case study, we evaluated deterministically the environmental impacts, life-cycle costs, and efficacy of multiple sustainable building innovations for rural residences versus more traditional construction. The rural research residence informing this study is an approximately 4800 square foot home (446 square meters) and located in a semiarid environment in Texas. The options used in this construction are compared directly against more traditional options for both cost and environmental effects.

The study evaluates home site placement; materials transportation; reclaimed wood framing; spray-foam insulation; window, fixture, and appliance selection; material recycling; rainwater harvesting design and engineering; aerobic septic system; xeriscaping; grid-tied solar arrays; electric car charging and use; on-demand water heaters; geothermal heating and cooling; and electrical back-up system options. The home has supported between 2 and 3 full-time, middle-aged residents (one adult worker) with seasonal demand of up to 20 individuals during holidays over the last 9 years. The residence was occupied shortly after its construction and has been in constant use.

### 2.1. Break-Even Analysis

Specific methods used include deterministic break-even analysis for each element evaluated (if one exists) based on acquisition costs of the sustainable option versus one or more other options. Break-even analysis evaluates monetary outflows of residential construction options (as well as any returns) and evaluates at what point (if ever) total costs of both options intersect [58]. The break-even point is determined using Equation (1). The break-even point is then when total costs of one option equal total costs of another option. In this equation,  $FC$  stands for fixed costs,  $VC$  represents variable costs (e.g., maintenance and operations), and the index set represents the option number and time index. There are some semi-variable costs (e.g., step functions for item replacements) involved in the construction analysis, and these are included in the variable costs.

$$FC_{1t} + VC_{1t} - FC_{2t} - VC_{2t} = 0 \quad (1)$$

### 2.2. Net Present Value

As part of the analysis, this case study evaluated three different construction possibilities for the original research residence and their associated profitability using net present value (NPV). Two of the three construction options are at opposite ends of the spectrum (traditional versus sustainable), while the third uses many of the sustainable elements with a positive NPV. NPV is calculated according to Equation (2), where  $i$  is the index for the option selected,  $R_t$  is the net cash inflow and outflows at time  $t$ ,  $A$  is the accumulation rate ( $1 +$  return rate), and  $n$  is the number of time periods evaluated [59]. The time period used for NPV analysis is 15 years.

$$NPV_j = \sum_{t=1}^n \frac{R_t}{A^t} \quad (2)$$

### 2.3. Construction Components Evaluated/Data Sources

The case study involves a single structure built in one specific way; however, it also evaluates breakeven and NPV had it been built in alternative ways to provide useful comparisons for the reader. Table 1 provides the category, the items evaluated, the data sources, and the cradle-to-grave cost estimates with comments for those items. Some elements discussed in the case study are not included in the breakeven and NPV analysis, however. These elements (such as site placement) may have an effect in either direction, but the size and directionality are unknown.

**Table 1.** Construction categories and components evaluated (inflation at 3% per year).

Category	Traditional Option	15-Year Costs	Sustainable Option	15-Year Costs	Environmental Difference
Framing	Lumber	\$52,800	Engineered Lumber	\$53,184	24.5–90 Trees
Insulation	Fiberglass	\$14,4200	Icynene Foam	\$12,460	Reduced CO <sub>2</sub> or PVS
Fenestration	Standard	\$14,457	Energy Star	\$16,625	Reduced CO <sub>2</sub> or PVS
Water	Well	\$33,563	Rainwater Harvesting	\$32,111	Reduced H2O requirement
Wastewater	Anaerobic	\$ 7531	Aerobic	\$14,128	Fewer pollutants
Water Heaters	Electric H2O, Tank	\$22,915	Tankless	\$ 3000	Reduced CO <sub>2</sub> or PVS
Electricity	Grid	\$62,834	Solar	\$54,480	Reduced CO <sub>2</sub> or PVS
Vehicle	ICEV (x 2)	\$107,777	BEV (x 2)	\$92,288	Reduced GHG
HVAC	Heat Pump	\$112,383	Geothermal	\$30,644	Reduced CO <sub>2</sub> or PVS
<i>Total, Traditional</i>		\$428,680	<i>Total Sustainable</i>	\$308,920	

Abbreviations: Heating Ventilation Air Conditioning (HVAC), Internal Combustion Engine Vehicle (ICEV), Battery Electric Vehicle (BEV), Greenhouse Gases (GHG), Photovoltaic System (PVS).

In the subsequent sections, the study explicates the acquisition and operations and maintenance (O&M) costs for each of these categories. Data for each of the areas evaluated from breakeven were acquired from peer-reviewed literature where possible and from construction firms where there were no data (e.g., engineered lumber versus traditional studs). Data ranges were sought, and the midpoints of these ranges were used for deterministic calculations.

#### 2.4. Environmental and Qualitative Analysis

When relevant, an analysis of the environmental advantages of sustainable construction versus other options is provided. Relevant research from the literature is extracted to estimate carbon emissions, water quality, etc., similar to Fulton et al. (2020) [9]. Part of the sustainable construction assessment was a qualitative assessment involving elements of the triple bottom line (TBL) [60]. The experience of the research team and home resident augment the data-driven analysis.

#### 2.5. Data and Software

Data for the deterministic breakeven and return on investment (ROI) portions of this case study were garnered from previous research as well as data sources appropriate to the residence itself. All analyses were conducted in Microsoft Office Excel 2016 and R Statistical Software [54].

### 3. Results

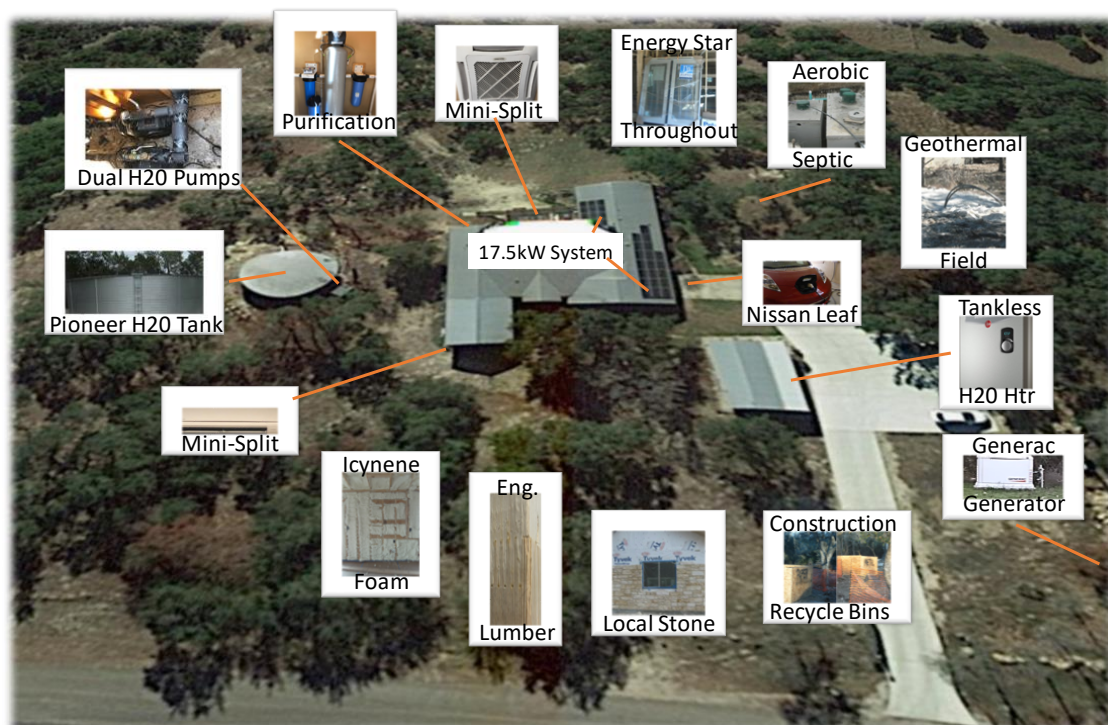
#### 3.1. Initial Considerations

##### 3.1.1. Construction Planning, Permitting, and Analyses

The land was two years prior to construction, as the design process required significant planning, permitting, and modeling. Aside from the typical surveying, permits for operating an on-site sewer facility and (later) driveway placement were required [61]. At the time, the maximum grid-tied PVS array permitted by the utility company was 10 kW, so a waiver was required based on analysis of user consumption. Utility pole transformer size was analyzed and found acceptable without resizing. Further, the utility company regulated the grid-tied interconnection of the backup propane generation system [62]. As an example of analysis conducted prior to building, the sizing of the rainwater harvesting system was estimated through simulation [43]. Construction waste management and recycling required significant preplanning, and the well placement for the geothermal HVAC had to be mapped and approved. The processes described here required approximately six months of lead time, which is a consideration should quicker construction be required. Construction planning, permitting, and analyses are not part of the break-even or NPV analyses.

### 3.1.2. Site Placement

The rural residence in the study was designed from the ground up to be sustainable, and the design considerations included geographical placement. The home site was selected to be north-facing to maximize solar capture (west-, south-, and east-facing panels) and to leverage predominant local winds (south to north) [20]. Further, the site selected minimized tree removal, reducing cost and effect on the environment. Qualitatively, the placement was a success in this construction, as the solar capture is as expected (discussed later), and the cost as well as the environmental impact of excess tree removal was avoided. Figure 4 is the Google Maps satellite image of the house with various sustainable callouts that are referenced later [63]. Site placement is not per se evaluated in the break-even and NPV analyses.



**Figure 4.** The residence as constructed.

### 3.1.3. Material Location/Transportation

One of the major sustainability considerations in residential construction is the transportation of materials [64]. As part of the rural residence design, only local materials (those within 50 miles) were selected. For example, local limestone was selected for the exterior. Reducing transportation requirements reduces emissions. One study found a 215% decrease in the amount of energy used in building and a 453% decrease in the impact of transportation when local building supplies were used [65]. The reduction in environmental impact is measurable and significant. Estimating the savings in construction for use of these materials is difficult and omitted from this case study.

### 3.1.4. Waste Collection and Recycling

During construction, bins for waste were used to recycle materials as appropriate (Figure 4). Metals, plastic, and glass were recycled, congruent with previous research [64]. Doing so allowed for reclaimed wood to be fabricated into engineered lumber and for used paper and metal to be used in other capacities. While this has little to no bearing on cost (perhaps 2.5% back to the builder [66]), it does have an effect on the environment. In terms of Global Warming Potential, recycling has the

greatest impact versus incineration or landfill options [67]. This is the last element that is not included in the break-even and NPV analyses.

### 3.2. Engineered Lumber/Finger-Jointed Studs

Reclaimed wood (specifically finger-jointed studs) were used in the residential construction (see Figure 4). These studs are also straighter and result in less wood wasted. They neither split nor twist like traditional studs [68]. Further, they have a strong vertical load capability, with evidence that many species (including pine) have better structural properties when finger-jointed, although that evidence is mixed [69].

#### 3.2.1. Environmental Considerations

A 20" diameter tree with 42 feet length of usable wood produces about 260 board feet. The Idaho Forest Products Commission estimated that a typical 2000 square foot house would use 102 trees of that size [70]. Assuming linearity, the rural residence, a 4800 square foot home (446 square meters, would have been estimated to require approximately 245 trees. Assuming an offset of even 25% of the wood requirements results in a reduction of about 61 trees. See Table 2. For this deterministic study, the estimate of trees saved would be between 24.5 and 98 given the size of the house.

**Table 2.** Estimate of trees saved by using engineered lumber (finger-jointed studs) in this case study.

% Offset of Traditional Lumber	Trees Saved
10%	24.5
15%	36.8
20%	49.0
25%	61.3
30%	73.5
35%	85.8
40%	98.0

#### 3.2.2. Acquisition and 15-Year Operations and Maintenance (O&M) Costs

The cost of finger-jointed studs may be more expensive than regular studs. For example, the retail cost of a 2 × 4 × 104 5/8" (0.6 × 1.2 × 2.7 meters) regular pine stud versus the same size finger-jointed stud is listed at \$3.62 [71] versus \$5.59 [72], respectively. This is a 54.4% cost increase for materials (much less than estimated by [69] for pine), which might be offset by lower labor costs due to engineered lumber's straightness.

The cost differential is not atypical, as many engineered lumber products have upcharges between 1.5 and 2 times the cost of traditional lumber [69,72]. One site estimates the total cost of traditional framing between \$4 and \$10 per square foot for labor and \$3 and \$6 per square foot for materials [73]. With a 30% reduction in labor costs for engineered lumber, low material costs for standard lumber, and 54.4% higher costs in engineered lumber, there are several ways in which finger-jointed studs might actually save money. Table 3 illustrates those combinations (2020 dollars).

Using the average estimate of \$7 for labor and \$4 for materials (traditional construction) and 30% reductions in labor (\$4.90) with 54.4% increases in materials (\$6.18, nontraditional construction) results in comparative estimates of \$52,800 (traditional stud construction) and \$53,184 (engineered lumber), underlined in Table 3. The total difference in cost is estimated to be nominal, but the environmental impact is not, as it saves old-growth trees [26]. O&M costs are considered nominal for the 15-year NPV analysis.



**Table 3.** Regular lumber versus finger-jointed studs cost per square foot of construction and total.

Regular Lumber, \$/ft <sup>2</sup>			Engineered Lumber, \$/ft <sup>2</sup>			Savings
Materials	Labor	A. Total \$ for House	Materials	Labor	B. Total \$ for House	A–B
\$3.00	\$10.00	\$62,400.00	\$4.62	\$7.00	\$55,776.00	\$6624.00
\$3.00	\$9.00	\$57,600.00	\$4.62	\$6.30	\$52,416.00	\$5184.00
\$4.00	\$10.00	\$67,200.00	\$6.16	\$7.00	\$63,168.00	\$4032.00
\$3.00	\$8.00	\$52,800.00	\$4.62	\$5.60	\$49,056.00	\$3744.00
\$4.00	\$9.00	\$62,400.00	\$6.16	\$6.30	\$59,808.00	\$2592.00
\$3.00	\$7.00	\$48,000.00	\$4.62	\$4.90	\$45,696.00	\$2304.00
\$5.00	\$10.00	\$72,000.00	\$7.70	\$7.00	\$70,560.00	\$1440.00
\$4.00	\$8.00	\$57,600.00	\$6.16	\$5.60	\$56,448.00	\$1152.00
\$3.00	\$6.00	\$43,200.00	\$4.62	\$4.20	\$42,336.00	\$864.00
\$5.00	\$9.00	\$67,200.00	\$7.70	\$6.30	\$67,200.00	\$0.00

### 3.3. Residential Envelope

Residential spray-foam insulation (Figure 4) provides a thermal barrier with exceedingly low conductivity (0.021 W/mK in one study [74]). Icynene spray foam has reasonable hygrothermal properties and is resistant to moisture migration; however, mechanical extraction and humidity controls may need to be installed (as in the case study) because of the tight environmental seal of the house and the requirement to exchange air. The practical relevance of the tight seal around the rural residence is that, during the heat of the summer in this semiarid region (in excess of 100 °F, 38 °C), the observed temperature in the attic spaces does not exceed 80 °F/26.7 °C with the house thermometer set to 76 °F/24.4 °C.

#### 3.3.1. Environmental Considerations

From an environmental perspective, water-blown Icynene spray-foam insulation has a reduced carbon footprint from better HVAC usage [9]. Still, other forms of insulation have better characteristics for insulation, although not necessarily cost profile [75]. In retrospect, alternative materials would probably be used for the case study residence if built now.

#### 3.3.2. Acquisition Costs and 15-Year O&M

The 2020 cost for open-cell spray-foam insulation is about \$0.35 to \$0.55 per board foot [76], which is lower than the cost estimated by Kalhor and Ememinejad [77] (\$0.80 to \$1.30) but nearly identical to the cost found on the manufacturer's website [78] (\$0.40 to \$0.60). To account for regional variation, the information from [76] is used for Icynene foam cost estimates. A 3.5" depth of spray converts to \$1.23 to \$1.93 per square foot or \$13.24 to \$20.77 per square meter. Fiberglass batt insulation runs \$0.64 to \$1.19 per square foot or \$6.89 to \$12.81 per square meter [76]. Assuming average costs of \$1.58 per square foot (spray-foam) and \$0.915 (fiberglass) with 8000 square feet of attic and walls to be insulated (estimated from case study house) results in cost estimates of \$12,640 and \$7320, respectively [79], but the second estimate is not complete.

Spray foam works as an air barrier, vapor barrier, water-resistant barrier, and insulation. There is no need for attic vents, test ductwork, or air-seal attics. When evaluated in this manner, it is actually 10–15% less expensive than traditional construction [79]. Adding 12.5% (the average between 10%-and 15%) to the \$12,640 estimate for spray-foam construction results in an estimate of \$14,420 for insulation, vapor barrier, vents, test duct work, etc. For the break-even analysis, then, the final values used were \$12,460 for the installation of Icynene and \$14,420 for use of fiberglass.

#### 3.3.3. Qualitative Assessment

Spray foam makes the attic space usable in hot weather. While this may be a minor point, it is an important consideration for homeowners considering building options.

### 3.4. Low Solar Heat Gain Coefficient (SHGC) and U-Factor Windows (Energy Star)

Solar Heat Gain Coefficient (SHGC) is defined as the fraction of incident solar radiation admitted through a window. In warm climates, windows should have solar heat gain coefficients (SHGC) less than 0.25 [80]. Further, the U factor, a factor that expresses the insulative value of windows, should be 0.4 or lower. Low-emissivity windows and doors with SHGC of 0.23 and U-Factor of 0.3 were used throughout the case study house.

#### 3.4.1. Environmental Considerations

The selection of Energy Star windows and doors resulted in a smaller sizing for the PVS system, as the demand for heating and cooling is 17% to 31% less [81]. There is no achievable carbon output reduction by use of these windows on a house that is already 100% reliant on PVS (except for gray energy). (For a traditional grid-powered residence, that savings might be between 246 and 6205 lbs. of CO<sub>2</sub> [81].)

#### 3.4.2. Acquisition and 15-Year O&M Costs

Low-emissivity windows are 10% to 15% more expensive than standard windows [82], although one study indicated that the cost was about \$50 more per window [83]. The typical cost range in 2020 dollars is \$385 to \$785, with an average of \$585 [84]. The Department of Energy estimates savings of \$125 to \$465 dollars a year from replacing windows with new windows that have higher Energy Star ratings [81], which is lower than estimated in [83]. Assuming average cost for Energy Star windows (\$585), 15% less expensive traditional windows (\$508.70), and a total of 25 windows (based on the case study house construction) results in acquisition costs of \$14,625 (Energy Star) versus \$12,717.50 (non-Energy Star). Exterior door costs vary greatly depending on type and nature. For the case study facility, one Energy Star double door and single door were installed at a cost of \$2000. Assuming a 15% premium (as in the case of the windows), standard doors would be estimated at \$1739.13. The total cost for Energy Star versus standard windows and doors is then \$16,625 and \$14,457, respectively (not including any applicable tax credits if available). No O&M costs are estimated during the 15-year window used for NPV analysis.

### 3.5. Rainwater Harvesting

The decision to install a rainwater harvesting system (RWH) versus a well or city water is one that is entirely dependent on the environment, the availability of municipal water, the homeowner's wishes, and regulations. In this case study, no city water sources were available. After a cost analysis, it was estimated that the cost for a well and the cost for a rainwater harvesting system (at the time of build) would be nearly identical largely due to well-depth requirements (1200').

Figure 5 depicts the RWH as currently installed in the rural residence. The system works as follows. Rainwater falls on the roof and is captured by gutters. The guttered water flows to the cistern where ~100 gallons or so is flushed out through a pipe with a ball float to eject the debris on the roof. Once the ball float seals the flushing tube, the water continues into French drain and basket filters and then into a cistern. Parallel on-demand pumps push water towards the house where it is processed through a sediment filter, charcoal regeneration system, and ultraviolet light, which is an effective method for inactivating pathogens through irradiation [85].

Quality considerations for water are significant. Using rainfall for potable house needs requires proper roof selection (ceramic or metal as examples), flushing (first flush), gross filtering (e.g., French drain and basket filters), storage (food-grade butyl rubber), pumping, cleansing (e.g., sediment filter and charcoal regeneration), purifying (ultraviolet purification as one example), and disposal of gray water (aerobic septic system). Baseline quality construction requirements are found in [86].

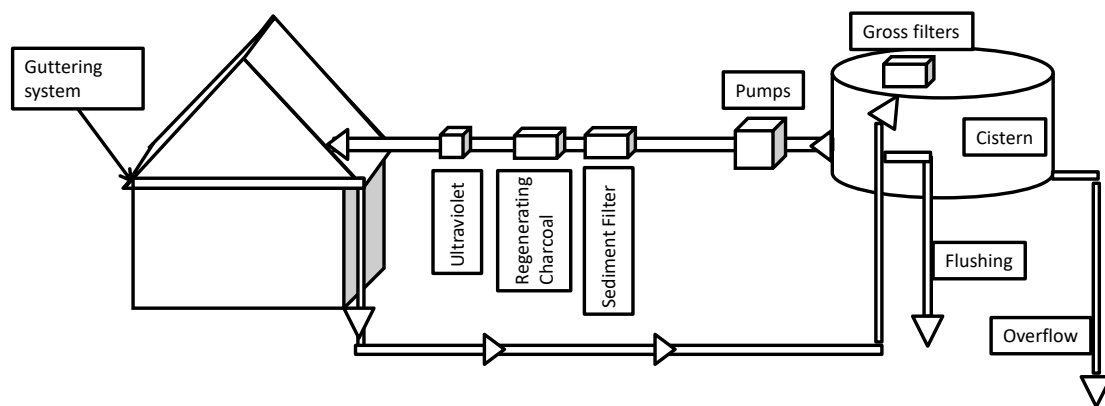


Figure 5. Rainwater harvesting system as designed.

Design of an RWH capable of meeting the needs of an entire household required simulation modeling, so that the distribution of the minimum in the cistern (order statistic) would be strictly greater than zero over all supply and demand considerations and all simulation runs. Details of the simulation are available from [43,45]. The final system selected included 4000 square feet of capture space and a 40,000-gallon cistern.

### 3.5.1. Environmental Considerations

Rainwater harvesting was selected for both sustainability and quality considerations; however, RWH is not always the least expensive option even given life-cycle costs [9]. From a sustainability perspective, RWH requires far less water for the same aquifer demand. Specifically, runoff, absorption/adsorption, and evaporation/transpiration reduce aquifer resupply by at least 30% [87]. On the other hand, RWH systems capture 75% to 90% of rainwater, depending on design and rainfall [86]. The amount of water pulled from the aquifer to supply one gallon is therefore at least 3.333 gallons, whereas well RWH systems capturing only 75% of the available rainfall require 1.333 gallons. The net savings to the aquifer is 2 gallons of water per 1 gallon demanded. Further, the water quality exceeds local and state requirements at the residence and should at similarly constructed residences when the RWH is constructed properly due to minimization of non-point source pollutants. The life-cycle impact for RWH has shown to be better than municipal water as well [88]. RWH also reduces carbon emissions, as water-related energy uses are significant (e.g., 19% of electricity use in California during the year 2001, [89]).

### 3.5.2. Acquisition, Operations, and Maintenance (O&M) Costs

Acquisition costs for the rainwater harvesting system (guttering, PVC piping, Pioneer 40K gallon cistern with butyl rubber liner and accessories) cost approximately \$25,500 in 2020 [90]. Current well drilling prices in Texas are about \$30 to \$55 per foot [91]. On this property, a 600' drilling depth is required. At the average \$42.50 per foot, the drilling cost alone would run \$25,500 in 2020.

Cost to maintain an RWH is reasonable. Ultraviolet tubes (replaced annually for typical use) as well as sediment filters and other system requirements cost approximately \$328 per year [92]. According to the Centers for Disease Control and Prevention, wells should also be inspected annually [93] at a cost of \$300 to \$500 [94]. The 15-year total costs are then \$31,500 (well) versus \$30,420 (RWH). When inflated by 3%, the costs are \$33,563 (well) and \$32,111 (RWH).

### 3.5.3. Qualitative Assessment

RWH is one of the best features both environmentally and practically. The water purification process results in high-quality, soft water, which is better for water-based appliances like coffee pots and

dishwashers. There is additional work required that the consumer must understand (filter replacement, gutter cleaning, etc.).

### 3.6. Water Fixtures

Selection of appliances and fixtures is important for a sustainable house reliant on 100% rainwater. Toilets, shower heads, and other water fixtures were low flow/high pressure, as the rural residence was only plumbed for rainwater harvesting.

#### 3.6.1. Environmental Considerations

Mayer et al. [95] estimate that toilets use 29% of indoor water consumption, while water used for showering/bathing, dishwashing, and laundry consume about 36%, 14%, and 21%, respectively. The Environmental Protection Agency (EPA) shows that high-pressure, low-flow shower heads reduce flow from 2.5 gallons per minute to 2.0 gallons per minute, a 20% reduction [96]. In semiarid regions (such as the location for the case study), the use of low-flow fixtures is vital.

#### 3.6.2. Acquisition and 15-Year O&M Costs

Costs for low-flow fixtures are comparable to standard fixtures, depending on brand. Further, Texas law requires the use of low-flow fixtures in new construction [97], so there are no cost acquisition differences measured among possible construction options. While dual-flush toilets are not required by Texas law, they were installed for additional water savings and at no additional cost. Break-even analysis did not include an analysis of low-flow fixtures, as they are required by law and are approximately equivalent in cost.

#### 3.6.3. Qualitative Assessment

Most of the low-flow appliances work as well or better than traditional fixtures. Selection of dual-flush toilets, however, must be done after consumer research. Dual-flush should not mean “flush twice.” These fixtures have underperformed due to improper selection.

### 3.7. Aerobic Septic

#### 3.7.1. Environmental Considerations

Cradle-to-grave water management requires that black water be treated responsibly and sustainably. In this area, aerobic septic systems are required by regulation. The residence construction included a Jet Biologically Accelerated Treatment (BAT) plant (also termed Biologically Accelerated Wastewater Treatment, BAWT, plant). BAT plants work by treating wastewater physically and biologically in a pre-treatment compartment. Water then flows through the treatment compartment where it is aerated, mixed, and treated by a host of biological organisms (a biomass). The mixture then flows to a settlement compartment where particulate matter settles, returning to the treatment compartment, leaving only odorless and clear liquid (gray water produced by the biomass), which is discharged through sprinkler heads [98]. Figure 4 shows the encased BAT system installed at the rural residence. Aerobic systems break down waste far quicker than anaerobic, due to the nature of the bacteria. The benefits to the environment include that: (1) pumps for transporting water to wastewater treatment plants are not necessary (and the associated energy costs); (2) treated water returned to the environment is cleaner; and (3) electricity for processing water (in this case) is largely, if not entirely, generated by the sun.

#### 3.7.2. Acquisition and O&M Costs

There is a cost penalty for installing such a system at this rural residence. Installing an anaerobic system averages \$3500, whereas an aerobic system costs about \$10,500 [99]. Maintaining the aerobic septic system is about \$200 annually [100], which is somewhat more than anaerobic systems [101].

To account for this differential, anaerobic costs were estimated at \$180 per year (a 10% discount). The 15-year acquisition and O&M costs for aerobic versus anaerobic systems was then estimated (after 3% inflation for O&M costs) at \$7531 (anaerobic) and \$14,128 (aerobic).

### 3.8. Tankless Water Heaters

One of the current additions to this research residence has been the inclusion of an on-demand electric water heater for a guest room, guest kitchen, and guest bathroom. Tankless electric water heaters require less space than tanked versions and do not constantly use energy to keep water warm. Natural gas options were not available for the case study, and electric heaters powered by PVS were as effective as solar water heaters aside from gray energy considerations.

#### 3.8.1. Environmental Considerations

Because any installation would be powered via PVS in the case study residence, there would be only the potential gray energy costs. If operated off of a coal-based grid, tankless electric water heaters would reduce greenhouse gas (GHG) emissions over a tanked system (although a heat pump water heater is even more effective in reducing emissions) [102]. The carbon footprint of tankless electric water heaters is much lower than that of systems with tanks, as it is in operation only when demanded. Tankless water heaters may be 99% efficient [103].

#### 3.8.2. Acquisition and 15-Year O&M Costs

The acquisition cost of an electric tankless heater is largely dependent on size, capability, and brand and may be larger than traditional tank versions; however, the acquisition cost for the installed unit was identical to the tank unit in this case study. Tankless units may also last 1.5 to 2 times as long as tank water heaters (20 years) and save 8% to 34% on water, depending on water demand; however, demand flow for multiple simultaneous operations must be evaluated prior to selection of a device [104].

Comparing the life cycle of a 50-gallon electric water heater with that of a tankless one requires some up-front assumptions. One study indicated that the life-cycle savings over traditional electric storage systems is \$3719 Australian dollars (about \$2500 US dollars) [105]. However, that study does not consider the possibility that all electrical power needed is generated by solar power.

The acquisition and installation costs for 2 × 50-gallon tank water heaters during initial construction was nearly \$3000 in the case study residence. Under coal-based grid power, the yearly costs are \$494 per tank or just under \$1000 for both systems; however, the case study residence relies on solar and thus avoids these costs. For tankless electric water heaters powered by PVS, the installation and acquisition costs are \$3000 for two units (high end) with zero annual costs and zero carbon emissions (other than solar gray power as discussed in the limitations).

The initial tanked systems installed were electric Marathon heaters with a lifetime warranty [106]. While there are likely labor costs associated with this warranty, we assume that they are nominal. Thus, operating and maintenance costs for standard water heaters are estimated at \$494 per tank per year for traditional construction with grid power, while the operation costs for tankless water heaters recharged solely by PVS are \$0. With identical acquisition costs and (assuming) zero maintenance costs due to warranties, the 15-year total costs are estimated at \$22,914 (traditional construction with standard tanked water heaters) versus \$3000 (tankless with 100% PVS). An assumption is that both systems will not require replacement during the 15-year horizon.

### 3.9. Solar Arrays

In a sustainable home located in semiarid regions, solar arrays are an obvious solution for producing energy requirements. This rural residence initially had installed a 7.25 kWh system (32 × 225 watt panels) with a Sunny Boy inverter (\$33,600 in 2011) and then subsequently added

another 9.585 kWh system ( $27 \times 355$  watt panels, \$31,317 in 2018) with a Solar Edge inverter after home expansion and capitalization of the original solar power system.

### 3.9.1. Environmental Considerations

From installation date until 31 January 2020, the initial 7.25 kWh system has produced 90.579 MWh of power in 35,212 hours of operation for 2.57 kWh per hour, saving 153,984 pounds of CO<sub>2</sub> emissions. The 9.585 kWh system has produced 25.86 MWh in about 18,240 hours since installation, saving 40,038.49 pounds of CO<sub>2</sub> emissions and resulting in only 1.4 kWh per hour. (The low result is due to installation in January and a month wait to replace the initial inverter (faulty) in January to February 2018).

The carbon dioxide avoidance by leveraging solar is significant over time. The footprint of solar is 6 g CO<sub>2</sub>e/kWh, while coal CCS is 109 g and bioenergy is 98 g. Wind power produces less emissions (4 g each); however, the rural residence location is a low-production wind area [32]. For 3500 kWh per month (or 42 MWh per year), the total annual difference in carbon emissions is 4.326 million g/CO<sub>2</sub>e.

### 3.9.2. Acquisition and 15-Year O&M Costs

The initial cost of both systems was approximately \$64,917. After 30% federal tax credits, the total cost was approximately \$44,441.90. Initial break-even analysis is based on both acquisition cost and energy cost as if both systems were installed on the expanded house. During the six months of April through September, the residence produced or banked more power than consumed. From October through March, the residence consumed more power than produced. During this month, the residents consumed 1699 kWh and produced only 1226 kWh. There is, however, no delivery or cost of power charge, because during the previous months, the residents produced more than consumed. The total consumption estimate is then about 2925 kWh for a 4800 square foot house in a cool month. When averaged over a single year, total consumption is approximately 3500 kWh per month. This equates to between about 1167 and 1750 kWh per person or 0.73 kWh per square foot.

A non-solar house consuming 3500 kWh per month under traditional utility billing at \$0.07 per kWh (cost at locality) with a \$14.77 customer charge (utility company determined) results in an annual estimated cost of \$3117.24 ( $\$259.77 \times 12$ ). The same consumption with 100% solar runs at \$33 grid-tied fee  $\times$  12 months = \$396. Total costs over 15 years with 3% inflation per annum are then \$62,834 (grid electricity) versus \$54,480 (PVS).

### 3.9.3. Qualitative Assessment

The PVS arrays are one of the best investments of the residence. There have been no uncovered maintenance costs; the systems are reliable. Coupled with the RWH system, the residence benefits from nearly all weather, gathering water from precipitation and harvesting the sun during even partially overcast days.

## 3.10. Electric Car Charging

### 3.10.1. Environmental Considerations

Electricity generated from PVS was used to charge an electric Nissan Leaf in the case study house. Additional panels were acquired directly for this purpose during the construction. Research suggests that battery electric vehicles (BEVs) may have higher GHG emissions than internal combustion engine vehicles (ICEV) if powered by a grid (at least in China) [107]. Given this research, the only sure way that carbon savings are achieved is charging them through renewable sources.

### 3.10.2. Acquisition Costs, 15-Year O&M Costs, and Residual

Assuming equivalent acquisition costs for a BEV and ICEV (~\$30,000 after tax credits), \$2400 annual gasoline and maintenance costs for the ICEV, \$1200 annual maintenance for the BEV, identical

replacement costs at year 7.5 (~\$36,000 after tax credits), and residual values of 22% versus 7% for ICEV and BEV, respectively, results in total costs of \$107,770 (ICEV) and \$92,288 (BEV). (ICEVs retain about 45% of their value over 4 years, while BEVs retain barely more than 25% on average [6], so using geometric decay over 7.5 years results in about 22% and 7% residual value). This estimate includes 3% inflation for maintenance and gasoline.

### 3.10.3. Qualitative Assessment

Unfortunately, early Nissan Leaf vehicles suffered from battery issues [108]. The owner divested after 3 years partially due to these issues. Improvements in the batteries of these vehicles as well as extended range models makes this vehicle an attractive option for minimizing gasoline and maintenance costs.

## 3.11. Geothermal Heating and Cooling

### 3.11.1. Environmental Considerations

As part of the construction, the rural residence was equipped with a closed-loop, geothermal system (see Figure 4). Vertical, closed-loop geothermal units are heat exchangers that leverage the fact that the temperature 200' below the Earth remains relatively constant. Geothermal systems may save between 25% and 75% on energy demands [109].

### 3.11.2. Acquisition and O&M Costs

The cost of the system including wells, unit, and ducting (complete) was \$26,500. The tax credit was 30% or \$7950, and so the end cost to the resident was \$18,550. ClimateMaster (the brand installed) estimates a \$1000 savings in electrical costs per year over an electric heat pump (\$3135 versus \$4169) [32]; however, PVS-powered systems have no directly attributable costs except for gray power. The system was replaced with a 5-ton, 18-seer American Standard Platinum heat pump unit in 2018 at a cost of \$16,255, over \$10,000 less expensive. (The reason for this replacement is discussed shortly). Assuming equal maintenance costs of \$600 per year, 3% inflation of O&M costs, the 15-year total cost for geothermal powered by PVS is \$30,644, whereas the cost for a heat pump and associated O&M is \$112,383 (grid-power).

### 3.11.3. Qualitative Assessment

The system operated with limited success for seven years, as the heat exchange and unit were unable to keep up with greater than 100 °F (38 °C) temperatures in its South Texas location, despite multiple attempts to improve the system (including adding an additional 200' well for heat exchange). This system was the most disappointing, as evidence even post-installation suggested that such a system would be effective in all climates [110]. That was not the experience in this single case study.

## 3.12. Generator or Other Backup System

The residents sought an eco-friendly solar power storage solution (e.g., Tesla Powerwall or the Chinese BYD B-box 10). All options were expensive (between \$80 to \$110 per kWh storage per year for 10 years) with decay rates that generate lithium ion battery disposal concerns after 10 years for most products [111]. Since the storage technology is still developing, a 22-kW propane-powered back-up generator, a device sufficient to empower the entire house (Figure 4), was installed. In well or rainwater harvesting systems that leverage pumps, back-up power is necessary to retain water during electrical outages. Propane is a green fuel that, when burned, has nominal effects on the environment [112]. The 1000-gallon propane tank and generator are sufficient to maintain full power to house for about 14 days under reasonable utilization conditions. The cost for this generator, automatic transfer switch, propane tank, underground installation, and connections was \$19,668.00. (A large portion of expense

involved burying the propane tank in rocky terrain.) While included in the discussion, this item is not part of break-even or NPV analysis.

### 3.13. Break-Even and NPV Analysis

Sustainable construction can generate a breakeven for the pocketbook and for the environment. Figure 6 illustrates the cost comparisons of the sustainable construction techniques discussed in this paper. Costs are inflated 3% per annum and reflect the previously detailed acquisition and O&M costs. The first matrix in this figure is traditional construction without environmentally intelligent land use. The second reflects the rural residence as designed, and the third matrix reflects sustainable construction without geothermal for the particular locality and residence.

Looking at Figure 6, the break-even year for 2020 construction would be by 2026. The additional cost of sustainable construction is estimated at \$54,329, which is much lower than might be expected due to the tax credits associated with solar and geothermal. A 15-year NPV analysis is provided at 3% and 5% cost of capital. At 3%, the analysis suggests a 15-year NPV of \$334,355 (traditional) versus \$250,339 million (sustainable), for a difference of \$84K. At 5% cost of capital, that difference falls to \$63K due to opportunity costs of committing capital up front.

### 3.14. Ongoing Sustainable Improvements

All add-on construction to the rural residence included mini-split HVAC systems (both in-wall and in-roof systems). These systems have more upfront costs but are much more energy efficient, as they do not lose energy through ductwork. Further, they are now inconspicuous and highly effective [113]. Also, these systems allow for better compartmentalization of conditioned air, as they do not rely on a set number of zones. See Figure 4 for pictures of in-roof and in-wall systems installed in the residence. In new construction, these systems should be considered due to their efficiency and elimination of ductwork and other requirements.

Another new construction consideration is the use of wireless multigang light switches. These fixtures can minimize wiring requirements by using a single drop instead of multiple drops. With the advent of 5G, it might be possible to eliminate CAT6 wiring during residential construction in the future as well.



	BLS Inflation	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03
<b>Traditional</b>	<b>Acquisition</b>	<b>O&amp;M 2020</b>	<b>O&amp;M 2021</b>	<b>O&amp;M 2022</b>	<b>O&amp;M 2023</b>	<b>O&amp;M 2024</b>	<b>O&amp;M 2025</b>	<b>O&amp;M 2026</b>	<b>O&amp;M 2027</b>	<b>O&amp;M 2028</b>	<b>O&amp;M 2029</b>	<b>O&amp;M 2030</b>	<b>O&amp;M 2031</b>	<b>O&amp;M 2032</b>	<b>O&amp;M 2033</b>	<b>O&amp;M 2034</b>	<b>O&amp;M 2035</b>
Framing: Stud	\$ (52,800)	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -
Insulation: Fiberglass	\$ (14,420)	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -
Windows/Doors: Standard	\$ (14,457)	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -
Water: Well	\$ (25,500)	\$ (400)	\$ (412)	\$ (424)	\$ (437)	\$ (450)	\$ (464)	\$ (478)	\$ (492)	\$ (507)	\$ (522)	\$ (538)	\$ (554)	\$ (570)	\$ (587)	\$ (605)	\$ (623)
Wastewater: Anaerobic	\$ (3,500)	\$ (200)	\$ (206)	\$ (212)	\$ (219)	\$ (225)	\$ (232)	\$ (239)	\$ (246)	\$ (253)	\$ (261)	\$ (269)	\$ (277)	\$ (285)	\$ (294)	\$ (303)	\$ (312)
Water Heaters: 2 x Tanks	\$ (3,000)	\$ (988)	\$ (1,018)	\$ (1,048)	\$ (1,080)	\$ (1,112)	\$ (1,145)	\$ (1,180)	\$ (1,215)	\$ (1,252)	\$ (1,289)	\$ (1,328)	\$ (1,368)	\$ (1,409)	\$ (1,451)	\$ (1,494)	\$ (1,539)
Electricity: Grid	\$ -	\$ (3,117)	\$ (3,211)	\$ (3,307)	\$ (3,406)	\$ (3,508)	\$ (3,614)	\$ (3,722)	\$ (3,834)	\$ (3,949)	\$ (4,067)	\$ (4,189)	\$ (4,315)	\$ (4,444)	\$ (4,578)	\$ (4,715)	\$ (4,857)
Vehicle: Gas	\$ (30,000)	\$ (2,400)	\$ (2,472)	\$ (2,546)	\$ (2,623)	\$ (2,701)	\$ (2,782)	\$ (2,866)	\$ (2,952)	\$ (3,040)	\$ (3,131)	\$ (3,225)	\$ (3,322)	\$ (3,422)	\$ (3,524)	\$ (3,630)	\$ (3,739)
HVAC: Heat Pump	\$ (16,255)	\$ (4,769)	\$ (4,912)	\$ (5,059)	\$ (5,211)	\$ (5,368)	\$ (5,529)	\$ (5,694)	\$ (5,865)	\$ (6,041)	\$ (6,222)	\$ (6,409)	\$ (6,601)	\$ (6,799)	\$ (7,003)	\$ (7,214)	\$ (7,430)
<b>Net Cash Flows</b>	<b>\$ (159,932)</b>	<b>\$ (11,874)</b>	<b>\$ (12,230)</b>	<b>\$ (12,597)</b>	<b>\$ (12,975)</b>	<b>\$ (13,365)</b>	<b>\$ (13,765)</b>	<b>\$ (14,178)</b>	<b>\$ (14,604)</b>	<b>\$ (15,042)</b>	<b>\$ (15,493)</b>	<b>\$ (15,958)</b>	<b>\$ (16,437)</b>	<b>\$ (16,930)</b>	<b>\$ (17,438)</b>	<b>\$ (17,961)</b>	<b>\$ (18,500)</b>
<b>Cumulative Cash Flow</b>	<b>\$ (159,932)</b>	<b>\$ (171,806)</b>	<b>\$ (184,036)</b>	<b>\$ (196,634)</b>	<b>\$ (209,609)</b>	<b>\$ (222,974)</b>	<b>\$ (236,739)</b>	<b>\$ (250,918)</b>	<b>\$ (265,521)</b>	<b>\$ (280,563)</b>	<b>\$ (296,056)</b>	<b>\$ (312,014)</b>	<b>\$ (328,451)</b>	<b>\$ (345,381)</b>	<b>\$ (362,819)</b>	<b>\$ (380,780)</b>	<b>\$ (399,279)</b>
Net Present Value, 3% Cost	\$ (334,355)																
Net Present Value, 5% Cost	\$ (302,081)																
<b>Sustainable</b>	<b>Acquisition</b>	<b>O&amp;M 2020</b>	<b>O&amp;M 2021</b>	<b>O&amp;M 2022</b>	<b>O&amp;M 2023</b>	<b>O&amp;M 2024</b>	<b>O&amp;M 2025</b>	<b>O&amp;M 2026</b>	<b>O&amp;M 2027</b>	<b>O&amp;M 2028</b>	<b>O&amp;M 2029</b>	<b>O&amp;M 2030</b>	<b>O&amp;M 2031</b>	<b>O&amp;M 2032</b>	<b>O&amp;M 2033</b>	<b>O&amp;M 2034</b>	<b>O&amp;M 2035</b>
Framing: Engineered	\$ (53,184)	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -
Insulation: Icynene	\$ (12,460)	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -
Windows/Doors: Energy Star	\$ (16,625)	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -
Water: RWH	\$ (25,500)	\$ (328)	\$ (338)	\$ (348)	\$ (358)	\$ (369)	\$ (380)	\$ (392)	\$ (403)	\$ (416)	\$ (428)	\$ (441)	\$ (454)	\$ (468)	\$ (482)	\$ (496)	\$ (511)
Wastewater: Aerobic	\$ (10,500)	\$ (180)	\$ (185)	\$ (191)	\$ (197)	\$ (203)	\$ (209)	\$ (215)	\$ (221)	\$ (228)	\$ (235)	\$ (242)	\$ (249)	\$ (257)	\$ (264)	\$ (272)	\$ (280)
Water Heaters: 2 x Tankless	\$ (3,000)	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -
Electricity: PVS	\$ (44,442)	\$ (498)	\$ (513)	\$ (528)	\$ (544)	\$ (561)	\$ (577)	\$ (595)	\$ (612)	\$ (631)	\$ (650)	\$ (669)	\$ (689)	\$ (710)	\$ (731)	\$ (753)	\$ (776)
Vehicle: Electric	\$ (30,000)	\$ (1,200)	\$ (1,236)	\$ (1,273)	\$ (1,311)	\$ (1,351)	\$ (1,391)	\$ (1,433)	\$ (1,476)	\$ (39,620)	\$ (1,566)	\$ (1,613)	\$ (1,661)	\$ (1,711)	\$ (1,762)	\$ (1,815)	\$ (1,870)
HVAC: Geothermal	\$ (18,550)	\$ (600)	\$ (618)	\$ (637)	\$ (656)	\$ (675)	\$ (696)	\$ (716)	\$ (738)	\$ (760)	\$ (783)	\$ (806)	\$ (831)	\$ (855)	\$ (881)	\$ (908)	\$ (935)
<b>Net Cash Flows</b>	<b>\$ (214,261)</b>	<b>\$ (2,806)</b>	<b>\$ (2,890)</b>	<b>\$ (2,977)</b>	<b>\$ (3,066)</b>	<b>\$ (3,158)</b>	<b>\$ (3,253)</b>	<b>\$ (3,351)</b>	<b>\$ (3,451)</b>	<b>\$ (3,555)</b>	<b>\$ (3,661)</b>	<b>\$ (3,771)</b>	<b>\$ (3,884)</b>	<b>\$ (4,001)</b>	<b>\$ (4,121)</b>	<b>\$ (4,244)</b>	<b>\$ (4,372)</b>
<b>Cumulative Cash Flow</b>	<b>\$ (214,261)</b>	<b>\$ (217,067)</b>	<b>\$ (219,957)</b>	<b>\$ (222,934)</b>	<b>\$ (226,000)</b>	<b>\$ (229,158)</b>	<b>\$ (232,411)</b>	<b>\$ (235,762)</b>	<b>\$ (239,213)</b>	<b>\$ (242,767)</b>	<b>\$ (246,429)</b>	<b>\$ (250,200)</b>	<b>\$ (254,084)</b>	<b>\$ (258,084)</b>	<b>\$ (262,205)</b>	<b>\$ (266,449)</b>	<b>\$ (270,821)</b>
Net Present Value, 3% Cost	\$ (250,339)																
Net Present Value, 5% Cost	\$ (239,449)																

Figure 6. Color-coded break-even and NPV analysis.

## 4. Discussion

### 4.1. Break-Even and NPV Analyses

For this case study, the break-even analysis and ROI suggest that sustainable land use and construction efforts can benefit the environment and the bottom line, which is congruent with other research [114]. The initial up-front costs may be quickly offset by savings depending on construction options, but there are upfront costs that must be considered as found in previous research [115]. In the case study here, only seven years were required for breakeven, which is earlier than empirical simulation might have suggested [9], possibly due to synergistic effects of multiple interventions applied simultaneously. This timeframe might be reduced by selecting subsets of options such as energy efficient HVAC versus geothermal HVAC, as in the hybrid ROI option investigated. Aside from the economic considerations, the environmental responsibility issues are clear. Avoiding carbon emissions is responsible construction.

In the break-even analysis, there were several construction options that resulted in near-zero break-even time, including the use of engineered lumber, Icynene foam, and Energy Star doors and windows. Other options such as 100% PVS and the purchase of an electric car saw delayed break-even points. Some sustainable efforts never saw any breakeven, including the aerobic septic system. Geothermal proved ineffective and expensive based on residents' desires and requirements, which runs counter to other evidence suggesting its utility in office buildings in another semiarid climate (Madrid), which does not have quite the same temperature spread as the location in Texas [116].

The additional cost of sustainable construction for the research residence in this case is estimated at \$54,329, and the 15-year NPV analysis showed \$84K and \$63K savings at 3% and 5% cost of capital for sustainable construction, respectively. There may be a positive return on investment for intelligent land use, transportation, and construction. Tax incentives and education are still necessary to encourage smart decisions and incentivize individuals [117]. These findings help inform construction decisions for businesses and for individuals in this region.

### 4.2. Environmental Findings

Perhaps more importantly, there is a significant environmental offset for this type of construction. Based on reasonable assumptions, the construction of this house saved between 25 and 90 trees due to the use of reclaimed wood [9]. The carbon dioxide avoidance by leveraging solar is significant, although there is a break-even consideration based on economic and environmental trade-offs congruent with other research [118]. The total estimated annual difference in carbon emissions was 4.326 million g/CO<sub>2</sub>e for this research residence. Environmental effects of burning gasoline in a vehicle were reduced to near zero by powering a BEV via PVS, and associated savings were achieved as in other research [6].

Further, the total water offset per demanded gallon is 2 gallons of water per 1 gallon demanded. A traditional residence consuming 10,000 gallons would require 33,333 gallons of rainfall to supply the ground water sources, whereas a rainwater system would require only 13,333 gallons. In semiarid regions, that difference is important for sustainability and aquifer preservation [43,45]. This rural residence illustrates that smart land use and sustainable construction save resources.

Aside from the sustainable options discussed in this case study, there are many, many more that might be considered, particularly with engineered performance improvement of materials. One example of this is the use of spent coffee grounds to improve thermal insulation [119]. Another example is the use of a prototype hybrid steel and wood purlins for roof construction rather than pure steel [120]. Materials improvements are likely to reduce environmental impacts of residential construction.

### 4.3. Policy Implications

There are also policy requirements for sustainable construction. That policy push towards sustainable construction is evolving to a universal mandate with penalties for failure to comply. The prime example is in California, where a new law passed a solar mandate where all new homes

built after 1 January 2020 must be equipped with a solar electric system. That system must be sized that it will offset 100% of the home's electricity usage. This mandate is one aspect of the California Energy Commission's initiative to have 50% of the entire State of California's energy production be from a clean energy source by 2030 [121]. Continuing with the California mandates on sustainability mandates, California passed another law recently signed by Gov. Brown that imposes water usage requirements. The law states that all California residents will be restricted to 55 gallons/day water usage by 2022 and is reduced to 50 gallons/day by 2030 [122]. While both initiatives discuss the mandates, neither has shown the penalty for failure to comply or even specifics on implementation. What is clear is that the mandates on both electric and water usage are the wave of the future and appear to be only the start in California, with certainty that other states will adopt similar measures. A proactive approach leveraging the analysis presented here and elsewhere will help both builders and buyers.

#### 4.4. Limitations

This is a single case study of a single rural residence, where some efforts were successful (e.g., solar power arrays and rainwater harvesting) and some were not (e.g., geothermal). The results for this single case study in a semiarid region are not generalizable to other regions. Further, land-use regulations vary from location to location, so what is achievable at this research location may be prohibited elsewhere. The case study is also limited in that complete cradle-to-grave life-cycle costs and impacts are not available for all components and that, as a case study, only one alternative technology was priced and investigated. For every category of construction, there are many available sustainable products. Where possible, we have documented environmental considerations; however, these are not the universe of effects.

Another major limitation of this study is that it does not include complete transaction costs (see [123–125]). Where possible, these are documented; however, they are nontrivial to estimate. Any final analysis should seek to improve these cost estimates.

## 5. Conclusions

### 5.1. Key Findings

This case study illustrates that proper rural residential construction and resource use can provide value to the consumer and reduce the impact of the built environment. There is a positive NPV obtainable for many eco-friendly construction options. A reasonable break-even expectation for sustainable construction options based on these construction requirements in this geographical area would be six years without geothermal HVAC, and the cost for the breakeven is \$54,329. The NPV suggested that the sustainable option was still the better choice at 3% and 5% cost of capital. Leveraging what works for both the environment and the consumer in a particular region requires dedication and focus of the residential construction industry.

Most important are the environmental offsets. By using sustainable building practices for new houses and renovations which are required in rural areas of Texas [56], carbon offsets and water conservation may be achieved, reducing the impact of the built environment on our planet. The savings for this single research property alone is estimated at 4.326 million g/CO<sub>2</sub>e annually. The effect of such sustainable building construction in rural communities may slow climate change.

### 5.2. Future Research

As a research residence, the design elements are not static. One element of future research includes adding lithium ion battery (LIB) backups for the PVS to achieve total grid separation. Understanding the feasibility, life-cycle costs, and environmental break-even of this effort would inform future engineering considerations, as evidence suggests LIB production has some carbon tail [126]. As part of future research, the team plans on evaluating the reduction of CAT6 Ethernet cables by adopting a true

wireless solution and the reduction of electrical wire by using dual-gang wireless light switches and requiring only one wired component.

Aside from the residence interventions, future research will include a meta-analysis of rural residential construction literature. Discovering best practices from multiple reports is important for generalizability beyond this case study. Sustainable construction options should positively affect the environment and the pocketbook.

**Author Contributions:** Conceptualization, L.F.; methodology, L.F., B.B.; validation, S.K., K.L.; formal analysis, L.F., B.B.; writing, L.F., B.B., M.B., K.L., S.K. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research received no external funding.

**Conflicts of Interest:** The authors declare no conflict of interest.

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