Article

A Publicly Available Cost Simulation of Sustainable Construction Options for Residential Houses

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Abstract: This publicly available simulation analysis compares baseline construction options versus sustainable options and evaluates both break-even costs as well as environmental effects. The simulation (https://rminator.shinyapps.io/sustain4/) provides users with comparative estimates based upon existing research on costs. This is the first simulation of its type that quantifies multiple sustainable construction options, associated break-even points, and environmental considerations for public use. Results estimate that a 100% solar solution for the baseline 3,000 square foot / 279 square meter house with 2 occupants results in a break-even of 9 years. The simulation includes options for rainwater harvesting or wells, Icynene foam, engineered lumber, Energy Star windows and doors, low flow water fixtures, aerobic / non-aerobic waste treatment or municipal services, and many other options. This is the first simulation of its type to provide publicly available sustainable construction analysis based on research, and it illustrates that sustainable construction might be both green for the environment and green for the pocketbook.

Keywords: construction, rainwater harvesting, simulation, solar

1. Introduction

Reducing the impact of the built environment is a necessary step to address concerns of climate change as well as population growth. Green building codes and certification (GBCC) have arisen to help provide best practice for green construction. Understanding what codes actually result in effective environmental changes that are positive for the consumer is necessary [1]. Incorporating requirements into GBCC systems improves environmental performance between 15-25% across 12 environmental impact categories when compared with the construction of a standard office building, as defined by National Institute of Standards and Technology [1].

In a recent study, electricity, tap water consumption, and employee commuting dominated 10 out of 12 environmental impact categories, categories that included global warming, human health consequences, eutrophication /acidification and use of water, as well as smog formation. For land use impacts, wood products contributed the most (perhaps, unsurprisingly) [2]. Overall, GBCC has been found to consume up to 25% less environmental impacts than standard building techniques. Specific improvements include acidification (25%), human health-respiratory (24%), and global warming (22%) [2].

Net Zero (or even Net Positive) construction involves the design of facilities that either consume no net energy (demand less supply) or that produce more energy than consumption [3], reducing global warming. Net Zero construction may even power user transportation [4].

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Rainwater harvesting removes the stress on below-ground and ground water sources for both residential and business construction (including hospitals) [5, 6].

While sustainable construction is important for the environment, there are economic considerations that will be evaluated by consumers prior to inclusion with new building. Therefore, green construction should be green for the pocketbook as well. This study evaluates break-even potential for user selected sustainable interventions. The study focuses only on options that involve power through electricity rather than natural gas or propane, as the residence informing the simulation was located in an area where neither natural gas nor propane were options. Natural gas, propane, and wind power will be investigated in future work.

The simulation analyzes best practice construction design for both the environment and the consumer selections of house design features. The motivation behind the simulation was to evaluate which green construction techniques might prove cost-effective. The components included in the simulation were informed partially by a residential research property and an author's decade-long experience with it. The research home, once the highest certified home for sustainable construction based on the National Association of Homebuilders standards [4], exists on 100% solar and 100% rainwater harvesting. The user interactive simulation is based on cost, demand, supply, and environmental considerations. The primary hypothesis is that many elements of green construction might also be green for the pocketbook as well. Break-even analysis is therefore produced.

This simulation and the associated analysis are unique. This is the first simulation of its type that quantifies multiple sustainable construction options, associated break-even points, and environmental considerations. Making this simulation publicly available provides a unique starting point for those considering sustainable construction.

2. Materials and Methods

In this simulation study, we evaluate break-even considerations, environmental impacts, and efficacy of multiple sustainable building innovations for residences. Included in the simulation are user options for lumber selection, insulation selection, window and door selection, the water system, the electrical system, the water heating system, geothermal heating and cooling, and vehicle selection. Vehicle selection is an important consideration, as an EV powered 100% by the home requires additional solar power but may reduce emissions and eliminates the owner's need for gasoline, all of which have impacts on costs and the environment.

A simulation of costs over time, based on construction materials selection provides information about the cost and environmental effects of residential construction decisions. Measured outputs include cost, demand for water / electricity, CO_2e emissions, trees required for the construction process, and water required to support the demand of occupants. The simulation is implemented in R Shiny [7] and freely available here: https://rminator.shinyapps.io/sustain4/ .

2.1. Residence Motivating the Simulation

Figure 1 is the Google Maps satellite image of the research house [8] that informed the simulation. This house includes all sustainable features available in the simulation. Median monthly electrical consumption is zero, and water costs involve only maintenance of the rainwater harvesting (RWH) system.

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Figure 1. The residence as constructed

2.2. Acquisition Costs and Selection of Lumber, Engineered vs. Traditional

Finger-jointed studs use reclaimed wood that might otherwise be discarded (Figure 2). They are straighter and result in less wood wasted. Further, they have a strong vertical load capability, with evidence that many species (including pine) have better structural properties when finger-jointed [9]. The residence and the simulation evaluate both financial and environmental effects of using this lumber.

Figure 2. Finger-jointed stud used in the residence construction

A 20" diameter tree with 42 feet length of usable wood produces about 260 board feet (.614 cubic meters). The Idaho Forest Products commission estimated that a typical 2,000 square feet (185.8 square meteres) house would use 102 trees of that size, 19.6 trees per square foot [10]. For the simulation, there is little quantitative support about the amount of reduction achieved in construction through the use of engineered lumber. This uncertainty translated to a uniform distribution with a conservative range of 10% to 20% reduction (flexible) based on the user input on trees per square foot (defaulted to 20, flexible). Equation 1 provides the operationalization for lumber usage. In this equation, the number of trees used is a binomial mixture, where *LUM* is an indicator for the use of engineered lumber. The resulting equation reduces consumption by 10 to 20% uniformly when engineered lumber is selected and 0% otherwise.

$$\#\,Trees = LUM \times \frac{trees}{ft^2} \times U(.8,.9) \times house\ size\ ft^2 + (1 - LUM) \times \frac{trees}{ft^2} \times house\ size\ ft^2 \qquad (1)$$

The cost of finger-jointed studs may be more expensive than regular studs. At one lumber site, retail cost of a 2 x 4 x 104 5/8" regular pine stud versus the same size finger-jointed stud is listed at $3.62 [11] versus $5.59 [12], respectively. This is a 54.4% cost increase for materials, which might be offset by lower labor costs due to engineered lumber's straightness. Engineered lumber typically results in a lowered installed cost per square unit [13].

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The cost differential is not atypical, as many engineered lumber products have upcharges between 1.5 and 2 times the cost of traditional lumber [14]. A reasonable estimate for the total cost of traditional framing between $4 to $10 per square foot for labor and $3 to $6 per square foot for materials [15]. These values were used in a uniform distribution for non-engineered lumber. Conservatively a uniform 10% to 20% reduction in labor costs and uniform 1.5 to 2.0 increase in material costs were used for engineered lumber calculations. Equation 2 shows the lumber cost calculations in the simulation. In this binomial mixture equation, the indicator variable *LUM* mixes traditional wood construction (*1-LUM*) with engineered wood construction (*LUM*). Traditional wood construction labor and material costs are modeled uniformly between $4 and $10 per square foot and between $3 and $6, respectively. For engineered wood construction, labor costs are reduced between 10 and 20% uniformly and material costs are 1.5 to 2.0 times higher. No operations and maintenance costs (O&M) were assessed for lumber selection due to its lengthy lifetime.

$$\begin{aligned}\$\,Lumber &= (1 - LUM) \times house\ size\ ft^2 \times \left(U(\$4, \$10) + U(\$3, \$6)\right) \\ &\quad + LUM \times house\ size\ ft^2 \times (U(\$4, \$10) \times U(.8, .9) + U(\$3, \$6) \times U(1.5, 2.0))\end{aligned} \tag{2}$$

2.3. Acquisition Costs of Air, Water, and Vapor Barriers

For the research house motivating this simulation, Icynene spray-foam was selected over other products (e.g., fiberglass, cork, pressed straw, coconut fiberboard, etc.) as it is multipurpose in that it provides an air barrier, vapor barrier, and water barrier, eliminating the need for attic vents, test ductwork, or air-seal attics. Icynene is environmentally friendly, made of 100% pure water-blown air, and it contains no chemicals [16]. Residential spray-foam insulation (Figure 3) provides a thermal barrier with exceedingly low conductivity (.021 W/mK in one study [17]). Spray foam has reasonable hygrothermal properties and is resistant to moisture migration. The practical relevance of the tight seal around the residence is that during the heat of the Texas summer (in excess of 100 degrees F), the observed temperature in the attic spaces does not exceed 80F/26.7C with the house thermometer set to 76F / 24.4C. The estimated wall U-values was .12, while the U-Values for the slab foundation (8″ to 8′ on the slope) are estimated between .07 to .83. The simulation includes an Icynene spray-foam option for these reasons.

Figure 3. Open-cell spray-foam insulation installed in the residence

The 2020 cost for open-cell spray-foam insulation is about $.35 to $.55 per board foot [18]. Assuming 3.5″ depth of spray converts to $1.23 to $1.93 per square foot, values used in the simulation of cost. Fiberglass batt insulation runs $.64 to $1.19 per square foot (2,359.17 cubic centimeters) [19]; however, this value provides an incomplete picture. Spray-foam works as an air barrier, vapor barrier, water-resistant barrier, and insulation. There is no need for attic vents, test

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ductwork, or air-seal attics. When evaluated in this manner, it is actually 10-15% less expensive than traditional construction [20]. To account for these components when selecting non-spray foam insulation, a uniform distribution between .85 and .90 was divided by the non-spray foam insulation costs to inflate them (see Equation 3). In this equation, the indicator variable *INS* is coded as 1 if Icynene foam is selected and 0 otherwise and *U* indicates a uniform variable on the ranges provided. No O&M costs were assigned for insulation, as all forms can last beyond 40 years.

$$\$\, Insulation = INS \times Size \times U(\$1.23, \$1.93) + (1 - INS) \times U(\$1.23, \$1.93) \,/\, U(.85, .90) \tag{3}$$

2.4. Acquisition Costs and Selection of Windows and Doors

In the simulation, the user has the opportunity to select Energy Star windows and doors similar to those used in the motivating residence's construction. The choice of windows and doors based on Solar Heat Gain Coefficient (SHGC) is important to the home energy usage. 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 .25 [21]. Further, the U factor, a factor that expresses the insulative value of windows, should be .4 or lower. Low emissivity Jeldwen windows and doors with SHGC of .23 and U-Factor of .3 were used throughout the research residence, a factor which motivated this simulation component.

Low emissivity windows are typically 10 to 15% more expensive than standard windows [22]. The typical cost range in 2020 dollars is \$385 to \$785 with an average of \$585 [23]. The Department of Energy (DOE) estimates savings of \$125 to \$465 dollars per year from replacing windows with new windows that have higher Energy Star ratings [24]. In the simulation, Energy Star windows are modeled as a 12% reduction from kWh based on DOE estimates [24]. The simulation requests that the user specify the number of windows and doors in the house and select whether they will be Energy Star certified (checkbox). Acquisition costs are shown in equation 4 based upon a 15% premium for Energy Star doors and windows per the Department of Energy. In this equation, *ENERGY* is an indicator variable indicating that Energy Star doors were installed. Doors need not be replaced during the maximum 40-year simulation, but windows are modeled as being replaced every 20 years.

$$\begin{aligned} \$\, Windows\ and\ Door\ Acquisition &= ENERGY \times \left(\#Doors \times U(\$900, \$1200) + \#\,Windows \times U(\$385, \$785)\right) \\ &+ (1 - ENERGY) \times \left(\frac{\#Doors \times U(\$900, \$1200) + \#\,Windows \times U(\$385, \$785)}{1.15}\right) \end{aligned} \tag{4}$$

2.5. Selection of Water System

The decision to install a rainwater harvesting system (RWH) versus a well or municipal water is one that is dependent on environmental considerations, the availability of municipal water, the homeowner's wishes, and regulations. For the residence that informed the simulation, no city water sources were available, so the choice was either well or RWH. After a cost analysis, it was estimated that the acquisition costs for a well and the cost for an RWH system would be nearly identical based on well depth and rainwater design considerations. The simulation provides the user the opportunity to select rainwater, well, or municipal water options. Because of its uniqueness and rarity, a short discussion of RWH systems is necessary.

2.5.1. *About Rainwater Harvesting Systems*

Figure 4 depicts the RWH as currently installed in the research 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. This is called the first flush. 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 [24]. The water is then used and exits to a septic system.

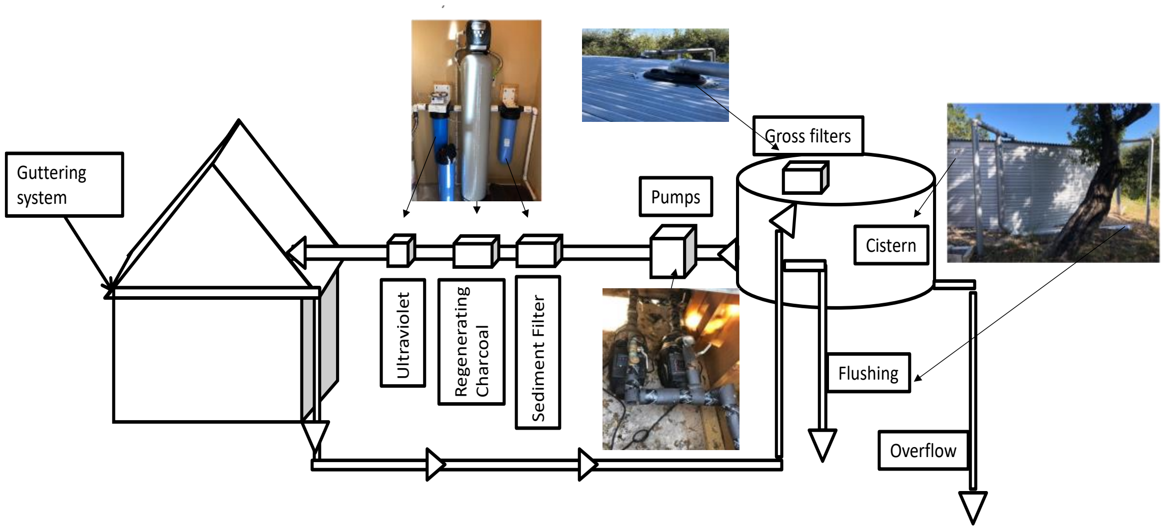

Figure 4. Rainwater harvesting system as designed

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, Figure 12), purifying (ultraviolet purification as one example, Figure 13), and disposal of gray water (aerobic septic system). For the research residence, *The Texas Manual on Rainwater Harvesting* [25] provided the baseline quality construction requirements.

Design of an RWH capable of meeting the needs of an entire household required separate 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 used for the residence that informed this model are available externally [5,26] .

2.5.2. *Acquisition Costs of Well, Rainwater, and City Options*

Acquisition costs for an RWH system (guttering, PVC piping, cistern with butyl rubber liner. and accessories) cost approximately $8,000 to $10,000 [27], but a large tank requirement can increase this value (e.g., $25,500 for the tank [28]). The cistern is the largest expense. The retail cost per gallon is 6.25 cents per gallon for a Pioneer tank at one location [27], although it is possible to use fiberglass tanks at a less expensive rate (.50 cents per gallon) [28]. Current well drilling prices in the U.S. are between $15 and $30 per foot and up to $50 for difficult terrain [29]. For the simulation, users select the well depth or the cistern size. If city or municipal water is available, there is no acquisition cost. Equation 5 illustrates how acquisition costs were assessed. In this equation, *WELL*

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is an indicator variable for the construction of a well with an associated cost distribution (triangular) based on [29] and well depth. *RWH* is an indicator variable for the selection of a rainwater system with the price equal to $.50 to $.70 per gallon of storage. This price includes complete installation of the system (including the pump). The indicator *CITY* is omitted, as municipal connection fees are nominal and not charged as part of the acquisition of a water system.

$$\$\,Water\ Acquisition\ = WELL \times T(\$15, \$30, \$50) \times Depth + RWH \times U(\$.5, \$.7) \times CisternSize \quad (5)$$

2.5.3. O&M Costs for Water

Equation 6 accounts for the annual maintenance and operations (M&O) of the water system selected for the simulation scenario. According to the EPA, the average American uses about 88 gallons of water per day [30]. The cost of municipal water in the US is approximately $.006 per gallon per person per day [31]. According to the Centers for Disease Control and Prevention (CDC), wells should also be inspected annually [32] at a cost of $300 to $500 per year [33]. Rainwater harvesting systems also have annual maintenance expenses. If gutter and roof cleaning is done by the owner, then the cost is estimated at $328 per year by the Environmental Protection Agency [34]. These costs are represented in Equation 6. In this equation, city water costs is based on a per gallon demand and a rate between ($.004, $.006) per gallon. Well O&M costs are $300 to $500 per the CDC, and RWH maintenance costs are centered around the EPA cost estimate. The accumulation rate is defined as 1 + inflation.

$$\begin{aligned} &Annual\ Cost\ of\ Water\ O\&M \\ &\quad = CITY \times 365\ days \times Occupants \times Annual\ Water\ Demand\ \times U(\$.004, \$.006) \\ &\quad \times Accumulation\ Rate^{k-1} + WELL \times U(\$300, \$500) \times Accumulation\ Rate^{k-1} \\ &\quad + RWH \times U(\$230, \$430) \times Accumulation\ Rate^{k-1} \end{aligned} \quad (6)$$

Selection of appliances and fixtures is important for a sustainable house reliant on 100% rainwater. Toilets, shower heads, and other water fixtures in the residence that inspired this simulation were low flow / high pressure (see Figure 15). Mayer et al. [35] 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 [36]. The Department of Energy estimates water savings between 25% and 60% [37], values used in the simulation. Costs for low flow fixtures are comparable to standard fixtures, so acquisition costs were omitted. Equation 7 is the water demand. In this equation, *LOW* is an indicator variable for installation of low-flow devices, and the mixture equation includes a uniform reduction of 25% to 60% if those fixtures are installed.

$$\begin{aligned} &Annual\ Water\ Demand \\ &\quad = LOW \times U(80{,}100)gl \times 365\ days \times Number\ of\ Occupants \times U(.4, .75) \\ &\quad + (1 - LOW) \times U(80{,}100)gl \times 365\ days \times Occupants \end{aligned} \quad (7)$$

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2.5.4 Acquisition, Replacements Costs and Environmental Considerations based on Selection of Water Heater, Adjusted Water Demand

One of the current additions to the research residence has been the inclusion of an on-demand electric, tankless water heater for a guest room, guest kitchen, and guest bathroom. These water heaters take up less space than those with tanks and do not constantly use energy to keep water warm. One study indicated that the life-cycle savings over traditional electric storage systems is $3,719 Australian dollars (about $2500 US dollars) [38]. However, that study does not consider the possibility that all electrical power needed is generated by solar. Further, the carbon footprint is much lower, as it is in operation only when demanded. Tankless water heaters may be as much as 99% efficient [38], saving 27 to 50% of kWh consumption [39]. The acquisition cost of an electric tankless heater is largely dependent on size, capability, and brand and may be higher than traditional tank versions; however, many high capacity electric versions are comparable in acquisition costs with traditional tank versions. Tankless may also last 1.5 to 2 times as long as tank water heaters (20 years) and save 8 to 34% on water (values used in the simulation), depending on water demand; however, demand flow for multiple simultaneous operations must be evaluated and proper capability systems selected [40]. The water demand reduction factor was included in the simulation by a unifom distribution between .66 and .92 as shown in Equation 8. Acquisition and replacement costs for tankless and tanked water heaters were based on user input for average cost (inflation adjusted), while the replacement life was estimated at 8-10 years (uniform distribution) for tanked heaters and 15-20 years (also uniformly distributed) for tankless [41].

$$\begin{aligned} &Annual\ Water\ Demand\ with\ Tankless\ Water\ Heater \\ &= U(.66,.92) \times LOW \times U(80{,}100)gl \times 365days \times Occupants \times U(.4,.75) \\ &+ U(.66,.92) \times (1 - LOW) \times U(80{,}100)gl \times 365days \times Occupants \end{aligned} \tag{8}$$

2.5.5. Environmental Consideration: Water Supply Requirements for Meeting Residents' Water Demand

For the simulation, users select from RWH, well, or city / municipal water sources. From a sustainability perspective, RWH requires far less water for the same aquifer demand (either well or municipal). Specifically, run-off, absorption / adsorption, and evaporation / transpiration reduce aquifer resupply to about 30% [42]. On the other hand, RWH systems capture 75% to 90% of rainwater, depending on design and rainfall [25]. The amount of water pulled from the aquifer to supply one gallon is therefore at 2.5 to 3.0 times as much as rainwater harvesting. Equation 9 illustrates how the simulation accounts for the water supply requirements to satisfy demand. *RWH* is an indicator variable indicating a rainwater harvesting system. This equation is adjusted later for selection of low flow devices and installation of tankless water heaters.

$$\begin{aligned} &Water\ Supply\ Requirements\ for\ Meeting\ Residents'\ Water\ Demand \\ &= RWH \times Water\ Demand\ / \ U(.75,.90) + (1 \\ &- RWH) \times U(2.5{,}3.0) \times Water\ Demand\ / \ U(.75,.90) \end{aligned} \tag{9}$$

2.6. Acquisition, O&M Costs and Environmental Considerations for Waste Management System

Cradle-to-grave water management requires that black water be treated responsibly and sustainably. Traditional municipal waste management and septic systems (aerobic and anaerobic) are two options for treating waste at residences, while traditional wastewater treatment plants are a third option. All three are available in the simulation.

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The research residence informing the simulation had installed 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 [43]. Figure 5 is the encased BAT system installed at the residence. Aerobic systems break down waste far quicker than anaerobic due to the nature of the bacteria.

Figure 5. Biological Accelerated Treatment plant during installation

Installing a typical anerobic system averages $3,500, whereas an aerobic costs about $10,500 [44]. Maintaining the aerobic septic system is about $200 annually [45], which is somewhat more than anaerobic systems [46] (modeled as 50% of the cost on average). There are benefits to the environment in 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, 3) electricity for processing water (in this case) is largely if not entirely generated by the sun. Equations 10 and 11 are the acquisition and operation costs for the simulation. In these equations, *AEROBIC* is an indicator variable for an aerobic septic system, *ANAEROBIC* indicates an anaerobic septic, and city waste management is omitted (zero cost and nominal O&M).

$$\$\,Acquisition = AEROBIC \times U(\$9{,}500, \$10{,}500) + ANAEROBIC \times U(\$2{,}000, \$3{,}000) \tag{10}$$

$$\$\,O\&M = Previous\ \ O\&M\$ + AEROBIC \times U(\$150{,}250) + ANAEROBIC \times U(\$100{,}200) \tag{11}$$

2.7. Acquisition / O&M Costs, Electrical Systems

The simulation provided the opportunity for 100% electric or 100% solar. No mix of other electrical sources was evaluated in the first version of the simulation. The research residence initially had installed a 7.25 kW system (32 x 225 watt panels) with a Sunny Boy inverter ($33,600 in 2011, Figure 18) and then subsequently added another 9.585 kW system (27 x 355 watt panels, $31,317 in 2018, Figure 19) with a Solar Edge inverter after home expansion and capitalization of the original solar power system. The total cost of both systems was $64,917. After 30% federal tax credits, the total cost to the resident was approximately $44,441.90. From installation date until 31 January 2020, the initial 7.25 kW system has produced 90.579 MWh of power in 35,212 hours of operation for 2.57 kWh per hour, saving 153,984 lbs CO2. The 9.585 kWh system has produced 25.86 MWh in about 18,240 hours since installation, saving 40,038.49 lbs CO2 emissions and resulting in only 1.4 kWh per hour. The efficacy of this system is one of the reasons that motivated this simulation.

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For the simulation, users are asked to select the percent of kWh provided by solar. Acquisition of a system includes extra capacity to account for .004% decay per year. In doing so, O&M costs for the duration of the simulation are built in [47]. To illustrate, a 30-year horizon would require 11.33% more panels. Further, users were required to select their state, as geography has an impact on capture. That impact was acquired by evaluating the ratio of the recommended photovaltaic system size recommended by manufacturers to the kWh used monthly (e.g., [48]). Cost per solar panel watt was a user option, set between $2 and $5 with the default value of $3.18 [49]. Equation 12 is the solar acquisition cost when selected, where *SOLAR* is an indicator variable for the inclusion of a solar system, *ENERGY* is an indicator variable for energy star windows / doors .

$$\begin{aligned}\$\,Solar\ Acquistion &= ENERGY \times \%\,Solar \times (1 - Tax\ Credit) \times \$\,per\ Watt\ \times (Total\ Monthly\ kWh) \\ &\times .88 + (1 - ENERGY) \times (1 - Tax\ Credit) \times \$\,per\ Watt\ \times (Total\ Monthly\ kWh)\end{aligned} \tag{12}$$

O&M costs for solar are negligible, particularly since the decay factor is included in the system [50]. Residential electricity rates are anticipated to be fairly stable over time as well [51]. For the simulation, the user inputs the initial cents per kWh, which are inflated over time based on the anticipated electrical inflation rate. Equation 13 provides the electrical O&M costs for the simulation. The total kWh is calculated later.

$$\begin{aligned}\$\,Electrical\ Cost &= \%\,Solar \times U(\$100, \$350) \times Accumulation\ Rate^{k-1} \\ &+ (1 - \%\,Solar) \times \$\,per\ kWh\ \times Total\ kWh\ \times Electrical\ Accumulation\ Rate^{k-1}\end{aligned} \tag{13}$$

From an environmental perspective, the carbon dioxide avoidance by leveraging solar is significant. The footprint of solar is 6 g CO2e/kWh, while coal CCS is 109 g and bioenergy is 98 g. Wind power produces less emissions (4 g); however, the research residence location is a low-production wind area [52]. Wind will be incorporated in a future version of the simulation. Equation 14 is the CO2e/kWh formula used in the simulation.

$$CO2e = \%\,Solar \times 6.0\ g\ \times Total\ kWh + (1 - \%\,Solar) \times 109g\ \times Total\ kWh \tag{14}$$

2.8. Acquisition / O&M for Vehicle (Important for EV Considerations.)

In the research residence, electricity generated from the solar panels was used to charge an electric Nissan Leaf (early adopter, see Figure 6). Nissan Leaf ownership costs over 8 years are estimated to be $36,537.82 with total 8-year energy costs (kWh) at $3,969 [53]. When powered by solar that is 100% capable of producing both home and automobile power, there are negligible O&M energy costs. Thus, the difference in cost between an equal value gasoline car (after accounting for any tax credits and residual) would be the maintenance and energy costs. In the simulation, the user selects the car acquisition cost for comparison (possibly zero to omit this element). Equation 15 reflects the implementation of the comparison in the simulation if a user selects an electric vehicle. The last portion of the equation uses the complement of the indicator for electric vehicles (*EV*) and multiplies that by the annual cost of driving. The use selects the starting gasoline cost (inflated), miles driven, and miles per gallon.

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$$\$\,Vehicle\ Acquisition\ \&\ O\&M = Initial\ Car\ Cost + Inflated\ Replacement\ Car\ Costs\ at\ Life\ Cycle\ End + 12 \times miles\ driven\ monthly\ /\ mpg \times gasoline\ cost \times (1 - EV) \tag{15}$$

Figure 6. Nissan Leaf and final charging station

2.9. *Acquisition Costs for Heating, Ventilation, and Air Conditioning*

As part of the research construction, the residence was equipped with a closed loop, geothermal system (see Figure 7). This became an option in the simulation. Vertical, closed-loop geothermal units are heat exchangers that leverage the fact the temperature 200′ below the Earth remains relatively constant. The cost of the system including wells, unit and ducting (complete) was $26,500. The tax credit for the research residence was 30% or $7,950, 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 ($3,135 versus $4,169) [54].

Acquisition costs for geothermal are much more than traditional heat pumps [55]. In the simulation, the user selects the tonnage required, and this tonnage is used to estimate the total install cost. Equation 16 illustrates the simulation implementation, where *GEO* is an indicator variable for the installation of a geothermal system.

$$\$\,HVAC\ Acquisition = GEO \times U(Tonnage \times 5000, Tonnage \times 6000) + (1 - GEO) \times U(Tonnage \times 1000, Tonnage \times 2000) \tag{16}$$

Geothermal systems may be more expensive but reduce kWh usage. This reduction is factored into the total kWh calculation in Equation 17 along with Energy Star windows and doors, tankless water heaters, and electric vehicle consumption. *ENERGY*, *GEO*, *TANKLESS*, and *EV* are indicator variables for the presence of Energy Star doors / windows, geothermal heating, tankless water heaters, and an electric vehicle, respectively.

$$base\ kWh\ Required = 12\ x\ monthly\ kWh - ENERGY\ x\ 12\ x\ monthly\ kWh \tag{17}$$

$$if\ GEO == 1\ then\ kWh\ required = base\ kWh\ reqired \times U(.5,.9)$$
$$if\ TANKLESS == 1, then\ kWh\ required = kWh\ required \times U(.5,.73)$$
$$Total\ kWh\ Required = kWh\ required + EV \times EVkWh \times miles \times 12$$

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Figure 7. Geothermal unit and vertical drilling of wells

2.9. Simulation Runs and Flowchart.

The number of simulation iterations is user specified from 1,000 to 8,000. A confidence interval of 95% is graphed across the break-even graph for users to evaluate the variability of the estimates. The default value is 2,000 iterations. Figure 8 is the flowchart.

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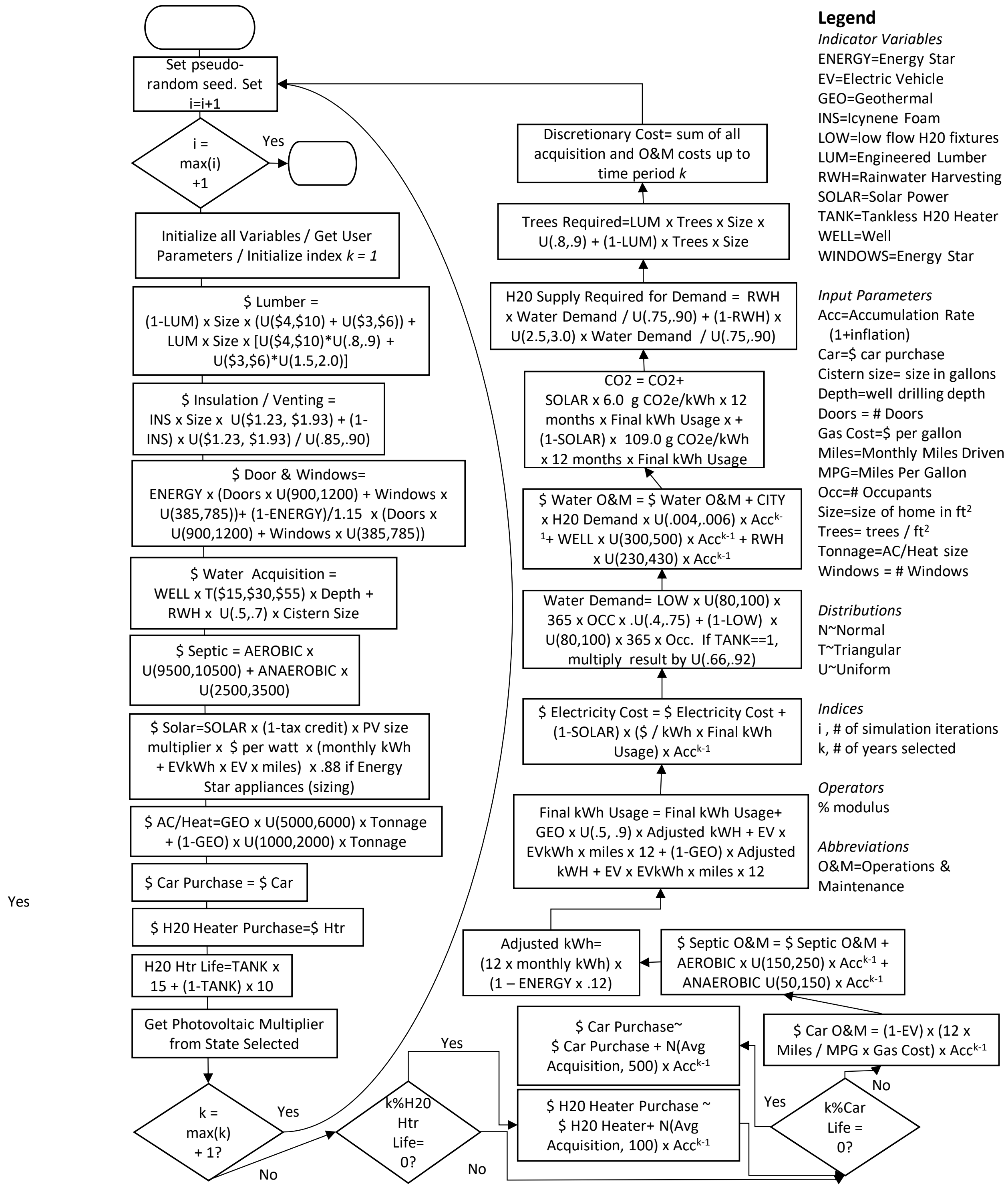

Figure 8. Flowchart for the simulation

2.10. Verification and Validation (V&V)

Since the simulation was written in R Shiny, several methods were available for verification and validation. To investigate validity, prior and posterior distributions were investigated to ensure that output distributions matched the input distributions. For validity across experimental conditions, a common random number stream was used. In doing so, we ensured that comparison

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differences would not be due to the selection of pseudo-random numbers alone. Third, visualization of the simulation results ensured that the outcomes were as expected.

3. Results

3.1. Baseline vs. Scenario 1

The baseline scenario was set to include the parameters in Figure 9. Runs were based on 30-year ownership, 3000 square feet construction (279 square meters), 25 windows, 3 external doors, 2 occupants, 2 water heaters, \$1000 water heater acquisition, 30% tax credit, 5 ton (4.5 metric ton) heat pump / geothermal heat pump in Texas, 1500 base kWh usage per month, \$.13 per kWh utility costs, \$3.30 per watt solar panels, 3% annual inflation, .3 kWh per mile for EV, \$30K base cost for vehicles, 1100 monthly miles, 30 mpg for gas vehicles, \$2.20 per gallon for gasoline, 8 year car life, and 2000 simulation runs. Comparative construction analysis in Figure 8 included all possible sustainable options offered in the simulation.

3.1.1. Scenario 1-All Sustainable Items Checked to Mimic Research Residence Components

Figure 10 shows the graphical results of the break-even analysis for Scenario 1. The break-even time based on this analysis is about 21 years due to the up front expenses. At 30 years, the cost savings is estimated to be \$80,000. Figure 11 breaks down both costs and environmental considerations for the baseline versus this construction. The sustainable construction option saves 56,921 kilograms of CO_2 and requires 5,501 fewer kilogallons of water to meet demand over the 30-year lifespan. The sustainable option requires 217 fewer MWh over the course of 30 years, and the grid cost is zero as solar provides 100% of the power required. While better for the environment, water and wastewater are more expensive for the sustainable construction and can never achieve any break-even.

3.1.2. Scenario 2-100% Solar, Geothermal, Tankless Water Heater, Engineered Lumber, Icynene Foam, Electric Vehicle, Energy Star Windows & Appliances, Low Flow Fixtures, Rainwater Harvesting, Aerobic Septic

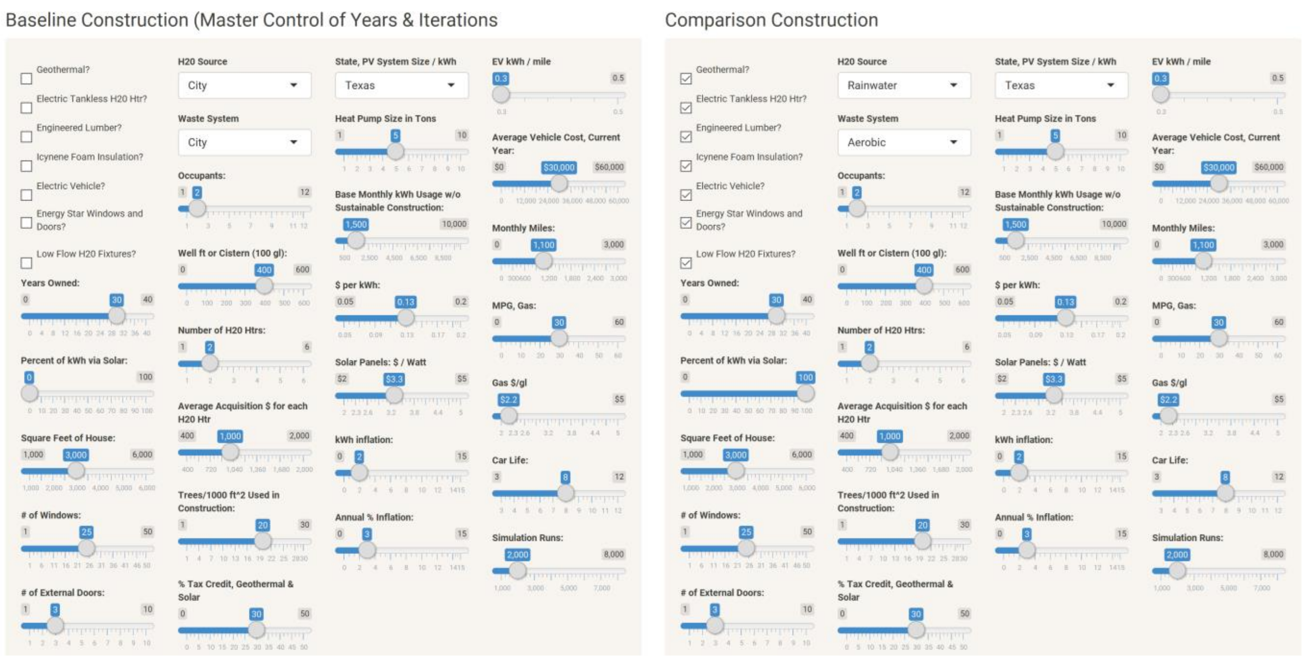

Figure 9. Baseline and comparison construction information, Scenario 1

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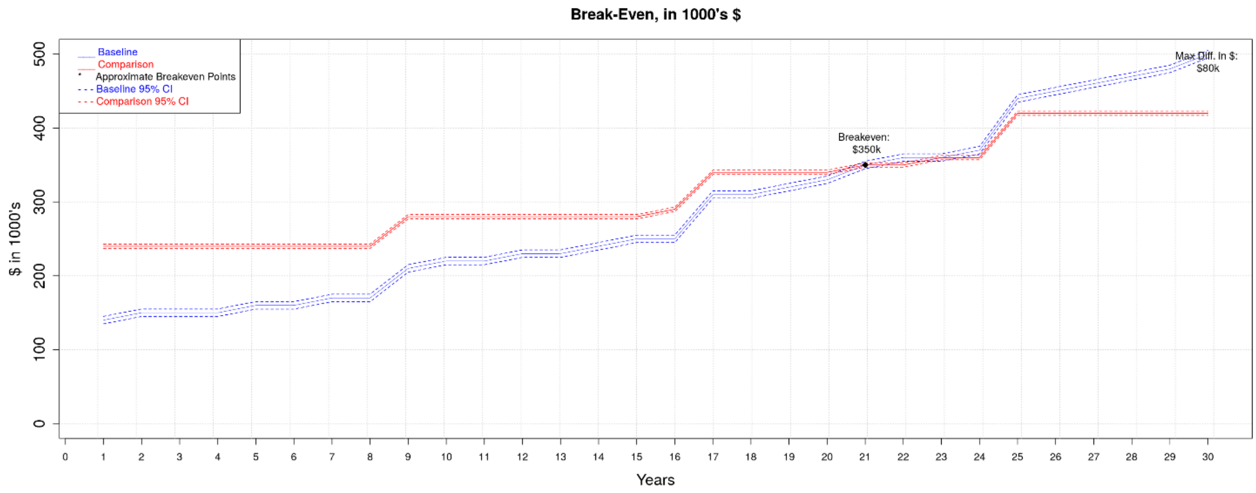

Figure 10. Break-even analysis for Scenario 1

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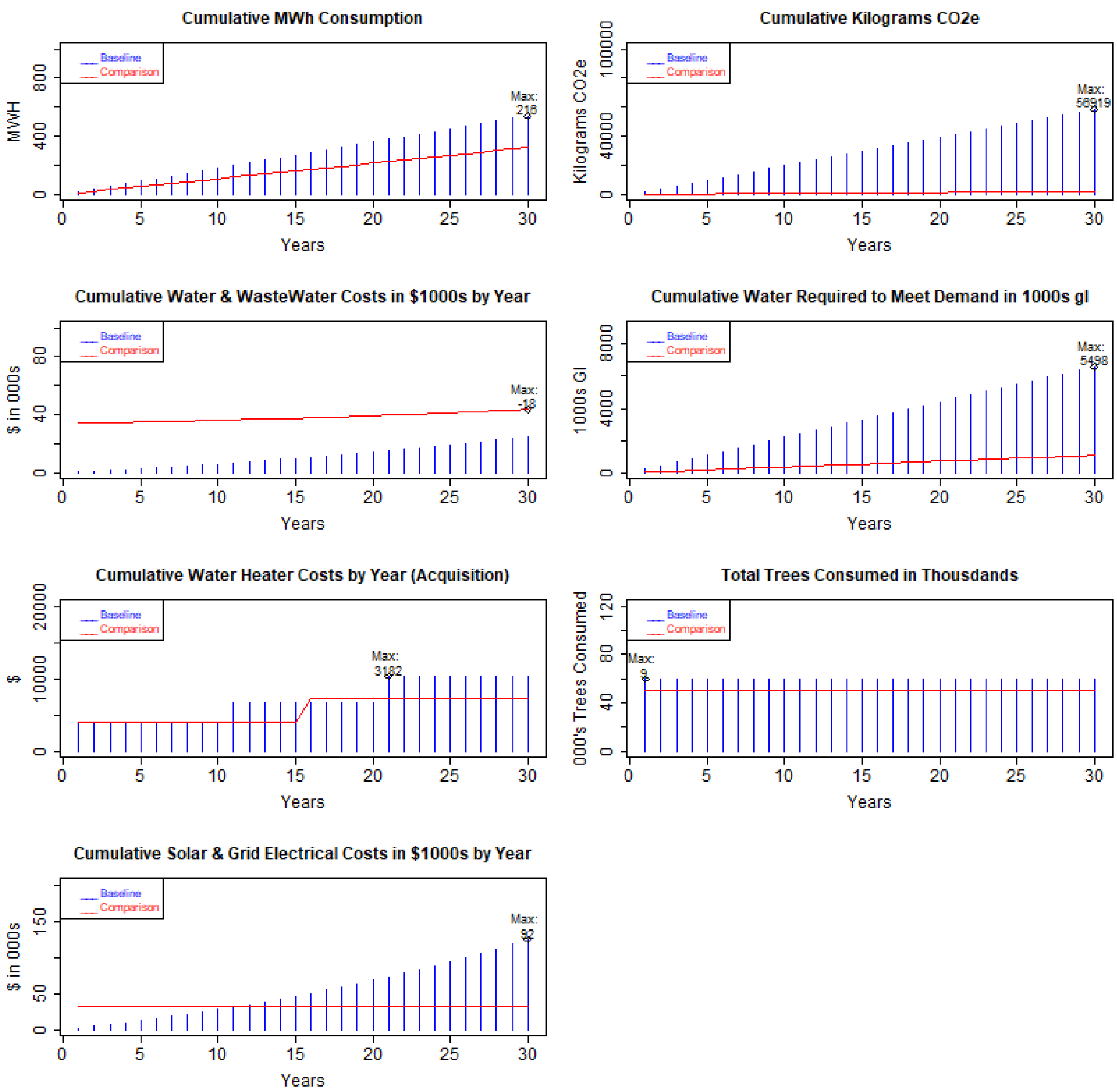

Figure 10. Comparison of costs and environmental costs are depicted for the baseline construction (left) versus the 100% solar construction (right). "*Max*" is the maximum difference between comparison construction and baseline construction.

3.1.2 Scenario 2-100% Solar Only

Scenario 2 includes 100% solar as the comparison option. Break even is at 9 years with the maximum cost savings at 30 years equal to $140,000. See Figure 11. CO2e savings over traditional construction total 55,620 kilograms. If tax credits are reduced to zero, then the break-even moves to 12 years rather than 9, and the 30-year maximum benefit is reduced to $130,000.

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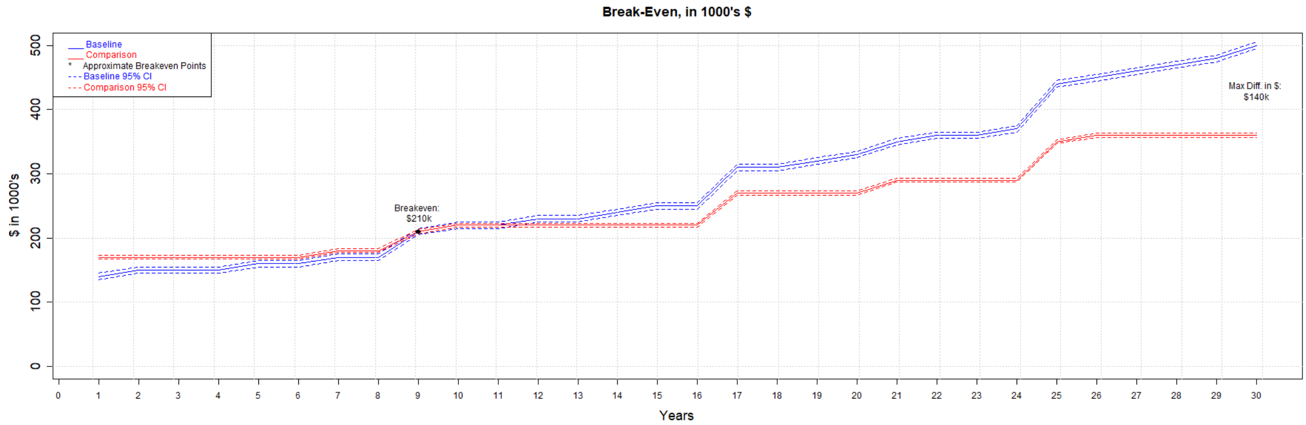

Figure 11. 100% solar versus the baseline

3.1.4 Comparison Tables for Various Scenarios

The number of scenarios available is beyond enumeration, as the simulation is designed to support user input. Thus, design of experiments and response surface methodology are outside the scope. Given the fixed parameters for the baseline discussed previously, comparison changes were made for many of the sustainable construction options. Interestingly, Icynene Foam and engineered lumber are not major contributors to the cost or break-even analysis. The hypothetical advantage of EV's is offset by the requirement for more solar in a 100% solar solution as well as gas prices. Other combinations are left to the user to explore. Table 1 illustrates the results.

Table 1. Comparison of simualtion results

Baseline Plus the Following	Years to Break Even	30-Year Savings in 000's	Notes
100% Solar	9	$140	
50% Solar	7	$70	
25% Solar	2	$25	
Geothermal	15	$50	
Electric Tankless	0	$80	
Energy Star Windows & Doors	2	$20	
Low Flow	0	$20	
Rainwater, 40 kilogallons	NA	NA	
Rainwater, 30 kilogallons	30	$0	
Electric Vehicle	NA	NA	(Requires more solar acquisition)
Aerobic	NA	NA	

4. Discussion

The results show that building a sustainable house can be both green for the environment and green for the pocketbook depending on the trade-off considerations of the consumer. The initial up-front costs may be quickly offset by savings depending on construction options. Of importance, we note that a 100% solar solution alone offsets the acquisition costs for the baseline construction in 9 years. Other options do similarly as well. Aside from the economic considerations, the

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environmental responsibility issues are clear. Avoiding carbon emissions is responsible construction. The analysis of individual construction options based on this simulation will help consumers with decision making.

The significance of this study is multi-fold. First, the study informs a unique, original decision-support simulation for consumers. Second, the study evaluates both break-even and environmental considerations for complex decisions associated with building. Third, the study shows that building sustainably may be green for the environment and the pocketbook.

4.1.1. Policy.

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 [56]. 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 [57]. 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.

Another implication of this analysis shows that the return on investment requires the occupant to live in the home for an extended period to make the up-front costs viable on the back end. An issue that is imperative to ensure economic break-even is the inclusion of accessibility as part of the engineering design process. One reason people must leave their homes is impairment of mobility and access. The solution to this from a policy perspective should be that all homes being built should also be required to meet basic American with Disabilities Act Accessibility Guidelines. The ADA does not apply to private residences, but a significant sustainability policy implication is that it should be extended along with the resource mandates as mentioned on power and water. These guidelines have minimum standards to exterior access, parking, hallway dimensions, bathroom access, as well as reach and appliance access. The International Code Council publishes new International Building Codes every 3 years, and the current code was published in 2018, known as ICC IBC-2018. The time is now to incorporate the ADA accessibility standards into the new code to be published in 2021, which would require all new construction, both private and public, to meet these standards. In so doing, this would allow individuals to remain in their homes longer, and experience longer ROI on all sustainability aspects of their home. While the residence discussed in this case study is not yet fully ADA compliant, it was designed with the minimum hallway, bathroom, and parking requirements to support future disability of its residents.

4.1.2. Limitations

The limitations of the simulation in this study are significant. First, only a limited subset of sustainable and non-sustainable construction components is considered. Many others will be added in future work, but modeling the universe is not realistic. Second, the estimates in this study are based on evidence and professional assessment; however, they may contain more error

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than modeled. Third, the distributions selected, while ostensibly reasonable, may be improved with additional analysis.

4.1.3. Future Sustainable Improvements and Modeling

All add-on construction to the residence included mini-splits (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 [58]. See Figure 25 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.

Figure 25. Mini-split units mounted in research residence, wall and roof versions

Another new construction consideration is the use of wireless multi-gang 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.

This is the first simulation of its type that quantifies multiple sustainable construction options, associated break-even points, and environmental considerations. In future simulations, wind power as well as natural gas and propane will be modeled. Distributions and parameters will be refined where possible, and additional input options for users will appear.

5. Conclusions

The study focuses on individual economics and technical components of constructing a sustainable family home. The individual commitment and passion imply a vision of long-term survival of our planet and society, a vision which is achievable from a consumer cost perspective. Thus, the study provides both a contribution to the growing sustainability culture in our regional, national, and international communities as well as presents an opportunity to further expand upon sustainability culture indicators. Other authors have presented research on a cultural sustainability index framework [50] to extrapolate and evaluate the effect of making a difference collectively as a society. Including an evaluation of cultural sustainability for multiple individual green family dwellings is a logical next step from the current study.

Supplementary Materials: Simulation

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

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