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Article

Green for the Environment and Green for the Pocketbook: A Decade of Living Sustainably

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Abstract: The question of building sustainable in a geographical locality is inexorably linked to cost. In 2011, one of the authors built a sustainable house that was (at the time) the highest certified sustainable home based on the National Association of Home Builder's standards for sustainable construction. This Texas house has been used for residential and research purposes for the past decade. In this case study, the authors evaluate components of the construction and their effectiveness as well as unseen secondary and tertiary effects. Some of the specific components discussed are home site placement; rainwater harvesting (100% of residential requirements); aerobic septic system; grid-tied solar array power; electric car charging; geothermal heating and cooling; reclaimed wood framing; spray foam installation; selection of windows, fixtures, and appliances; on-demand electric water heaters for guest areas; generator backups; and use of local items. Electric bills and water system improvements are discussed in detail, as improvements were made as part of residential and research requirements. This case study suggests that the financial outlay is worth the extra up-front costs if residents in this geographical area and climate will occupy the residence 7 years.

Keywords: construction, rainwater harvesting, solar, spray foam, finger-jointed studs

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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 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].

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],

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

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This qualitative case study analyzes best practice construction design for both the environment and the consumer based on one author's decade of living in a sustainably constructed residence. This residence was the highest-rated house ever certified by the National Association of Home Builders at the time it was built [4]. Both construction successes and failures are analyzed with commentary from both the environmental and consumer perspective. Where possible, cost-benefit analyses are provided.

2. Materials and Methods

In this case study, we evaluate life-cycle costs, environmental impacts, and efficacy of multiple sustainable building innovations to evaluate construction possibilities for residences. The particular 4,800 square foot home studied exists in a semi-arid environment (San Antonio, Texas.) Particularly foci of this qualitative case study include the efficacy of solar panels theoretically sufficient to power the homeowner's electrical demand as well as power an electric car and the utility of a rainwater harvesting system designed to support 100% of the homeowner's needs. The study evaluates home site placement; local materials extraction; 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; wireless switches to reduce wiring requirements; geothermal heating and cooling; and electrical back-up system options. The primary hypothesis is that construction of a large house in a semi-arid environment using sustainable techniques could be green for the pocketbook as well as green for the environment.

3. Results

3.1. Initial Considerations

3.1.1. Site Placement

The residence in the study was designed from the ground up to be sustainable, and the design considerations included geographical placement. The home site (5.3 acres on a hill just North of San Antonio, Texas) 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) [7]. 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 1 is the Google Maps satellite image of the house [8].

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Figure 1. The residence as constructed

3.1.2. Material Location / Transportation

One of the major sustainability considerations in residential construction is the transportation of materials. As part of the house design, only local materials (those within 50 miles) were selected. For example, local limestone was selected for the exterior (Figure 2). Reducing transportation requirements reduces emissions. While the extent of the carbon emission reduction is unknown, the use of local materials achieved at least some reduction in environmental impact. Further, material overhead for distant transportation of materials was avoided, logically reducing costs. The amount of that reduction is unknown and not estimated.

Figure 2. All construction materials were native.

3.1.3. Waste Collection and Recycling

During construction, bins for waste were used to recycle materials as appropriate (Figure 3). Doing so allowed for reclaimed wood to be reclaimed as engineered lumber and for used paper and metal to be recycled. While this has little to no bearing on cost, it does have an effect on the environment.

Figure 3. Bins established for paper / metal collection during construction

3.2. Engineered Lumber / Finger-Jointed Studs

Finger-jointed studs use reclaimed wood that might otherwise be discarded (Figure 4). 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].

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Figure 4. Finger-jointed stud used in the residence construction

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 2,000 square feet house would use 102 trees of that size [10]. Assuming linearity, the 4800 square feet home 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 1.

Table 1. 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

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.

The cost differential is not atypical, as many engineered lumber products have upcharges between 1.5 and 2 times the cost of traditional lumber [13]. HomeAdvisor estimates the total cost of traditional framing between $4 to $10 per square foot for labor and $3 to $6 per square foot for materials [14].

With a 30% reduction of 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 actually save money. Table 2 illustrates those combinations (2020 dollars)

Table 2. Regular lumbar versus finger-jointed studs at 1.54 and 0.70 times materials and labor, respectively

Regular Lumbar, $ / ft²		**Engineered Lumber, $ / ft²**		**4800 Sq. Ft.**
Materials	*Labor*	*Materials*	*Labor*	*Cost Savings*
3.00	10.00	4.62	7.00	6,624.00

3.00	9.00	4.62	6.30	5,184.00
4.00	10.00	6.16	7.00	4,032.00
3.00	8.00	4.62	5.60	3,744.00
4.00	9.00	6.16	6.30	2,592.00
3.00	7.00	4.62	4.90	2,304.00
5.00	10.00	7.70	7.00	1,440.00
4.00	8.00	6.16	5.60	1,152.00
3.00	6.00	4.62	4.20	864.00
5.00	9.00	7.70	6.30	-

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, non-traditional construction) results in comparative estimates of $52,800 (traditional) and $53,184 (non-traditional). The total difference in cost is estimated to be nominal. The total difference in environmental impact is not.

3.3. Spray Foam Insulation

Residential spray-foam insulation (Figure 5) provides a thermal barrier with exceedingly low conductivity (.021 W/mK in one study [15]). Spray foam has reasonable hygrothermal properties and is resistant to moisture migration; however, mechanical extraction and humidity controls were installed because of the tight environmental seal of the house and the requirement to exchange air. 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.

Figure 5. Open-cell spray-foam insulation

The 2020 cost for open-cell spray-foam insulation is about $.35 to $.55 per board foot. Assuming 3.5" depth of spray converts to $1.23 to $1.93 per square foot. Fiberglass batt insulation runs $.64 to $1.19 per square foot. Assuming average costs of $1.58 per square foot (spray-foam) and $.915 (fiberglass) with 6,000 square feet of attic and walls to be insulated results in cost estimates of $9,480 and $5,490, respectively [17].

The analysis above, however, is incomplete. 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. Inflating the estimated cost of $9,480 by 10% to account for all traditional construction requirements results in $10,428 for standard construction.

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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 .25 [18]. Further, the U factor, a factor that express 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 house (Figure 6).

Figure 6. Windows and doors must match environmental considerations

Low emissivity windows are 10 to 15% more expensive than standard windows [19]. The typical cost range in 2020 dollars is $385 to $785 with an average of $585 [20]. 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 [21]. Assuming average cost for Energy Star windows ($585), 15% cheaper traditional windows ($508.70), and a total of 25 windows results in acquisition costs of $14,625 (Energy Star) versus $12,717.50 (non-Energy Star). The $1,907.50 difference would be offset in about 6.5 years at the average $295 energy savings.

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, 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 an aquifer-draining well and the cost for a rainwater harvesting system would be nearly identical ($20,000). Rainwater harvesting was selected for both sustainability and quality considerations. From a sustainability perspective, RWH requires far less water for the same aquifer demand. Specifically, run-off, absorption / adsorption, and evaporation / transpiration reduce aquifer resupply by at least 30% [22]. On the other hand, RWH systems capture 75% to 90% of rainwater, depending on design and rainfall [23]. 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.

Figure 7 depicts the RWH as currently installed in the 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 (Figure 8). Once the ball float seals the flushing tube, the water continues into French drain and basket filters (Figure 9) and then into a cistern (Figure10). Parallel on-demand pumps (Figure 11) 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

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inactivating pathogens through irradiation [24]. The water is then used and exits to an aerobic septic system (not shown).

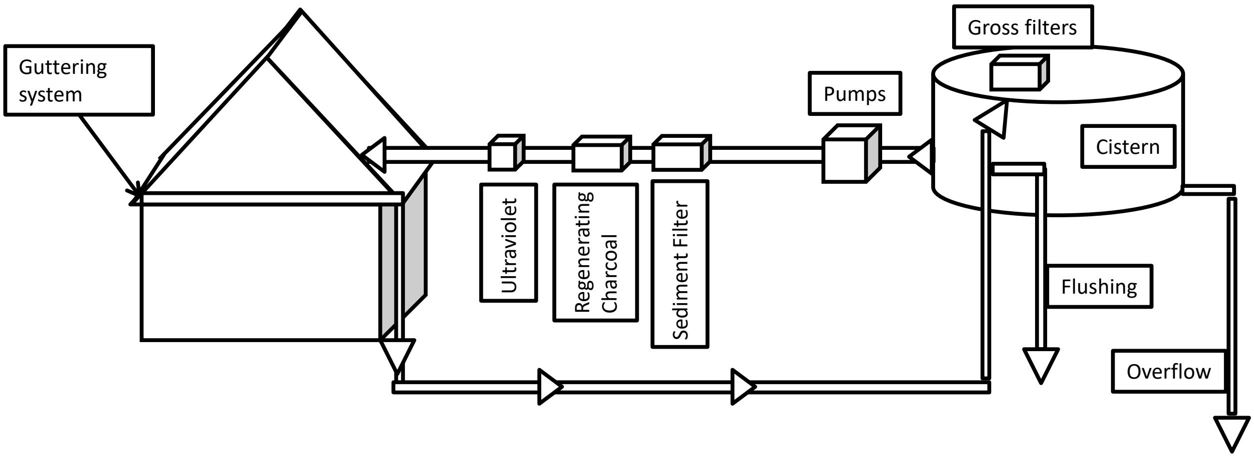

Figure 7. Rainwater harvesting system as designed

Figure 8. First flush system

Figure 9. French drain and basket filter location (inside the black tank lid)

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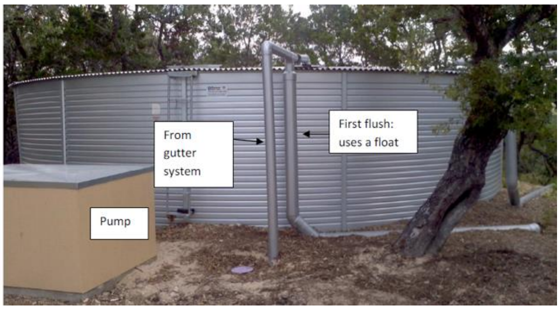

Figure 10. RWH components after installation

Figure 11. Parallel on-demand pumps

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). *The Texas Manual on Rainwater Harvesting* [23] provided the baseline quality construction requirements.

Figure 12. From right to left: sediment filter, charcoal regeneration, ultraviolet filter (spare tank in front)

Figure 13. Ultraviolet purification and example light

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 [5,25] . The final system selected included 4000 square feet of capture space and a 40,000 gallon cistern.

To date, the observed minimum in the tank (the order statistic of most importance) has been 75% by dipstick measurement. The system was over-engineered in a deliberate way. The homeowners estimate that with a full tank, they will retain water in the tank for approximately two years without any rainfall.

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 [26]. Current well drilling prices in Texas are $30 to $55 per foot [27]. On this property, a 600′ drilling depth is required. At the average $42.50 per foot, the drilling cost alone would run $25,500 now.

Cost to maintain the system has been reasonable. Ultraviolet tubes (replaced annually for typical use) as well as sediment filters and other system requirements cost approximately $100 per year. According to the Centers for Disease Control and Prevevntion, wells should also be inspected annually [28] at a cost of $300 to $500 per month [29]. The system is cost effective. Further, the water quality exceeds local and state requirements. Since it is soft, there is no residue when washing anything (Figure 14).

Figure 14. Water clarity and softness

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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 (see Figure 15), as the residence sought to sustain itself using only rainwater harvesting. Mayer et al. [30] 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 [31]. Costs for low flow fixtures are comparable to standard fixtures. There are no cost savings or increases.

Figure 15. Low flow (dual flush) toilet, installed

3.7 Aerobic Septic

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 owner 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 [32]. Figure 16 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.

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Figure 16. Biological Accelerated Treatment plant during installation

There is no cost benefit for installing such a system at this residence. Installing an anerobic system averages $3,500, whereas an aerobic costs about $10,500 [33]. Maintaining the aerobic septic system is about $200 annually [34], which is somewhat more than anaerobic systems [35]. There are, however, 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.

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 (see Figure 17). These water heaters take up less space and do not constantly use energy to keep water warm. 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. Tankless 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 [36].

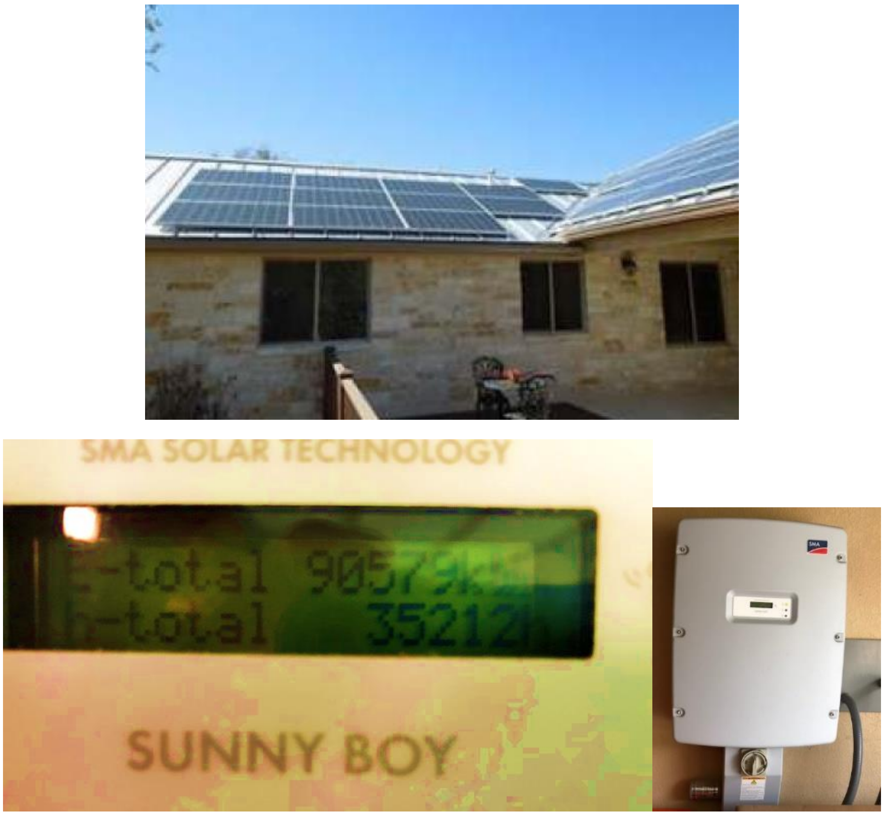
Figure 17. Rheem tankless water heater (image labeled and authorized for reuse)

Comparing the life-cycle of a 50-gallon electric water heater with that of a tankless requires some up-front assumptions. One study indicated that the life-cycle savings over traditional electric storage systems is $3,719 Australian dollars (about $2500 US dollars) [37]. 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 99% efficient [38].

The acquisition and installation costs for 2 x 50 gallon tank water heaters during initial construction was nearly $3,000. Under traditional grid power, the yearly costs are $494 per tank or just under $1000. For tankless water heaters under solar, the installation and acquisition costs are $3000 for two units (high end). There are zero annual costs.

3.9. Solar Arrays

In a sustainable home located in semi-arid regions, solar arrays are an obvious solution for producing energy requirements. This residence initially had installed a 7.25 kWh system (32 x 225 watt panels) with a Sunny Boy inverter ($33,600 in 2011, Figure 18) and then subsequently added another 9.585 kWh 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 approximately $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 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_2 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_2 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.



Part II **Residential Energy Efficient Property Credit** (See instructions before completing this part.)

Note. *Skip lines 15 through 25 if you only have a* ***credit carryforward from 2010.***

15	Qualified solar electric property costs	**15**	33,600.
16	Qualified solar water heating property costs	**16**	
17	Qualified small wind energy property costs	**17**	
18	Qualified geothermal heat pump property costs	**18**	26,500.
19	Add lines 15 through 18	**19**	60,100.
20	Multiply line 19 by 30% (.30)	**20**	18,030.

Figure 18. Initial 7kWh system (top left) with inverter (bottom left), total power production (upper right), and acquisition costs (lower right)

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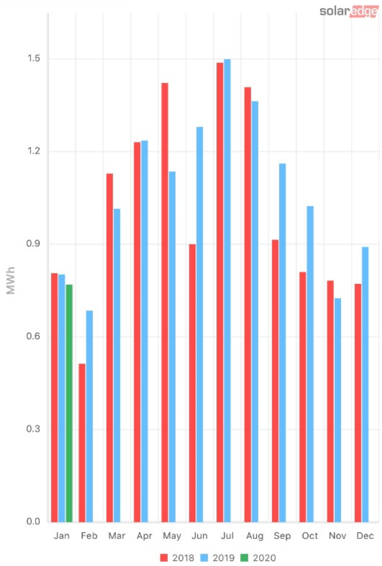

Item Code	Description	Price Each	Amount
Solar Installation	$31,317.00	31,317.00	31,317.00
	27 355 watt panels with optimizers		
	solar edge inverter		
	monitoring device to track electrical production from system		
	racking/labor and material to connect to main electrical		
	applicable permits		

Figure 19. 10 kWH SolarEdge system (top left) with inverter (bottom left), power production (upper right), and acquisition costs (lower right)

Initial break-even analysis is based on both acquisition cost and energy cost as if both systems were installed on the expanded house. Figure 20 illustrates the residence usage after power generation for a one-year period. During the six months of April through September, the residents produced or banked more power than consumed. From October through March, the resident consumed more power than produced. The $32.72 bill provided is a connection fee. During this month, the residents consumed 1699 kWh and produced only 1226 kWh. There is, however, no delivery or cost of power charge, as 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.

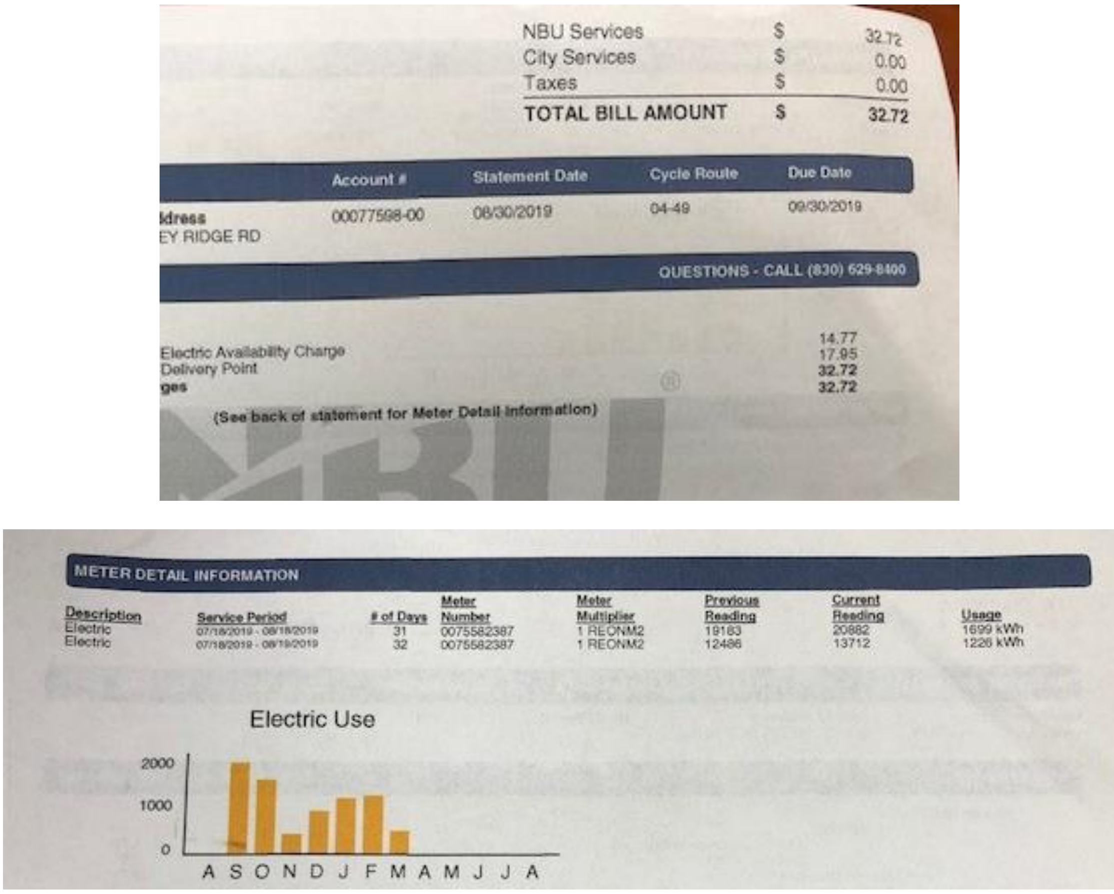

Figure 20. Electric bill, 9/30/2019 (both production, top, and consumption, bottom)

A non-solar house consuming 3500 kWh per month under traditional utility billing at $.07 per kWh with at $14.77 customer charge results in an annual estimated cost of $3,117.24 ($259.77 x 12). The same consumption with solar runs $498.00 ($33 x 6 months + $50 x 6 months). Residential electricity rates are anticipated to be fairly stable over time [39]. The break-even point for both systems is estimated to be about 17 years; however, this does not account for avoidance of automobile gasoline charges assuming the use of an electric car.

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 each); however, the residence location is a low-production wind area [40].

3.10. *Electric Car Charging*

Electricity generated from the solar panels was used to charge an electric Nissan Leaf (early adopter, see Figure 21). The gasoline avoidance in doing so was significant. Assuming equivalent acquisition costs for electric versus non-electric cars, a $100 avoidance in gasoline each month and holding all other variables constant, the net annual savings for solar would be $3,117.24 - - $702 = $3,819.24 for a break-even of 11.6 years. Unfortunately, early Nissan Leaf vehicles suffered from battery issues [41]. The owner divested after 3 years due to this issues as well as a change in employment location. 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.

Nissan Leaf ownership costs over 8 years are estimated to be $36,537.82 with total 8-year energy costs (kWh) at $3,969 [42]. When powered by solar that is 100% capable of producing both

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home and automobile power, there are no 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. Assuming a gasoline car experiences the average 13,476 miles driven per year (107,808 over 8 years), 30 miles per gallon, and $3.00 per gallon of gas (while ignoring maintenance costs) results in a fuel cost estimate of $10,780.80, which is 2.72 times that of the electric car option.

Figure 21. Nissan Leaf and final charging station

3.11. Geothermal Heating & Cooling

As part of the construction, the residence was equipped with a closed loop, geothermal system (see Figure 22). Vertical, closed-loop geothermal units are heat exchangers that leverage the fact the temperature 200' below the Earth remains relatively constant. The system operated with limited success for seven years, as the heat exchange and unit was unable to keep up with greater 100 degree F temperatures in its South Texas location. The cost of the system including wells, unit and ducting (complete) was $26,500. The tax credit 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) [43]. 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 and fully effective.

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Figure 22. Geothermal unit and vertical drilling of wells

3.11. Generator or Other Backup System

The residences have explored many options (from Tesla Powerwall to the Chinese BYD B-box 10) for retaining produced solar energy rather than feeding it back into the utility grid. All options are 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 [44].

Since the storage technology is still developing, the residents opted for a 22 kWh propane-powered back-up generator, a device sufficient to empower the entire house (Figure 23). Back-up power is necessary to retain water during electrical outages, as the house is still grid-tied. Propane is a green fuel that, when burned, has nominal effects on the environment [45]. The 1,000 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.

Figure 23. Generac 22 kWh whole-house generator and propane tank

3.12. *Overall Analysis*

Sustainable construction can generate a break-even for the pocketbook and for the environment. Figure 24 illustrates the cost comparisons of the sustainable construction techniques discussed in this paper. Costs are inflated based on BLS forecasts [46].

Looking at Figure 24, the breakeven for 2020 construction would be about 2026. The additional cost of sustainable construction is estimated at $54,733, which is much lower than might be expected due to the tax credits associated with solar and geothermal. The use of geothermal, though, was not effective, even after several modifications. Eliminating the geothermal in favor of high-seer heat pump would reduce the tax credit to $19,475 and the acquisition cost to $16,255. The cost of this sustainable construction is $52,438.

Appendix A is a 15-year net present value analysis (NPV) assuming cost of capital is 5%. This analysis suggests a $160,222 savings for sustainable construction with geothermal and a $186,338 savings without geothermal. Total estimated costs are $(2,278,943), ($2,118,721), and $(2,092,604) for traditional, sustainable with geothermal, and sustainable without geothermal, respectively.

If the residents were to begin the construction process all over, every sustainable element would be included except for geothermal. The expansion of the number of solar panels would have been completed when first built in preparation for expansion. Additional considerations for lead-acid batteries, powerwalls, etc. would be included as part of the process.

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	BLS Inflation	*0.03*	*0.03*	*0.03*	*0.03*	*0.03*	*0.03*
Traditional House & Car	**2020**	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**
Lumber	$ (52,800)	$ -	$ -	$ -	$ -	$ -	$ -
Insulation / Vents	$ (10,428)	$ -	$ -	$ -	$ -	$ -	$ -
Windows	$ (12,718)	$ -	$ -	$ -	$ -	$ -	$ -
Well Water	$ (25,500)	$ (400)	$ (412)	$ (424)	$ (437)	$ (450)	$ (464)
Electricity (100%)	$ -	$ (3,117)	$ (3,211)	$ (3,307)	$ (3,406)	$ (3,508)	$ (3,614)
Gas for Car	$ (1,348)	$ (1,348)	$ (1,388)	$ (1,430)	$ (1,473)	$ (1,517)	$ (1,562)
Anaerobic Septic	$ (3,500)	$ (150)	$ (155)	$ (159)	$ (164)	$ (169)	$ (174)
2 x H20 Tank	$ (3,000)	$ (1,000)	$ (1,030)	$ (1,061)	$ (1,093)	$ (1,126)	$ (1,159)
Heat Pump	$ (16,255)	$ (4,169)	$ (4,294)	$ (4,423)	$ (4,556)	$ (4,692)	$ (4,833)
Tax Credits	$ -	$ -	$ -	$ -	$ -	$ -	$ -
Net Cash Flows	$ (125,548)	$ (10,184)	$ (10,489)	$ (10,804)	$ (11,128)	$ (11,462)	$ (11,806)
Cumulative Cash Flow	$ (125,548)	$(135,732)	$(146,221)	$(157,025)	$(168,153)	$(179,615)	$(191,421)
With Geothermal	**Acquisition**						
Sustainable House & Car	**2020**	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**
Engineered Lumber	$ (53,184)	$ -	$ -	$ -	$ -	$ -	$ -
Spray Foam	$ (9,480)	$ -	$ -	$ -	$ -	$ -	$ -
Energy Star Windows*	$ (14,625)	$ -	$ -	$ -	$ -	$ -	$ -
H20 Harvesting	$ (25,500)	$ (100)	$ (103)	$ (106)	$ (109)	$ (113)	$ (116)
Solar (100%)+Electric	$ (64,917)	$ (498)	$ (513)	$ (528)	$ (544)	$ (561)	$ (577)
Electric Car Gas		$ -	$ -	$ -	$ -	$ -	$ -
Aerobic Septic	$ (10,500)	$ (200)	$ (206)	$ (212)	$ (219)	$ (225)	$ (232)
2 x Tankless on Solar	$ (3,000)	$ -	$ -	$ -	$ -	$ -	$ -
Geothermal**	$ (26,500)						
Tax Credits	$ 27,425		$ -	$ -	$ -	$ -	$ -
Net Cash Flows	$ (180,281)	$ (798)	$ (822)	$ (847)	$ (872)	$ (898)	$ (925)
Cumulative Cash Flow	$ (180,281)	$(181,079)	$(181,901)	$(182,747)	$(183,619)	$(184,518)	$(185,443)
Without Geothermal	**Acquisition**						
Sustainable House & Car	**2020**	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**
Engineered Lumber	$ (53,184)	$ -	$ -	$ -	$ -	$ -	$ -
Spray Foam	$ (9,480)	$ -	$ -	$ -	$ -	$ -	$ -
Energy Star Windows*	$ (14,625)	$ -	$ -	$ -	$ -	$ -	$ -
H20 Harvesting	$ (25,500)	$ (100)	$ (103)	$ (106)	$ (109)	$ (113)	$ (116)
Solar (100%)+Electric	$ (64,917)	$ (498)	$ (513)	$ (528)	$ (544)	$ (561)	$ (577)
Electric Car Gas		$ -	$ -	$ -	$ -	$ -	$ -
Aerobic Septic	$ (10,500)	$ (200)	$ (206)	$ (212)	$ (219)	$ (225)	$ (232)
2 x Tankless on Solar	$ (3,000)	$ -	$ -	$ -	$ -	$ -	$ -
Heat Pump	$ (16,255)						
Tax Credits	$ 19,475		$ -	$ -	$ -	$ -	$ -
Net Cash Flows	$ (177,986)	$ (798)	$ (822)	$ (847)	$ (872)	$ (898)	$ (925)
Cumulative Cash Flow	$ (177,986)	$(178,784)	$(179,606)	$(180,452)	$(181,324)	$(182,223)	$(183,148)
*savings in use of solar electric							
**ineffective							

Figure 24. Color-coded break-even analysis

3.13. Ongoing Sustainable Improvements

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 [47]. 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.

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Figure 25. Mini-split units, in wall and in roof

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.

4. Discussion

The results show that building a sustainable house can be green for the environment and green for the pocketbook. The initial up-front costs may be quickly offset by savings depending on construction options. In the case study here, only seven years were required for break-even. Aside from the economic considerations, the environmental responsibility issues are clear. Avoiding carbon emissions is responsible construction.

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 [48]. 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 [49]. 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.

5. Conclusions

The study focuses on individual economics and technical components of constructing a net zero family home. The individual commitment and passion implies 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.

This green building study and analysis demonstrate attention to cultural vitality and continuity [50]. The researcher created a home to adapt to changing climate and energy structures and created this home to adapt to future energy structures. For example, he attended to the rugged nature of the Texas hill-country geography through inclusion of solar panels, aerobic septic system, and water collection. In addition, the researcher through his personal selection and design attended to aesthetic and creative features of the green dwelling. The home in the current study inspires other citizens in the community to commit to a culture of sustainability.

The individual "green" family dwelling described in the study represents a family's lifestyle, memories, and place of being [50]. In this culture of family being and identity, the green home incorporates a spirit of the natural beauty of the Texas Hill Country, including a minimalistic design. Because the family was involved in the construction, the family has had the opportunity to adapt and be empowered in leading in change relative to sustainable living. A story exists in the needs, learning, adaptation, and success of each "green" family, living in each "green" home. An opportunity exists for future studies to incorporate behavioral assessments and tips for multiple "green" families and businesses.

To develop a culture of sustainability, the beliefs, assumptions, and philosophies must become embedded in many citizens so that as a society, we collectively own green construction, learning, adaptation, and living. Construction best practices and green living must be perpetuated and owned collectively to make a global impact on reducing our footprint and increasing our sustained living on our planet.

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Appendix A

	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
Traditional House & Car	**2020**	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**	**2031**	**2032**	**2033**	**2034**	**2035**
Lumber	$ (52,800)	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
Insulation / Vents	$ (10,428)	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
Windows	$ (12,718)	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
Well Water	$ (25,500)	$ (315)	$ (324)	$ (334)	$ (344)	$ (355)	$ (365)	$ (376)	$ (387)	$ (399)	$ (411)	$ (423)	$ (436)	$ (449)	$ (463)	$ (476)
Electricity (100%)	$ -	$ (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)
Gas for Car	$ (1,348)	$ (1,348)	$ (1,388)	$ (1,430)	$ (1,473)	$ (1,517)	$ (1,562)	$ (1,609)	$ (1,657)	$ (1,707)	$ (1,758)	$ (1,811)	$ (1,865)	$ (1,921)	$ (1,979)	$ (2,038)
Anaerobic Septic	$ (3,500)	$ (150)	$ (155)	$ (159)	$ (164)	$ (169)	$ (174)	$ (179)	$ (184)	$ (190)	$ (196)	$ (202)	$ (208)	$ (214)	$ (220)	$ (227)
2 x H20 Tank	$ (3,000)	$ (1,000)	$ (1,030)	$ (1,061)	$ (1,093)	$ (1,126)	$ (1,159)	$ (1,194)	$ (1,230)	$ (1,267)	$ (1,305)	$ (1,344)	$ (1,384)	$ (1,426)	$ (1,469)	$ (1,513)
Heat Pump	$ (16,255)	$ (4,169)	$ (4,294)	$ (4,423)	$ (4,556)	$ (4,692)	$ (4,833)	$ (4,978)	$ (5,127)	$ (5,281)	$ (5,440)	$ (5,603)	$ (5,771)	$ (5,944)	$ (6,122)	$ (6,306)
Tax Credits	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
Net Cash Flows	$ (125,548)	$ (10,099)	$ (10,402)	$ (10,714)	$ (11,035)	$ (11,366)	$ (11,707)	$ (12,059)	$ (12,420)	$ (12,793)	$ (13,177)	$ (13,572)	$ (13,979)	$ (14,399)	$ (14,830)	$ (15,275)
Cumulative Cash Flow	$ (125,548)	$ (135,647)	$ (146,049)	$ (156,763)	$ (167,798)	$ (179,164)	$ (190,872)	$ (202,930)	$ (215,350)	$ (228,143)	$ (241,320)	$ (254,892)	$ (268,871)	$ (283,270)	$ (298,100)	$ (313,376)
	$ (2,278,943)	NPV @ 5% assumed cost of capital														

With Geothermal	Acquisition															
Sustainable House & Car	**2020**	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**	**2031**	**2032**	**2033**	**2034**	**2035**
Engineered Lumber	$ (53,184)	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
Spray Foam	$ (9,480)	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
Energy Star Windows*	$ (14,625)	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
H20 Harvesting	$ (25,500)	$ (100)	$ (103)	$ (106)	$ (109)	$ (113)	$ (116)	$ (119)	$ (123)	$ (127)	$ (130)	$ (134)	$ (138)	$ (143)	$ (147)	$ (151)
Solar (100%)+Electric	$ (64,917)	$ (498)	$ (513)	$ (528)	$ (544)	$ (561)	$ (577)	$ (595)	$ (612)	$ (631)	$ (650)	$ (669)	$ (689)	$ (710)	$ (731)	$ (753)
Electric Car Gas		$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
Aerobic Septic	$ (10,500)	$ (200)	$ (206)	$ (212)	$ (219)	$ (225)	$ (232)	$ (239)	$ (246)	$ (253)	$ (261)	$ (269)	$ (277)	$ (285)	$ (294)	$ (303)
2 x Tankless on Solar	$ (3,000)	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
Geothermal**	$ (26,500)															
Tax Credits	$ 27,425		$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
Net Cash Flows	$ (180,281)	$ (798)	$ (822)	$ (847)	$ (872)	$ (898)	$ (925)	$ (953)	$ (981)	$ (1,011)	$ (1,041)	$ (1,072)	$ (1,105)	$ (1,138)	$ (1,172)	$ (1,207)
Cumulative Cash Flow	$ (180,281)	$ (181,079)	$ (181,901)	$ (182,747)	$ (183,619)	$ (184,518)	$ (185,443)	$ (186,396)	$ (187,377)	$ (188,388)	$ (189,429)	$ (190,502)	$ (191,606)	$ (192,744)	$ (193,916)	$ (195,123)
	$ (2,118,721)	NPV @ 5% assumed cost of capital														

Without Geothermal	Acquisition															
Sustainable House & Car	**2020**	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**	**2031**	**2032**	**2033**	**2034**	**2035**
Engineered Lumber	$ (53,184)	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
Spray Foam	$ (9,480)	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
Energy Star Windows*	$ (14,625)	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
H20 Harvesting	$ (25,500)	$ (100)	$ (103)	$ (106)	$ (109)	$ (113)	$ (116)	$ (119)	$ (123)	$ (127)	$ (130)	$ (134)	$ (138)	$ (143)	$ (147)	$ (151)
Solar (100%)+Electric	$ (64,917)	$ (498)	$ (513)	$ (528)	$ (544)	$ (561)	$ (577)	$ (595)	$ (612)	$ (631)	$ (650)	$ (669)	$ (689)	$ (710)	$ (731)	$ (753)
Electric Car Gas		$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
Aerobic Septic	$ (10,500)	$ (200)	$ (206)	$ (212)	$ (219)	$ (225)	$ (232)	$ (239)	$ (246)	$ (253)	$ (261)	$ (269)	$ (277)	$ (285)	$ (294)	$ (303)
2 x Tankless on Solar	$ (3,000)	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
Heat Pump	$ (16,255)															
Tax Credits	$ 19,475		$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
Net Cash Flows	$ (177,986)	$ (798)	$ (822)	$ (847)	$ (872)	$ (898)	$ (925)	$ (953)	$ (981)	$ (1,011)	$ (1,041)	$ (1,072)	$ (1,105)	$ (1,138)	$ (1,172)	$ (1,207)
Cumulative Cash Flow	$ (177,986)	$ (178,784)	$ (179,606)	$ (180,452)	$ (181,324)	$ (182,223)	$ (183,148)	$ (184,101)	$ (185,082)	$ (186,093)	$ (187,134)	$ (188,207)	$ (189,311)	$ (190,449)	$ (191,621)	$ (192,828)
*savings in use of solar electric																
**ineffective	$ (2,092,604)	NPV @ 5% assumed cost of capital														

	$ (2,278,943)	NPV Traditional		
	$ (2,118,721)	NPV Sustainable w/Geothermal	$ 160,222	PV Difference (Traditional - NPV Sustainable w/Geothermal)
	$ (2,092,604)	NPV Sustainable w/out Geothermal	$ 186,338	PV Difference (Traditional - NPV Sustainable wout/Geothermal)

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