ISE 662 – Final Paper
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Balancing Sustainability and Economics: A Multi-Criteria Decision Analysis of Residential Alternatives in Saudi Arabia

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1.0 Abstract:

The escalating demand for energy and water resources in Riyadh, Saudi Arabia, necessitates the exploration of sustainable construction alternatives for residential buildings. This study employs a decision theory approach to evaluate the economic, social acceptance, and environmental viability of six sustainable construction alternatives, comparing them to basic construction methods. The overarching aim is to improve the quality of life, conserve resources, and mitigate environmental impacts. The alternatives analyzed are A1 (basic construction methods), A2 (spray foam insulation), A3 (Fiberglass batts), A4 (Rooftop solar panels), A5 (Solar water heaters), A6 (low-flow fixtures), and A7 (Greywater recycling systems).

A cost-benefit analysis, multi-attribute utility analysis, and sensitivity analysis were conducted to assess the alternatives based on various objectives such as quality of life, convenience, sustainability, and economic criteria. The Multi-Attribute Utility (MAU) model focused on factors like house appearance, maintenance, noise reduction, space utilization, and eco-friendliness.

Net Present Value (NPV) analysis was utilized to evaluate the economic feasibility of each alternative over 10 and 20-year timeframes, using tariff prices in Saudi Arabia and California as benchmarks. The analysis incorporated infrastructure costs, operational costs, savings in US dollars, and resale value.

The results showed that A3 (Fiberglass batts) and A5 (Solar water heaters) had positive NPVs in the short term with KSA tariffs, while A2 (Spray foam insulation) exhibited the highest NPV for long-term savings or under higher tariff costs. The study emphasized the importance of considering multiple criteria when selecting sustainable residential alternatives, as the dominance of alternatives varies based on the weight assigned to different factors. The developed MAU model empowers stakeholders to effectively evaluate residential alternatives, considering various objectives that contribute to quality of life, convenience, and sustainability.

In conclusion, households should consider multiple objectives to make better-informed decisions and policymakers should promote the adoption of sustainability alternatives by balancing incentives between tariff prices and offering incentives to reduce the investment costs of sustainable systems.

2.0 Introduction & Background:

Rapid urbanization and population growth in Riyadh, Saudi Arabia, have led to a significant increase in the demand for energy and water resources within the residential sector [1]. This heightened resource consumption has raised concerns about sustainability, environmental impact, and the need for efficient resource management. In response, Saudi Arabia has launched several initiatives addressing environmental protection, sustainability, and climate change. As a result, the adoption of sustainable construction methods and technologies for residential buildings has emerged as a potential solution to alleviate these challenges [2]. Implementing these initiatives and agreements requires economic and social transformation, emphasizing the need to understand the importance of sustainability, the ways to achieve sustainable development, and the economic and social objectives associated with households' decisions to transition towards greater sustainability.

This study aims to develop a decision analysis framework to evaluate sustainable construction alternatives for households in Riyadh. Factors considered in the analysis include the economic aspects by addressing infrastructure, operational costs, and resale (salvage) value for alternatives to calculate the net present value (NPV). Additionally, qualitative measures were analyzed to address objectives that focus on added value to the quality of life. The goal is to support informed decision-making for new home construction.

3.0 Literature Review:

3.1- Importance of Sustainability

Sustainability is essential for several reasons. It enhances the quality of life, promotes healthier environments, and conserves natural resources. When managed effectively, sustainability fosters an economically efficient system that satisfies present needs without compromising future generations' ability to meet their own requirements [3].

3.2- Population Growth and Sustainability

The challenges posed by global population growth underscore the importance of sustainability. Saudi Arabia experiences a high average population growth rate of 1.6%, while the international growth rate hovers around 1% [4,5]. This population growth inevitably leads to an increasing demand for food, water, and energy supplies, emphasizing the need to pursue sustainable development to fulfill these demands.

3.3- Sustainable Development in the GCC Region

Achieving sustainable development necessitates a comprehensive understanding of the interdependencies between food, water, and energy resources. The Middle East, and particularly the GCC countries, possess significant solar potential but limited water resources. Consequently, it is worth examining whether constructing water-efficient systems to address water scarcity would be more advantageous than capitalizing on the region's solar potential. Table 1 in appendix presents the Food, Water, Energy index for GCC countries, with average scores of 0.64, 0.9, and 0.2 for the Food Sub-index, Energy Sub-index, and Water Sub-index, respectively. This data highlights the region's abundant energy potential and limited water resources. Additionally, Table 2 compares the total renewable water resources per capita in Saudi Arabia, United States, Egypt, China, and France, illustrating the stark contrast in available water resources among these countries.

Country	Total renewable water resources per capita (m3/inhab/year)
United States of America	2,71.83 E
China	3,232.55 E

France	1,930.43 E
Egypt	561.88 E
Saudi Arabia	68.94 E
United Arab Emirates	15.17 E

Table 2: Total Renewable Water Resources/ Capita in 2020. AQUASTAT Database - FAO, accessed in April 2023[8].

3.4- The Importance of Focusing on Buildings' Sustainability

Buildings are considered the largest consumers of natural resources, according to the US Green Building Council [9]. Additionally, the sustainability of buildings has significant social, environmental, and economic impacts. For instance, in the United States, buildings account for 39% of total energy use, 68% of total electricity consumption, 12% of total water consumption, and 38% of carbon dioxide emissions [10]. Similarly, in Saudi Arabia, buildings account for 49% of total energy use and 80% of total electricity consumption [11].

Implementing alternatives such as energy-efficient construction (insulation systems), water-efficient construction (greywater systems and low-flow fixtures), and solar energy systems (rooftop solar panels and solar water heaters) can contribute to the development of sustainable, energy-efficient, and cost-effective buildings. The market for these systems in Saudi Arabia has been expanding significantly, but primarily in large-scale projects rather than residential applications. This raises the question: is integrating water-efficient construction or solar energy systems in residential buildings (homes) cost-effective? What other objectives contribute to the decision-making process of households when considering constructing a new home?

This paper will explore the opportunities and challenges in achieving urban sustainability through the development of sustainable buildings in the Middle East region. In doing so, this study employs a decision theory approach to evaluate the economic and environmental viability of six sustainable construction alternatives, comparing them to basic construction methods.

3.5- Residential Building Demand and Household Statistics in Saudi Arabia

To comprehend the demand for residential buildings in Saudi Arabia, it is essential to examine relevant household statistics. According to the General Authority for Statistics in Saudi Arabia, the average household size was estimated to be 5.5 persons per household in 2021 [29]. The average residential water and electricity consumption per person was reported to be approximately 300 liters per day and 9,000 kWh per year, respectively [30, 31]. Moreover, although the average size of a residential plot may vary depending on various factors, a study by Al Garni and Awasthi (2017) determined that the average size of a residential plot in Riyadh, is approximately 600 square meters [32]. Table 6 provides a summary of key statistics related to households in Saudi Arabia.

Statistics	
Average household size	5.5 persons/ household
Average residential water consumption per person	300 liters/day

Average residential electricity consumption per person	9000 kWh per year
Average size of a residential plot in Riyadh	600 square meters

Table 3: Residential Building Demand and Household Statistics in Saudi Arabia [29, 30, 31, 32]

4.0 Analysis Framework & Methodology:

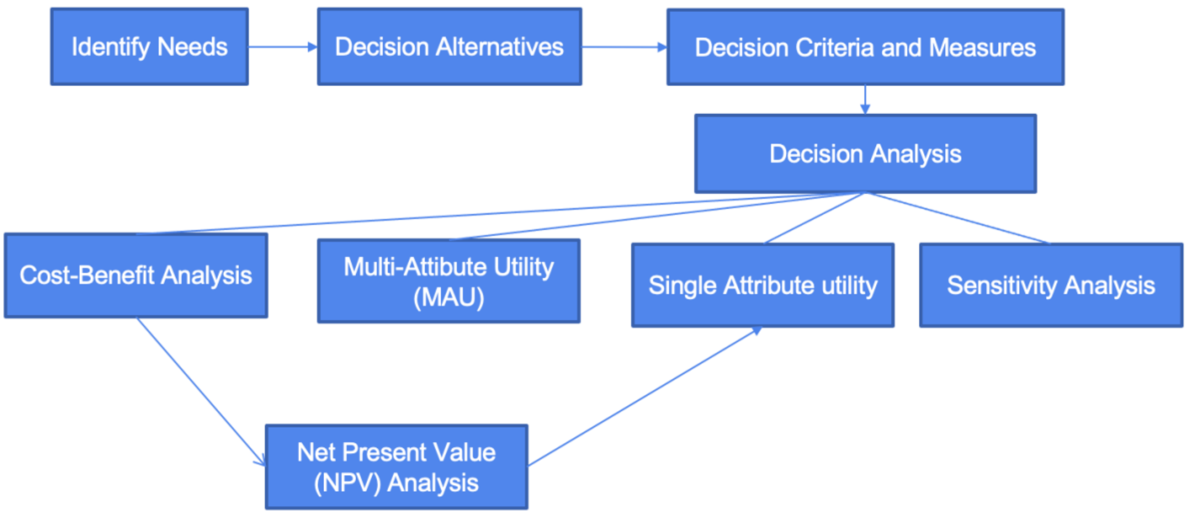

Figure 1: Analysis framework and methodology.

The analysis framework for this paper consists of several steps, as illustrated in Figure 1. First, identifying the needs, problem statement, and opportunities for improvement. Next, various decision alternatives were explored, studied, and designed to address these needs. Subsequently, decision criteria and measures were established to evaluate the alternatives. These criteria are then analyzed to develop Multi-Attribute Utility (MAU), Single Attribute Utility (SAU), and Sensitivity Analysis tools, which can assist households in Riyadh in making informed decisions. Throughout the process of analyzing the problem, the decision alternatives, criteria, and measures are continuously refined and improved through an extensive literature review that supports the assumptions used in the development of the decision analysis tools.

5.0 Analysis:

5.1- Economic Impact Analysis:

The economic impact analysis plays a crucial role in assessing the viability of the seven sustainable construction alternatives for residential buildings in Riyadh. This section presents the figures and calculations used to evaluate the economic criteria of each alternative.

5.1.1- Energy Consumption in Saudi Arabia and the USA

- Figure 2 showcases the total energy consumption in Saudi Arabia from 2010 to 2020, providing insights into the national energy landscape and its evolution over the years.

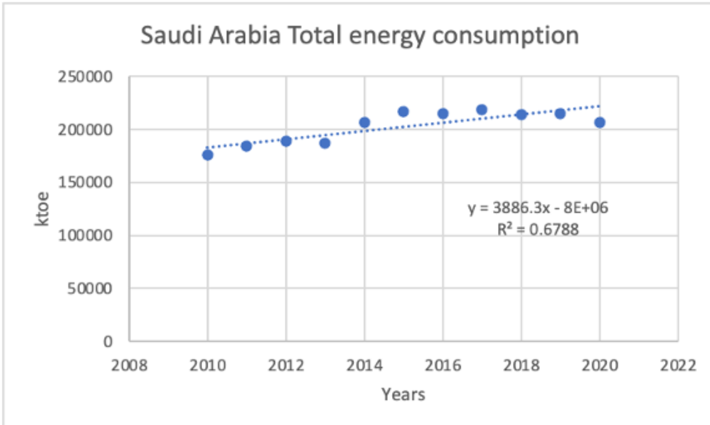

Figure 2: Saudi Arabia total energy consumption. Data source: [33], Analysis: Waleed Alhayaza

- Figure 3 displays the average retail electricity prices in the United States of America from 2015 to 2021, which serves as an international benchmark for comparison.

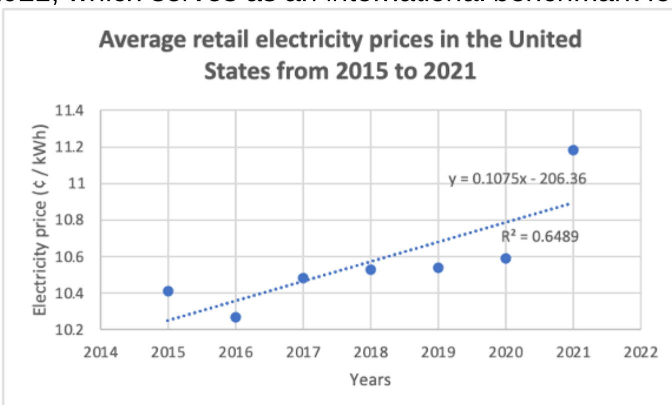

Figure 3: Avg. retail electricity prices in the USA. Data source: [34] , Analysis: Waleed Alhayaza

5.1.2- Solar Energy Potential in Riyadh.

- Figure 4 illustrates the estimated solar energy potential in Riyadh for 6 kW and 10 kW systems, emphasizing the region's solar energy capacity and potential benefits.

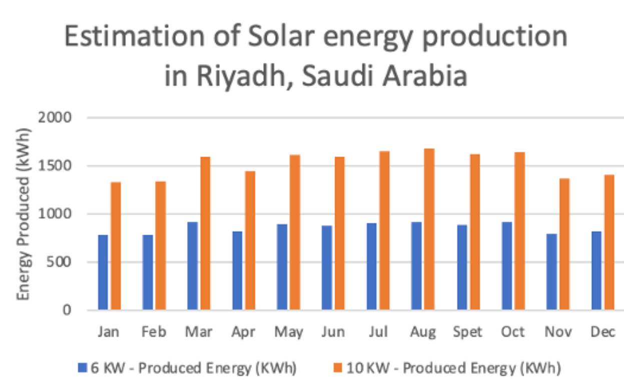

Figure 4: Estimation of the solar energy potential in Riyadh. Data source: " [33], Analysis: Waleed Alhayaza

5.2- Decision Criteria for Sustainable Home Construction

In the context of sustainable home construction, household owners in Riyadh need to consider a variety of decision criteria to ensure a balance between economic, quality of life, and sustainability aspects. Table 6 illustrates the key decision criteria, which are further elaborated below:

A- **Economic Decision Criterion:** To address the economic decision criterion the Net Present Value (NPV) was calculated for each alternative. NPV calculations are a crucial financial indicator that allows homeowners to evaluate the profitability of their investment over time. It takes into account factors such as infrastructure cost, operational cost, and resale value (salvage value), helping owners make well-informed decisions on sustainable construction alternatives.

B- **Quality of Life Criteria:** House appearance, space utilization, and noise level play significant roles in the decision making process as they focus on providing a comfortable living environment. Scores for noise level compared the impact on noise level if any.

C- **Convenience Criteria:** The ease and frequency of required maintenance are crucial factors in determining the long-term feasibility and cost-effectiveness of different construction methods. However, beyond maintenance costs, homeowners should consider the inconvenience associated with the maintenance process.

D- **Sustainability Criteria:** Eco-friendly alternatives that address water, energy, carbon footprint, and waste management concerns are vital in promoting sustainable home construction. To preserve the environment homeowners should prioritize solutions that contribute to resource conservation, reduced emissions, and effective waste management practices.

Decision Criteria	Measures
1. Economic criteria:	
1.1 Net Present Value (NPV)	SAR/ $US
2. Quality of life criteria:	
2.1 House appearance.	Constructed
2.2 Space Utilization.	Square meters
2.3 Noise reduction.	Constructed
3. Convenience:	
3.1 Ease and frequency of required maintenance.	Constructed
4. Sustainable:	
3.1 Eco Friendly	Constructed (yes/ no)

Table 6: Objectives (Decision Criteria) & their corresponding measures.

By considering these decision criteria, household owners in Riyadh can make better informed decisions that support sustainable home construction while balancing economic, quality of life, and environmental factors.

5.2.1- Evaluating Alternatives Using Decision Criteria Scores:

The studied alternatives were analyzed and assigned scores ranging from 0 to 5 to assess their impact on quality of life, specifically in terms of space utilization, noise reduction, and house appearance. Moreover, the convenience criteria were addressed by examining the ease and frequency of required maintenance for each alternative. Lastly, the sustainability criteria were evaluated using a binary (yes/no) criterion to determine whether the alternative is eco-friendly or not.

To assess noise reduction, the alternatives were studied for their contributions to mitigating noise transmission. As a result, A1: basic construction methods received a score of 0 due to high noise levels transmitted through walls. In contrast, A2: spray foam insulation received a score of 5 because it significantly reduces noise transmission. A3: Fiberglass batts were given a score of 3, as they also reduce noise transmission through walls but with a less substantial impact compared to A2. Lastly, A4: rooftop solar panels (10KW), A5: solar water heaters, A6: low-flow fixtures, and A7: greywater systems each received a score of 5, as they neither generate nor contribute to noise compared to the other alternatives.

Regarding space utilization criteria and house appearance, it is essential to consider building codes, exterior design, and local architectural styles. For instance, flat-roofed houses with roof access are a prevalent architectural style in Saudi Arabia, while gable-roofed houses are less common. This factor can impact space utilization, as solar panels installed on flat-roofed houses may occupy accessible roof space that could be utilized differently. Figures 5 and 6 in the appendix show examples of residential architectural styles in Saudi Arabia compared to the sustainable city in Dubai to assess the impact with and without solar panels.

For the space utilization criteria, A1: basic construction methods received a score of 4 as it does not incorporate any additional space-saving features. Alternatives A2: spray foam insulation and A3: fiberglass insulation scored 5, as they require minimal space for installation. Conversely, A4: rooftop solar panels and A5: solar water heaters scored 3 and 4, respectively, as they occupy roof space. Finally, A6: low-flow fixtures and A7: greywater systems received scores of 5 and 4, respectively, as they need minimal installation space and the greywater system can be installed in less-utilized areas like basements or garages.

House appearance criteria is a qualitative measure that varies between stakeholders. For instance, some may consider the presence of solar panels as a symbol of sustainability and give it a high rating. Others may prioritize the house's exterior appearance and aesthetic appeal. To address these varying perspectives, a separate criterion was created for sustainability, and house appearance scores were assigned based on whether the system could alter the exterior appearance and potentially impact the house's aesthetic appeal. Therefore, Alternatives A1: basic construction methods, A2: spray foam insulation, A3: fiberglass insulation, A6: low-flow fixtures, and A7: greywater systems scored 5 as they do not affect the exterior appearance. On the other hand, A4: rooftop solar panels and A5: solar water heaters scored 3 as they both alter the exterior appearance of the house.

For ease and frequency criteria scores, the weather and environment in Riyadh, Saudi Arabia were taken into consideration. A1: basic construction methods received a score of 3, as moderate maintenance is needed due to the high demand for air conditioning systems. Alternatives A2: spray foam insulation, A3: fiberglass insulation, A6: low-flow fixtures, and A7: greywater systems scored 5, as they seldom require maintenance. Finally, A4: rooftop solar panels and A5: solar water heaters scored 2, as they necessitate occasional maintenance and cleaning, especially in light of frequent dust storms in the region.

Lastly, the sustainability criteria assigned a score of 5 to all eco-friendly alternatives (A2-A7) and a score of 0 to the non-eco-friendly alternative A1: basic construction methods. Table 7 summarizes the scores for the alternatives and the objectives.

		Alternatives						
Objectives								
Benefit	**Measures**	**A1: Basic construction**	**A2: Spray foam insulation**	**A3: Fiberglass batts**	**A4: Rooftop solar panels**	**A5: Solar water heaters (400-liter system).**	**A6: Low-flow fixtures**	**A7: Greywater recyclying systems**
House Appearance	Constructed	5	5	5	3	3	5	5
Ease & frequency of **Maintenance**	Constructed	3	5	5	2	4	5	4
Noise Reduction	Constructed	0	5	3	5	5	5	5
Space utlization	Constructed (inches)	4	5	5	3	4	5	4
Eco friendly	Constructed (yes/ no)	0	5	5	5	5	5	5

Table 7: Objectives and associated scores for each alternative.

In summary, the evaluation of alternative scores within the decision criteria offers valuable insights into the strengths and weaknesses of each option with regard to quality of life, convenience, and sustainability. These scores empower stakeholders to better comprehend their objectives and the benefits of each alternative, facilitating informed decision-making when selecting sustainable home construction methods that best align with their priorities and preferences. In the following analysis, the weighted utility for each alternative will be assessed and compared, incorporating the Net Present Value (NPV) factor as an additional consideration.

5.3- Net Present Value (NPV) Analysis

To address the economic decision criteria for each alternative, the NPV analysis was conducted. The calculations for each alternative took into account the following factors:

- **Infrastructure costs:** The initial investment required for the installation and setup.
- **Operational costs:** The ongoing expenses associated with maintaining and operating.
- **Savings:** The amount of energy produced in kWh or water saved in m^3, which was multiplied by corresponding tariff prices for electricity and water utilities to calculate the savings in dollars.
- Resale (**Salvage**) Value: The potential resale value for alternatives that can be resold, such as rooftop solar panels and solar water heaters, calculated by incorporating the degradation in performance rate and its impact on the original price. However, alternatives such as greywater system and low-flow fixtures, the systems cannot be resold as they would be integrated in the system, yet they have an overall positive impact on the resale value of the real state (house).

By analyzing the economic impact and calculating the NPV for each sustainable construction alternative, household owners in Riyadh can make informed decisions that take into account both the short-term and long-term financial implications of their choices.

Assumptions:
Building upon the Saudi household statistics presented in the literature review, the following assumptions were used for the calculations: The average residential water and electricity consumption per person is 300 liters/day and 9,000 kWh per year. The average household size is six persons, but ten residents were assumed targeting larger household sizes. Furthermore, based on literature, the average size of a residential plot in Riyadh is 600 square meters [32].

5.3.1- Infrastructure and Operational Costs of Alternatives

Table 8 presents the calculated infrastructure costs for the seven alternatives based on the literature review. The basic construction methods serve as the baseline, having the lowest initial investment cost. However, they also have the highest operational costs due to high energy consumption, particularly in extreme weather conditions such as the hot climate of Riyadh.

Understanding buildings' energy sustainability requires analyzing the energy flow and load distribution. In Saudi Arabia, approximately 52% of the produced electricity is consumed by cooling systems [34]. Consequently, utilizing insulation can significantly enhance energy efficiency and thermal performance in residential buildings. Research by the International Energy Agency suggests that insulation could reduce energy consumption for cooling by 20% to 40%, depending on the type of system used [22].

In this research paper seven two insulation systems were considered: Spray foam insulation, a higher-cost and more efficient material, and fiberglass batts, a lower-cost, less efficient material. The average infrastructure cost and average energy savings for each system were $30 per square meter and $10 per square meter, with 40% and 20% savings in total energy consumption, respectively. For a 600 square meter house, the infrastructure cost for each system would be $17,760 USD (66,600 SAR) for spray foam insulation and $6,456 USD (24,210 SAR) for fiberglass batts. These costs are in line with a report by the International Energy Agency (2013), which estimated that the incremental costs for energy-efficient construction in the Middle East ranged from 5% to 15% of the total construction cost [22].

The infrastructure cost for rooftop solar panels was determined based on a study by Alawaji, which reported that the average cost of installing solar photovoltaic (PV) systems in Saudi Arabia ranged from SAR 6.8 to SAR 9.1 per watt (USD 1.81 to USD 2.43 per watt) in 2018 [23]. Accordingly, the installation costs for 6 kW and 10 kW solar panels would be around SAR 55,000 ($15,000) and SAR 91,000 ($25,000), respectively. The average cost for installing a 10 kW system in Saudi Arabia is higher than the average cost in the United States by approximately $4,000. This was calculated by taking the average installation cost for a 10 kW system and the average tax credit value of SAR 78,800 ($21,000) from various states in the US [27, 28]. Furthermore, to incorporate annual maintenance costs for cleaning and inspection given Riyadh weather, $100/ year would reflect average maintenance costs.

For solar water heaters, the infrastructure cost for a 400-liter system was estimated to range from SAR 3,500 to SAR 5,500 [24], with an average cost of SAR 4,500 ($1,200). Annual maintenance cost per year was %2 of infrastructure cost as per a study by Mekonnen [42]. The next alternative, low-flow fixtures, accounted for the following costs per bathroom: a low-flow showerhead at $50, a low-flow faucet at $100, and a low-flow toilet at $300, totaling $450 per bathroom. Assuming ten bathrooms per household, the total cost would be $4,500.

Lastly, the greywater systems' installation cost was based on Heather Kinkade's estimation of $10,000 to $20,000 [26], with an average cost of $15,000. While maintenance costs vary based on several factors, a study by Ghishi estimated the maintenance cost to 2.5% [36]. This comprehensive analysis of the infrastructure and operational costs for the seven construction alternatives will enable homeowners in Riyadh to make informed decisions that align with their economic, quality of life, and sustainability objectives.

Alternatives	Infrastructure Cost	Maintenance Cost
A1: Basic construction methods	1,850 SAR/square meter ($493)	0
A2: Spray foam insulation	66,600 SAR ($ 17,760)	0
A3: Fiberglass batts	24,250 SAR ($ 6,500)	0
A4: Rooftop solar panels (10KW).	SAR 91,000 ($24,300)	$100/ year.
A5: Solar water heaters (400-liter system).	SAR 4,500 ($1,200)	$30/ year
A6: Low-flow fixtures (Assumed 10 bathrooms).	$450 per Bathroom.	0
A7: Greywater recycling systems.	56,250 SAR ($15,000)	0

Table 8: Alternatives infrastructure cost & operational cost.

5.3.2- Energy and Water Savings for Alternatives

Table 9 presents a summary of energy savings in kWh and water savings in m^3 for the seven alternatives. Additionally, the table shows the corresponding cost savings in US dollars based on tariffs in Saudi Arabia and California.

- For the second alternative, spray foam insulation, a 40% energy consumption reduction is achieved. With a per-person consumption of 9,000 kWh in a household of ten residents (90,000 kWh), the savings amount to approximately 36,000 kWh. On the other hand, fiberglass batts offer a 20% efficiency, resulting in savings of about 18,000 kWh. Based on the tariffs in Saudi Arabia (4.80¢/kWh) and California (19.90¢/kWh), the estimated energy savings using the corresponding tariffs for spray foam insulation are around $1,720 in Saudi Arabia and $7,164 in California. For fiberglass batts, the savings are approximately $900 and $3,600, respectively.
- For the fourth alternative, assuming 10 kW solar PV system with a capacity factor of 20%. The annual electricity generation (savings) would be: 10 kW * 8,760 hours/year * 20% = 17,520 kWh/year.

- The fifth alternative, a 400-liter solar water heater system, offers annual energy savings of between 3,000 and 5,000 kWh, with an average of 4,500 kWh.
- For the sixth alternative, low-flow fixtures, they save an average of 40% of indoor water use. Considering ten residents per household and an average consumption of 300 liters/day per person, the average monthly water consumption for a household is 54,000 liters. The average savings would be around 21,600 liters per month.
- Finally, the seventh alternative, greywater systems, can save between 30-50% of a household's total water consumption by recycling water from showers, sinks, and laundry for irrigation, toilet flushing, and other non-potable uses [35]. An average of 25% savings of a household's total water consumption was assumed for this analysis.

Alternatives	Energy savings in (kWh) and Water savings in (m^3)	Savings in US$ (KSA Tariffs)	Savings in US$ (California Tariffs)
A1: Basic construction methods	0	0	0
A2: Spray foam insulation	36,000 kWh	SAR 6480 ($1720)	SAR 26,900 ($7164)
A3: Fiberglass batts	18,000 kWh	SAR 3300 ($900)	SAR 13,500($3600)
A4: Rooftop solar panels.	17,520 kWh/year	SAR3153 ($840)	SAR 13,075 ($3,487)
A5: Solar water heaters.	4,500 kWh	SAR 810 ($216)	SAR3,400 $900
A6: Low-flow fixtures.	21,600 liters/month.	SAR 52 ($14)/ year	SAR 90 ($23.89)/year
A7: Greywater recycling systems.	13,500 liters/month.	SAR 33 ($9) per year	SAR 722 ($193)/year

Table 9: Energy & Water Savings for Alternatives and Cost Savings Based on Tariffs in Saudi Arabia and California.

5.3.3- Resale value for alternatives.

In addition to energy and water savings, the resale value or added value to the property price for each alternative is another crucial factor to consider. Table 10 summarizes the potential resale value for alternatives that can be resold, such as rooftop solar panels and solar water heaters, and the potential added value to the property price for other alternatives that cannot be resold but have a positive impact on the resale value of the house. The resale value is influenced by several factors including the condition of the alternative at the time of sale.

For the basic construction methods (A1), there is no added resale value, as it represents the baseline scenario. The insulation alternatives (A2 and A3) could potentially slightly increase the resale value of a house due to their energy-saving benefits. However, the exact amount is difficult to quantify, and therefore their resale values were assumed to be negligible.

Rooftop solar panels (A4) have a resale value, which is influenced by factors such as the age of the system, the remaining warranty period, and the efficiency of the panels. According to a Solar Reviews article, used solar panels can be sold for 20-70% of their original price, depending on their condition [49]. For the purpose of this analysis, a conservative estimate of 30% of the original price was assumed as the resale value for the solar panels to account for the risk of damage caused by dust storms.

Solar water heaters (A5) have a potential resale value as well, although it might be lower than that of solar panels due to factors such as wear and tear, efficiency loss, and the age of the system. A conservative estimate of 20% of the original price was assumed for this analysis.

Low-flow fixtures (A6) and greywater recycling systems (A7) are integrated into the house and cannot be resold as separate systems. Therefore, their resale values were assumed to be negligible.

Alternatives	Potential resale value	Potential resale value ($)
A1: Basic construction methods	No value added	0
A2: Spray foam insulation	Slightly added value to house resale only	0
A3: Fiberglass batts	Slightly added value to house resale only	0
A4: Rooftop solar panels (10KW).	30% of original price [49]	$ 7,300
A5: Solar water heaters (400-liter system).	20% of original price [49]	$ 240
A6: Low-flow fixtures (Assumed 10 bathrooms).	Slightly added value to house resale only	0
A7: Greywater recycling systems.	Slightly added value to house resale only	0

Table 10: Potential resale value for alternatives.

5.3.4- Net Present Value Analysis for Residential Sustainability Alternatives.

Table 11 provides a summary of the infrastructure cost, maintenance cost, annual savings in US dollars using KSA tariffs and California tariffs, and estimated resale value for each of the seven residential alternatives. These factors are crucial for assessing the economic viability of each alternative over time. The Net Present Value (NPV) for each alternative is calculated in Table 12, taking into account savings in US dollars, infrastructure costs, maintenance costs, and potential resale value. The discount rate is set at 5%, considering the relatively low risk associated with residential sustainability alternatives. The NPV calculations are conducted for two different timeframes: 10 and 20 years. This analysis will be used in the next section to develop a multi-attribute utility model that serves as a decision support tool for homeowners to understand the weighted utility of each alternative in comparison to its NPV.

Alternatives	Savings in US$ (KSA Tariffs)	Savings in US$ (California Tariffs)	Infrastructure Cost	Maintenance Cost	Potential resale value ($)
A1:Basic construction methods	0	0	493	0	0
A2: Spray foam insulation	1720	7164	17760	0	0
A3: Fiberglass batts	900	3600	6500	0	0
A4: Rooftop solar panels.	840	3487	24300	100	7290
A5: Solar water heaters.	216	900	1200	30	240
A6: Low-flow fixtures.	14	24	4500	0	0
A7: Greywater recycling systems.	9	193	15000	0	0
Discount Rate (5%)	0.05				

Table 11: Summary of Annual Savings, Infrastructure Costs, Maintenance Costs, and Estimated Resale Value for Residential Sustainability Alternatives

Alternatives	KSA Tariffs NPV (10 years)	KSA Tariffs NPV (20 years)	California Tarrifs NPV (10 years)	California Tarrifs NPV
A1:Basic construction methods	-493	-493	-493	-493
A2: Spray foam insulation	-935.05	15445.9	50468.57	118697.14
A3: Fiberglass batts	2168.93	10740.36	27785.71	62071.43
A4: Rooftop solar panels.	-8823.53	-1730.56	15292.49	47594.99
A5: Solar water heaters.	867.03	2652.07	7339.32	15638.64
A6: Low-flow fixtures.	-4299.17	-4165.83	-4271.43	-4042.86
A7: Greywater recycling systems.	-14539.29	-14453.57	-13161.9	-11323.81

Table 12: Net Present Value Analysis for Residential Sustainability Alternatives (10 and 20-year timeframes).

Table 12 presents the NPV calculations for each of the residential sustainability alternatives over 10 and 20-year periods. This analysis allows homeowners to better understand the economic viability of each alternative over time, taking into consideration the financial benefits and costs associated with their adoption.

In summary, the Net Present Value analysis provides a comprehensive evaluation of the financial implications of adopting each of the studied residential sustainability alternatives. This information can be used to make informed decisions about which alternatives are most suitable for a particular household, taking into account the local context and tariffs.

5.4- Multi-Attribute-Utility (MAU):

In order to address the different objectives that households in Saudi Arabia would consider when constructing a new home, a consequence table was developed to analyze the alternatives, targeted objectives, and their corresponding scores discussed in section 5.2.1. The consequence table represents the relationship between the alternatives and the targeted objectives. It also highlights the range, rank weight, and rated weight for each alternative. Subsequently, a normalized weight was derived by analyzing the differences between the alternatives and included in Table 13. These factors are essential for comparing and evaluating the alternatives based on multiple criteria.

Consequence Table														
		Alternatives							Weights					
Objectives									Range					
Benefit	Measures	A1: Basic construction	A2: Spray foam insulation	A3: Fiberglass batts	A4: Rooftop solar panels	A5: Solar water heaters (400-liter system).	A6: Low-flow fixtures	A7: Greywater recycling systems	Worst	Best	Rank weight	Rated weight	Normalized weight (%)
House Appearance	Constructed	5	5	5	3	3	5	5	3	5	3	80	22.86
Ease & frequency of **Maintenance**	Constructed	3	5	5	2	4	5	4	2	5	2	90	25.71
Noise Reduction	Constructed	0	5	3	5	5	5	5	0	5	1	100	28.57
Space utlization	Constructed (inches)	4	5	5	*3*	4	5	4	3	5	4	60	17.14
Eco friendly	Constructed (yes/ no)	0	5	5	5	5	5	5	0	5	5	20	5.71
Net Present Value (NPV)- KSA tarif	in US $	-493	-1379.05	2071.43	-9917.03	825.03	-4366.7	-14914.29			**sum:**	**350**	**99.99**

Table 13: Consequence Table addressing the multiple alternatives and targeted objectives.

The single-attribute values are highlighted in table 14, which presents the unweighted and weighted utility scores for each alternative based on the different objectives. These scores allow for a comprehensive assessment of the alternatives and can be used to make informed decisions regarding the most suitable options for a particular household.

Single-attribute values								
		Alternatives						
Objectives Benefit	Measures	A1: Basic construction	A2: Spray foam insulation	A3: Fiberglass batts	A4: Rooftop solar panels	A5: Solar water heaters (400-liter system).	A6: Low-flow fixtures	A7: Greywater recyclying systems
House Appearance	Constructed	100	100	100	0	0	100	100
Ease & frequency of **Maintenance**	Constructed	33.33	100	100	0	66.6666667	100	66.67
Noise Reduction	Constructed	0	100	60	100	100	100	100
Space utlization	Constructed (inches)	50	100	100	0	50	100	50
Eco friendly	Constructed (yes/ no)	0	100	100	100	100	100	100
Unweighted Utility		36.67	100	92	40	63.3333333	100	83.33
Weighted Utility		40	99.99	88.562	34.28	59.99	99.99	82.85
NPV (KSA Tariffs, 10 years)		-493	-1379.05	2071.43	-9917.03	825.03	-4366.7	-14914.29

Table 12: Single-attribute values, weighted utilities, and NPV(KSA Tariffs, 10 years).

The next section, "6.0 Analysis Results & Evaluation", will address and discuss the results of the MAU, providing insights into the relative performance of each alternative and aiding in the decision-making process.

6.0 Analysis Results & Evaluation:

The Multi-Attribute Utility (MAU) model evaluated the effectiveness of each residential sustainability alternative, considering factors such as house appearance, ease and frequency of maintenance, noise reduction, space utilization, and eco-friendliness. Figure 7 illustrates the weighted utility of alternatives compared to their NPV over a 10-year period using KSA tariffs.

The NPV analysis revealed that Alternatives A3 (Fiberglass batts) and A5 (Solar water heaters) had the most positive NPV values over a 10-year period. A2 (spray foam insulation) showed significant potential for savings with increased tariff costs, either over a 20-year duration in Saudi Arabia (Figure 9) or under California tariffs (Figure 10), resulting in substantial positive NPV values.

Moreover, A3 (Fiberglass batts) ranked third in weighted utility, which provides an advantage when considering the NPV over 10 years. However, under higher tariff costs, similar to California or a 20-year NPV calculation, A2 (spray foam insulation) would outperform all other alternatives, as shown in Figures 9 and 10. Especially, if the weight on NPV is low as shown in figure 8. Furthermore, the analysis shows that A6 (Low-flow fixtures) is dominated by A2 (spray foam insulation) if the factors considered were weighted utility and NPVs as thy have equivalent weighted utility yet A2 has higher NPV value. However, if the factors considered were weighted utility and initial investment cost A6 (Low-flow fixtures) would dominate all other alternatives as shown in figure 11.

Alternative A4 (Rooftop solar panels) involved a relatively high initial investment cost but offered long-term savings, especially with California tariffs. The estimated resale value of the solar panels added to their attractiveness. On the other hand, alternatives A6 (Low-flow fixtures) and A7 (Greywater recycling systems) had lower NPV values but positively impacted eco-friendliness and quality of life criteria, essential considerations for some households.

A sensitivity analysis on the weight of NPV (KSA tariffs over 10 years) is presented in Figure 8. The analysis indicates that with a zero weight on NPV, alternatives A6 (low-flow fixtures) and A2 (spray foam insulation) dominate. When the weight on NPV is between zero and 0.25, A2 (spray foam insulation) prevails. When the weight on NPV exceeds 25%, A3 (fiberglass insulation) emerges as the leading alternative.

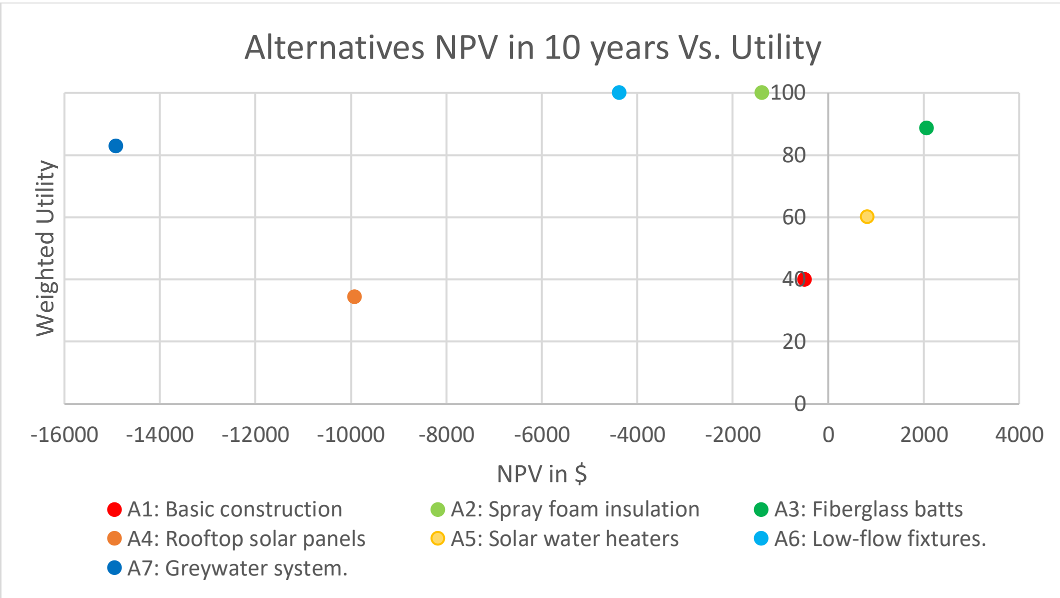

Figure 7: Alternatives weighted utility Vs. NPV (KSA tariffs in 10 years).

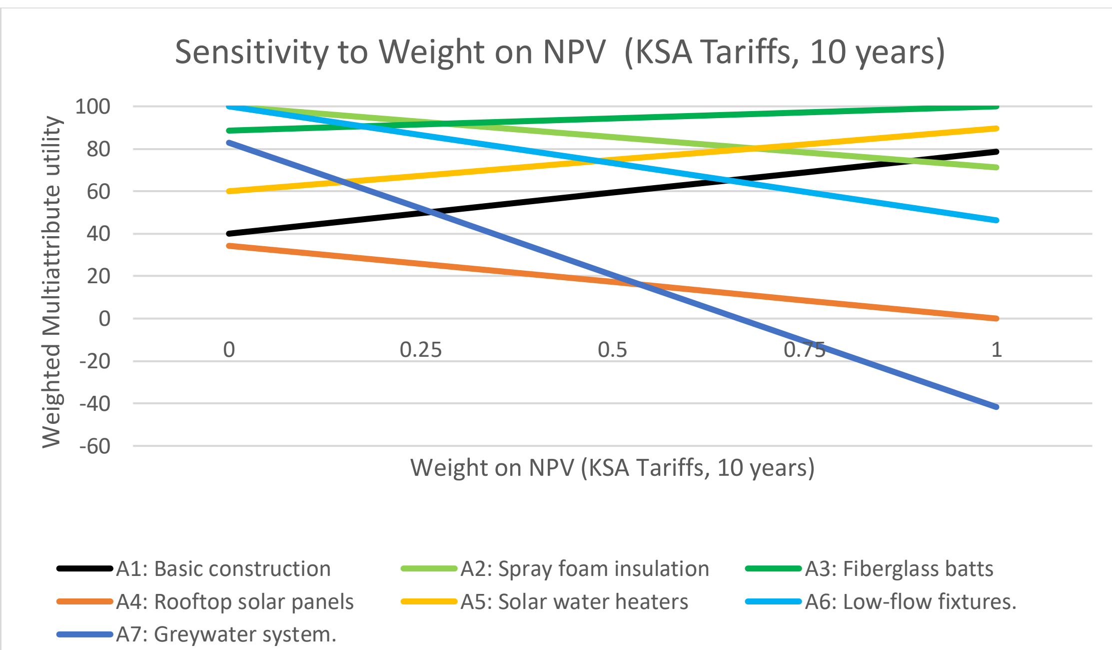

Figure 8: Sensitivity to weight on NPV (KSA tariffs in 10 years).

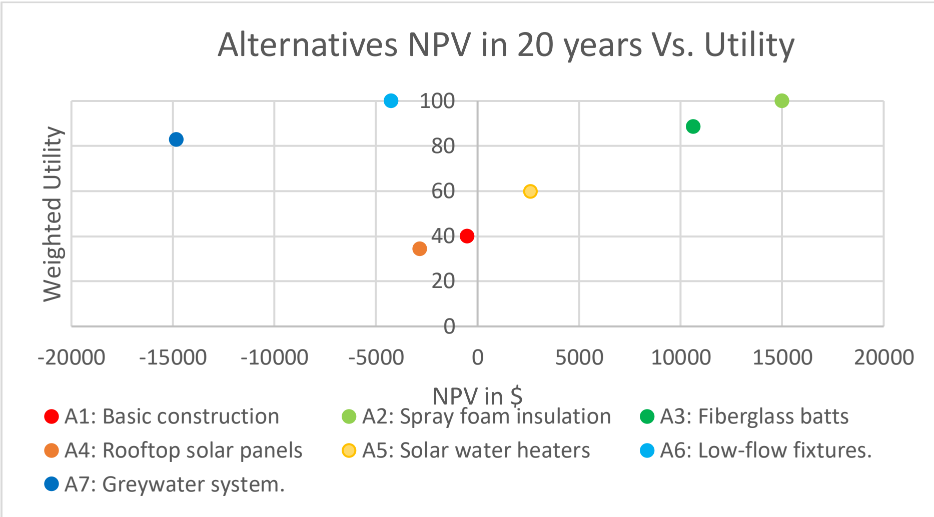

Figure 9: Alternatives weighted utility Vs. NPV (KSA tariffs in 20 years).

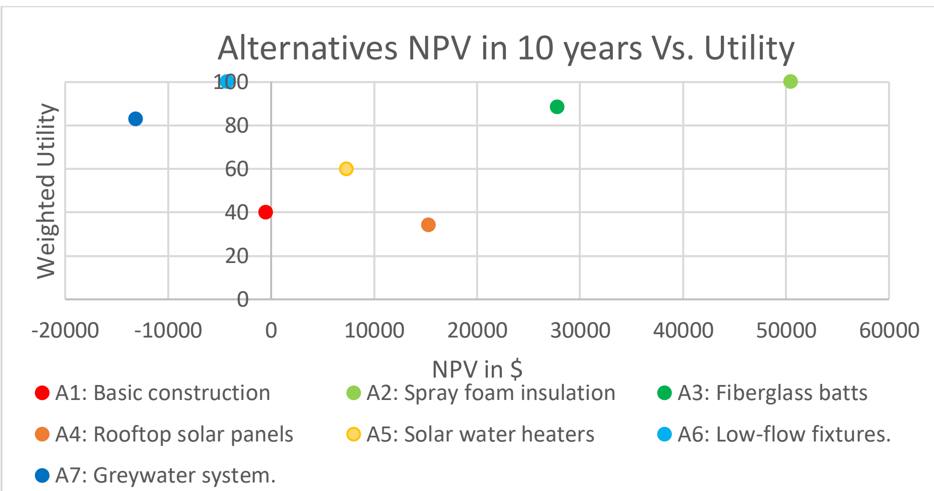

Figure 10: Alternatives weighted utility Vs. NPV by changing only savings (California tariffs in 10 years).

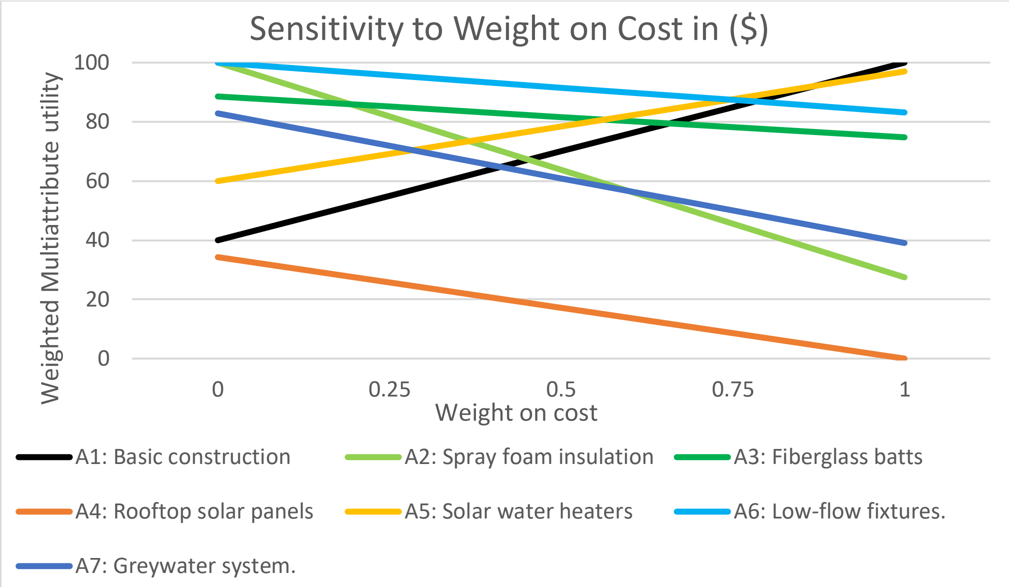

Figure 11: Sensitivity to weight on initial investment cost.

7.0 Conclusions & Recommendations:

In conclusion, sustainability enhances people's lives by fostering healthier ecosystems and preserving natural resources. Alternatives A2 (spray foam insulation), A3 (Fiberglass batts), A4 (Rooftop solar panels), A5 (Solar water heaters), A6 (low-flow fixtures), and A7 (Greywater recycling systems) are sustainable options that address household needs through energy and water-efficient systems.

The Net Present Value (NPV) analysis served as an effective tool for evaluating the economic viability of the alternatives across different timeframes (10 and 20 years) and under various tariff prices, particularly those in Saudi Arabia and California, which provided an international benchmark for comparison. The analysis revealed that A3 (Fiberglass batts) and A5 (Solar water heaters) had positive NPVs in the short term with KSA tariffs. Although A3 had a higher NPV value and weighted utility than A5, it required over five times the initial investment cost. Conversely, A2 (Spray foam insulation) exhibited the highest NPV for long-term savings under KSA tariffs or under higher tariff costs like California tariffs.

The Multi-Attribute Utility model developed in this study empowers stakeholders, particularly Saudi Arabian households, to effectively evaluate residential alternatives by considering various objectives that contribute to quality of life, convenience, and sustainability, as well as the corresponding weights for each criterion. This approach allows stakeholders to consider multiple objectives in their decision-making process, enabling them to evaluate the weighted utility of each alternative and compare it against the others while considering their economic goals. Alternatives' weighted utility can then be analyzed and compared with NPV and initial investment costs, helping stakeholders understand their sensitivity to these factors.

The study emphasized the importance of considering multiple criteria when selecting sustainable residential alternatives, as the dominance of alternatives varies based on the weight assigned to different factors. Therefore, the recommendations below outline which alternative is suitable depending on the objectives:

KSA Tariff:

- If the weight on NPV is high for a short period (10 years), alternatives A3 (Fiberglass batts) and A5 (Solar water heaters) dominate other alternatives, with A3 offering higher NPV and weighted utility but requiring a higher investment. If sensitivity to initial investment cost is high, A5 (Solar water heaters) is an exceptional economic alternative with moderate weighted utility.
- For longer-term savings, particularly with increased tariff costs like in California or longer timeframes, A2 (Spray foam insulation) emerges as the best alternative.
- When the weight on NPV is low, alternatives A2 (Spray foam insulation) and A6 (low-flow fixtures) dominate, with A6 being preferable if the stakeholder prioritizes low initial investment and A2 dominating if NPV is considered more important.

California Tariff:

- Alternative A2 (Spray foam insulation) dominates all other alternatives when the tariff cost is high.
- A4 (Rooftop solar panels) becomes a very viable option for long-term savings and resale value, despite the high initial investment.

Finally, Alternative A7 (Greywater recycling systems) remains a viable option for its contributions to eco-friendliness and quality of life, despite lower NPV values and weighted utility.

In summary, households should consider multiple objectives to make better-informed decisions. It is also essential to consider the potential increase in tariff costs, which would make the alternatives necessary not only for sustainability and quality of life objectives but also for addressing economic aspects.

Ultimately, sustainability is crucial to help the environment and, therefore, improve everyone's quality of life. Policymakers should promote the adoption of sustainability alternatives by balancing incentives between tariff prices and offering incentives to reduce the investment costs of sustainable systems.

8.0 Appendix:

Country	FEW Score	FOOD SUB-INDEX	Food Accessi-bility	Food Availability	ENERGY SUB-INDEX	Energy Accessi-bility	Energy Availability	WATER SUB-INDEX	Water Accessi-bility	Water Availability	Water Adaptive Capability
Bahrain			0.45		0.90	0.96	0.84	0.26	1.00	1.00	0.02
Kuwait	0.39	0.64	0.47	0.87	0.92	0.96	0.88	0.10	0.99	1.00	0.00
Oman	0.54	0.60	0.43	0.83	0.88	0.96	0.80	0.30	0.95	0.41	0.07
Qatar			0.57		0.92	0.96	0.89	0.17	0.99	1.00	0.01
Saudi Arabia	0.51	0.61	0.42	0.87	0.89	0.96	0.83	0.25	0.98	0.93	0.02
UAE	0.45	0.70	0.58	0.85	0.91	0.96	0.85	0.14	0.99	0.92	0.00
GCC Average	0.47	0.64	0.49	0.86	0.90	0.96	0.85	0.20	0.98	0.88	0.02

Table 1: Rand's FWE Index for GCC [6,7]

8.1- Water and Electricity Tariffs for Residential Consumption:

Country/ State	Tariffs in $
Saudi Arabia	4.80¢ / kWh
California, USA	19.90¢ / kWh
Egypt	4.40¢ / kWh
Kuwait	2.29¢ / kWh
Qatar	3.30¢ / kWh
United Arab Emirates	8.10¢ / kWh

Table 4: Electricity tariff prices (¢ / kWh) in different countries [12, 13, 14]

Country/ State	Tariffs ranges in $/ m^3
Saudi Arabia	0.03 to 1.60
California, USA	1.59
Egypt	0.04 to 0.31
Kuwait	1.46
United Arab Emirates	0.89 to 2.87

Table 5: Electricity tariff prices ($ / m^3) in different countries [15, 16,17,18]

Figure 5: Flat-roofed houses reflecting the local style of buildings with and without solar panels. [45, 46]

Figure 6: Gable-roofed houses Vs. flat-roofed houses impact on space utilization and aesthetic appearance [43, 44]

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10.0 References:

[1] Al Garni, H., & Awasthi, A. (2017). Solar PV power plants: A review of grid-connected photovoltaic systems in Saudi Arabia. Renewable and Sustainable Energy Reviews, 79, 860-866.
[2] Alrashed, F., & Asif, M. (2015). Prospects of energy conservation in buildings in Saudi Arabia. Sustainable Cities and Society, 14, 17-27.
[3] "Sustainable Development." UNESCO, 20 Aug. 2015, https://en.unesco.org/themes/education-sustainable-development/what-is-esd/sd#:~:text=The%20concept%20of%20sustainable%20development,to%20meet%20their%20own%20needs.%E2%80%9D. "
[4] "World Population 2022." *World Population 2022 (Demographics, Maps, Graphs)*, https://worldpopulationreview.com
[5] "Saudi Arabia Population 2022." *Saudi Arabia Population 2022,* https://worldpopulationreview.com/countries/Saudi-Arabia-population.
[6] Efron, Shira. *Food Security in the Gulf Cooperation Council - Rand*. https://www.rand.org/content/dam/rand/pubs/external_publications/EP60000/EP67748/RAND_E
[7] "Rand Research on Food, Energy, and Water Security." *RAND*, https://www.prgs.edu/pardee-initiative/food-energy-water/resources/links.html.
[8] "AQUASTAT Database - FAO." *Food and Agriculture Organization*, https://www.fao.org/aquastat/statistics/query/results.html.
[9] "Benefits of Green Building." *U.S. Green Building Council*, https://www.usgbc.org/articles/benefits-green-building.
[10] "Importance of Green Building." *Green Built Alliance*, 10 Oct. 2018, https://www.greenbuilt.org/about/importance-of-green-building/.
[11] Felimban, Ahmed, et al. *Assessment of Current Energy Consumption in Residential Buildings in Jeddah Saudi Arabia.*
[12] Electricity Tariffs - Saudi Electricity Company - SE, 2023
[13] QatarPetrolPrices. "Qatar Electricity Prices, September 2022." GlobalPetrolPrices.com, 2023, https://www.globalpetrolprices.com/Qatar/electricity_prices/.
[14] "Gasoline and Diesel Prices by Country." GlobalPetrolPrices.com, 2023
[15] Kuwait Ministry of Electricity and Water. "Kuwait Leans on Expats in Water Tariff reshuffle24 August 2017." Global Water Intelligence, 27 Aug. 2017, https://www.globalwaterintel.com/news/2017/34/kuwait-leans-on-expats-in-water-tariff-reshuffle#:~:text=The%20new%20tariff%20structure%20introduced,an%20earlier%20price%20of%20%240.58.
[16] National Water Company. (n.d.). Tariffs. Retrieved from https://www.nwc.com.sa/English/OurServices/Pages/Tariffs.aspx
[17] Sharm El Sheikh Environmental Center. (2020). Water prices in Egypt. Retrieved from https://sharm-ec.com/en/water-prices-in-egypt/

[18]]"Egypt Today. (2020). Electricity prices in Egypt remain stable for the next fiscal year. Retrieved from https://www.egypttoday.com/Article/3/88116/Electricity-prices-in-Egypt-remain-stable-for-next-fiscal-year
[19] "Saudi Arabia Energy Information." Enerdata, 24 Mar 2023.
[20] "U.S. Retail Electricity Prices 2021"
[21] Warsame, A. (2017). Factors Affecting Construction Costs in Riyadh. Journal of Engineering, 3(3), 89-97.
[22] International Energy Agency. (2013). Transition to Sustainable Buildings: Strategies and Opportunities to 2050.
[23] Alawaji, S. H. (2001). Evaluation of solar water heating in Saudi Arabia. Renewable Energy, 24(3-4), 499-505.
[24] "Solar Water Heater." WATER HEATERS, https://shop.saudiceramics.com/en/water-heaters/solar-water-heater.html.
[25] Home advisor.
https://www.homeadvisor.com/?gclid=Cj0KCQjw3a2iBhCFARIsAD4jQB1rtSGdAR-Ks8YTt3rDXie-xb51oeJjQLiFkxqsz63ZY-nPyZYEk0UaAkB4EALw_wcB
[26] Heather Kinkade, 2021.
[27] Sendy, Andrew. "How Much Does a 6KW Solar Power System Cost and How Much Electricity Does It Produce?" *Solar Reviews*, Solar Reviews, 26 Aug. 2018, https://www.solarreviews.com/blog/how-much-does-a-6kw-solar-power-system-cost-and-how-much-electricity-does-it-produce.
[28]Younes. "How Much Does a 10kw Solar System Produce?" *RenewableWise*, 1 Feb. 2022, https://www.renewablewise.com/how-much-does-a-10kw-solar-system-produce/.
[29] General Authority for Statistics (GaStat) - Kingdom of Saudi Arabia. (2021). Statistical Yearbook of 2021. Retrieved from https://www.stats.gov.sa/sites/default/files/en-statistical-yearbook-2021.pdf (Page 84, Table 3-15)
[30] International Energy Agency (IEA). (2019). Saudi Arabia - Countries & Regions. Retrieved from https://www.iea.org/countries/saudi-arabia
[31] World Bank. (n.d.). World Development Indicators: Water productivity, total (constant 2010 US$ GDP per cubic meter of total freshwater withdrawal). Retrieved from https://data.worldbank.org/indicator/ER.GDP.FWTL.M3.KD?locations=SA
[32] Al Garni, H., & Awasthi, A. (2017). A decision-making model for selecting sustainable residential construction technologies in the Kingdom of Saudi Arabia. Journal of Cleaner Production, 161, 1047-1063. Retrieved from https://www.sciencedirect.com/science/article/pii/S0959652617314422
[33] Felimban, Ahmed, et al. Assessment of Current Energy Consumption in Residential Buildings in Jeddah Saudi Arabia.
[34] "Benefits of Green Building." U.S. Green Building Council, https://www.usgbc.org/articles/benefits-green-building.
[35] The Center for Complex Engineering Systems CCES - King Abdulaziz City for Science & Technology (KACST) | Massachusetts Institute of Technology (MIT).
[36] Ghisi, E., Ferreira, D. F., & Oliveira, R. (2006). An analysis of the potential for potable water savings by using rainwater and greywater in a multi-storey residential building in southern Brazil. Building and Environment, 41(2), 204-210.
[37] K. J. McCartney and M. A. Nicol, "Developing an adaptive control algorithm for Europe," Energy and Buildings, vol. 38, pp. 153-160, 2006.

[38] M. K. Kumaran, "Review of the hygrothermal performance of fibrous insulation materials," Journal of Building Physics, vol. 32, pp. 131-159, 2008.
[39] H. Akbari, L. S. Rose, and H. Taha, "Analyzing the land cover of an urban environment using high-resolution orthophotos," Landscape and Urban Planning, vol. 63, pp. 1-14, 2003.
[40] "Solar water heating systems: A buyer's guide," Canadian Renewable Energy Network, 2002. Available: http://canmetenergy-canmetenergie.nrcan-rncan.gc.ca/fichier.php/codectec/En/2001-121/2001-121_e.pdf
[41] T. H. Driscoll, "Water conservation technologies for residential buildings," ASHRAE Journal, vol. 42, pp. 46-52, 2000.
[42] Mekonnen, M. M., & Hoekstra, A. Y. (2017). Four billion people facing severe water scarcity. Science Advances, 2(2), e1500323.
[43] "Solar Panel Roof Stock Photos And Images - 123RF." 123RF Stock Photos, 2023, https://www.123rf.com/stock-photo/solar_panel_roof.html.
[44] New Housing Project Launched in Riyadh - Middle East Observer." Middle East Observer, 13 Apr. 2021, https://meobserver.org/housing-project-in-riyadh/.
[45] Paton, Callum. "This Sustainable City in Dubai Is Entirely Powered by Solar Energy." Business Insider, 11 Jan. 2018, https://www.businessinsider.com/dubai-sustainable-city-uae-2018-1.
[46] U.S. Department of Energy, "Estimating the cost and energy efficiency of a solar water heater," Energy Saver, 2011. Available: http://energy.gov/energysaver/articles/estimating-cost-and-energy-efficiency-solar-water-heater
[47] A. Friedl and C. Heschl, "Greywater recycling in Austria - a literature review on applied treatment technologies and experiences with operation," in Proceedings of the 11th International Conference on Urban Drainage, 2008.
[48] R. A. Manning, "Low-flow plumbing fixtures," in Water Management in the '90s: A Time for Innovation, 1991, pp. 303-308.
[49] "Selling or Buying Used Solar Panels: What to Know." SolarReviews, 16 Mar. 2021, https://www.solarreviews.com/blog/all-about-used-solar-panels.