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Framework for Developing a Low-Carbon Energy Demand in Residential Buildings Using Community-Government Partnership: An Application in Saudi Arabia

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Abstract: Rapid population growth has led to significant demand for residential buildings around the world. Consequently, there is a growing energy demand associated with increased greenhouse gas (GHG) emissions. The residential building energy demand in arid countries such as Saudi Arabia is supplied with fossil fuel. The existing consumption pattern of fossil fuels in Saudi Arabia is less sustainable due to the depletion of fossil fuel resources and resulting environmental impacts. Buildings built in hot and arid climatic conditions demand high energy for creating habitable indoor environments. Enormous energy is required to maintain a cool temperature in hot regions. Moreover, climate change may have different impacts on hot climatic regions and affect building energy use differently. This means that different building interventions may be required to improve the performance of building energy performance in these geographical regions, thereby reducing the emissions of GHGs. In this study, this framework has been applied to Saudi Arabia, a hot and arid country. This research proposes a community–government partnership framework for developing low-carbon energy in residential buildings. This study focuses on both the operational energy demand and a cost-benefit analysis of energy use in the selected geographical regions for the next 30 years (i.e., 2050). The proposed framework primarily consists of four stages: (1) data collection on energy use (2020 to 2050); (2) setting a GHG emissions reduction target; (3) a building intervention approach by the community by considering cost, energy, and GHG emissions using the Technique for Order of Performance by Similarity to the Ideal Solution (TOPSIS) to select the best combinations in each geographical region conducting 180 simulations; and (4) a clean energy approach by the government using grey relational analysis (GRA) to select the best clean energy system on the grid. The clean energy approach selected six different renewable power generation systems (i.e., PV array, wind turbine, hybrid system) with two storage systems (i.e., battery bank and a combination of electrolyte, fuel cell, and hydrogen tank storage). This approach is designed to identify the best clean energy systems in five geographical regions with thirty scenario analyses to define renewable energy-economy benefits. This framework informs through many engineering tools such as residential building energy analysis, renewable energy analysis, multi-criteria decision analysis (MCDA) techniques, and cost-benefit analysis. Integration between these engineering tools with the set of energy policies and public initiatives is designed to achieve further directives in the effort to reach greater efficiency while downsizing residential energy demands. The results of this paper propose that a certain level of cooperation is required between the community and the government in terms of financial investments and the best combinations of retrofits and clean energy measures. Thus, retrofits and clean energy measures can help save carbon emissions (enhancing the energy performance of buildings) and decrease associated GHG emissions, which can help policy makers to achieve low-carbon emission communities.

Keywords: community-government partnership; building energy; energy and environmental performance management; clean energy; building intervention; renewable energy

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1. Introduction

1.1. Background

Worldwide, the demand for residential buildings has become a significant demand due to increasing population growth rates. As a result, there has also been a growing energy demand associated with the increase in greenhouse gas (GHG) emissions. The residential building energy demand in arid countries such as Saudi Arabia accounts for 52% of the total national electricity consumption [1,2]. The existing consumption pattern of fossil fuels in Saudi Arabia is less sustainable due to the depletion of fossil fuel resources and subsequent environmental impacts. The carbon dioxide level increased from 172 million tons in 1990 to 625 million tons in 2018 from the consumption of fossil fuels and related industrial operations [3].

Moreover, only 30% of Saudi nationals own their own homes. Furthermore, around two-thirds of the population is under the age of 30. This estimation suggests that to meet the needs of growing populations, the country must build 2.5 million new homes by 2025. This is a challenging task to complete. The residential energy demand in Saudi Arabia is increasing due to population growth, high economic growth, heavily subsidized electricity rates, and the use of air conditioners during summer [4].

1.2. Literature Review

Communities tend to apply the "hierarchy of sustainable energy use prioritization strategy" [5], which places great emphasis on energy conservation, energy efficiency, and renewable energy. Energy conservation is described as household-based behavioral activities that affect residential building carbon reduction (e.g., turning off lighting and A/C). Energy efficiency aims to improve residential building's products and services to reduce carbon production and manage the required energy for households efficiently (e.g., double glazed windows and LED lights). These methods represent a community-based approach to reducing carbon dioxide in residential buildings [6–8]. Renewable energy is generated from clean energy resources such as solar panels and wind turbine technology to meet energy demands. The combination of energy efficiency and energy conservation and the integration of renewable energy are considered essential for building a long-term energy approach vision [6–8].

Recently a new regulation has been proposed regarding energy efficiency and renewable energy in newly constructed residential buildings in the European Union [9]. Kuronen et al. [10] proposed the 4P approach, a Public–Private–People Partnership planning for the low-carbon framework in urban planning designed to bring future inhabitants to residential developments [10]. The literature concerning collaborative community and government approaches in managing energy consumption and carbon dioxide in residential buildings is limited. There is scarce evidence available on how such a joint partnership could be effective. Thus, this paper aims to develop a community-government partnership framework combining building intervention and clean energy approaches that would require significant stakeholders' contribution (e.g., from the tech-industry, economic, political, and public sectors) to fast track progress towards reaching carbon reduction targets.

Under a community–government partnership, the best GHG emission reduction strategy can be identified by considering renewable energy and building energy efficiency with respect to government–community collaboration. The framework included a building intervention approach for the community and a clean energy approach for the government. The building intervention approach considers appositive impact, a comprehensive combination of estimated energy consumption behavior, and GHG emissions produced by common residential building types in Saudi Arabia. On the other hand, the clean energy approach investigates different renewable options to reduce GHG emissions. Combining these two approaches is designed to identify the best combinations for meeting the country's GHG emissions reduction targets.

2. Methodology

2.1. Framework Development

A community-government partnership framework is proposed for developing low-carbon residential buildings in hot and arid developing countries, as shown in Figure 1. The framework comprises two approaches for achieving GHG reduction targets: a building intervention approach by the government's community and a clean energy approach. The first component identifies the national GHG emissions target required to meet the standards of the Paris Agreement and integrates the GHG emissions reduction roadmap know-how (as explained in Figure 2 below). Secondly, the building intervention approach is a community action and adaptation approach toward energy efficiency techniques and energy conservation awareness in residential buildings. Thirdly, the clean energy approach is a government policy to identify a suitable integration between the most suitable and affordable studied combinations and clean energy systems for the country. This framework shows the connection between the approaches to gain optimum energy performance in the operational and a clean energy selective in the country's residential sector. The following sections will explain how these approaches work and the possible tools for building modeling and long-term energy estimation, lifecycle costing analysis, solar PV power and wind turbine structure calculations, and multi-criteria decision analysis.

2.1.1. GHG Emissions Reduction Approach

At first, national energy and GHG emissions reduction policies are reviewed based on the studied country. In addition, international GHG emission reduction mechanisms, such as those of the Paris Agreement, are reviewed in Appendix B. National and international policies are the basis for defining the national GHG emissions reduction targets. GHG emissions reduction targets are established based on the literature reviews. The targets can be achieved by the actions of communities (building owners) and government regulations. These two approaches are discussed separately.

Furthermore, it should be noted that the GHG emissions approach depends on the country's GHG emissions reduction target, potential strategies to be applied by the communities' building intervention approach, and the government's clean energy approach. These strategies can be explained in the road map process of GHG emissions reduction, which illustrates the sequence of optimum combinations within a country. Thus, we need to understand how much various communities/residents are willing to invest in their housing interventions for the next few years (e.g., 30 years). Moreover, we must determine how to estimate how much particular communities contribute to the GHG emissions reduction target. Answering these questions is a part of defining the direction of a community-based approach. To define the government approach, we must determine how much the government envisions reducing GHG emissions within the country.

Furthermore, we must also determine how much the government should invest into clean energy for the next few years (e.g., 30 years) in order to meet these targets. However, there should be some convergence between the two approaches that can lead to identifying a feasible set of measures for GHG emissions reduction for hot climates. Figure 2 explains the road map for the GHG emissions strategy.

2.1.2. Building Intervention Approach (Community)

The community building intervention approach depends on alternative combinations in energy efficiency and energy conservation interventions (energy saving options (ESO)) for residential buildings. For these combinations, the Technique for Order of Performance by Similarity to Ideal Solution (TOPSIS) is applied to evaluate and identify the best combinations that suit each geographical region in the studied country. Residential building intervention strategies must be acceptable to the community to implement the selected combinations in exciting and new residential constructions in the country.

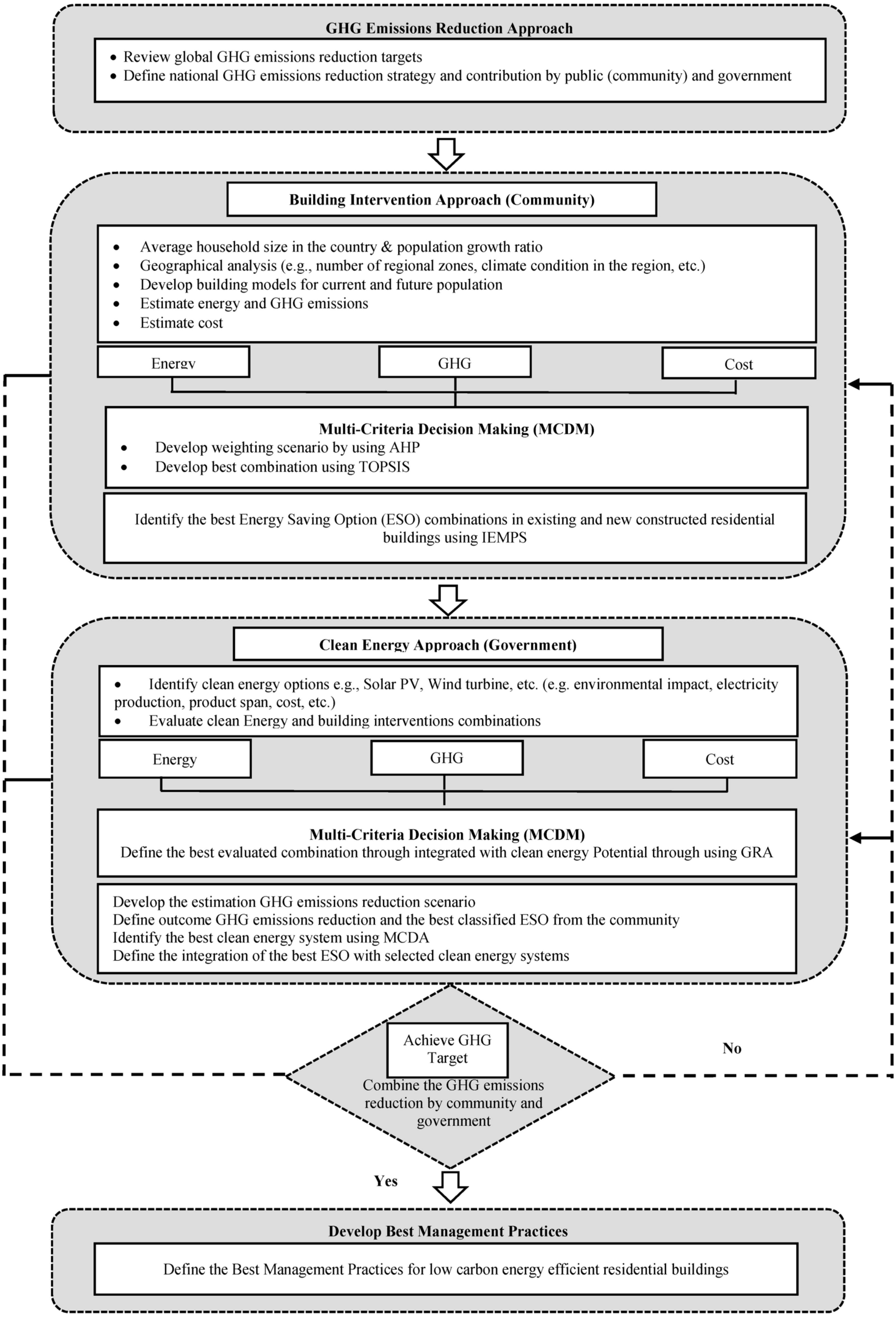


Figure 1. Community–government partnership framework for using low-carbon energy in buildings.

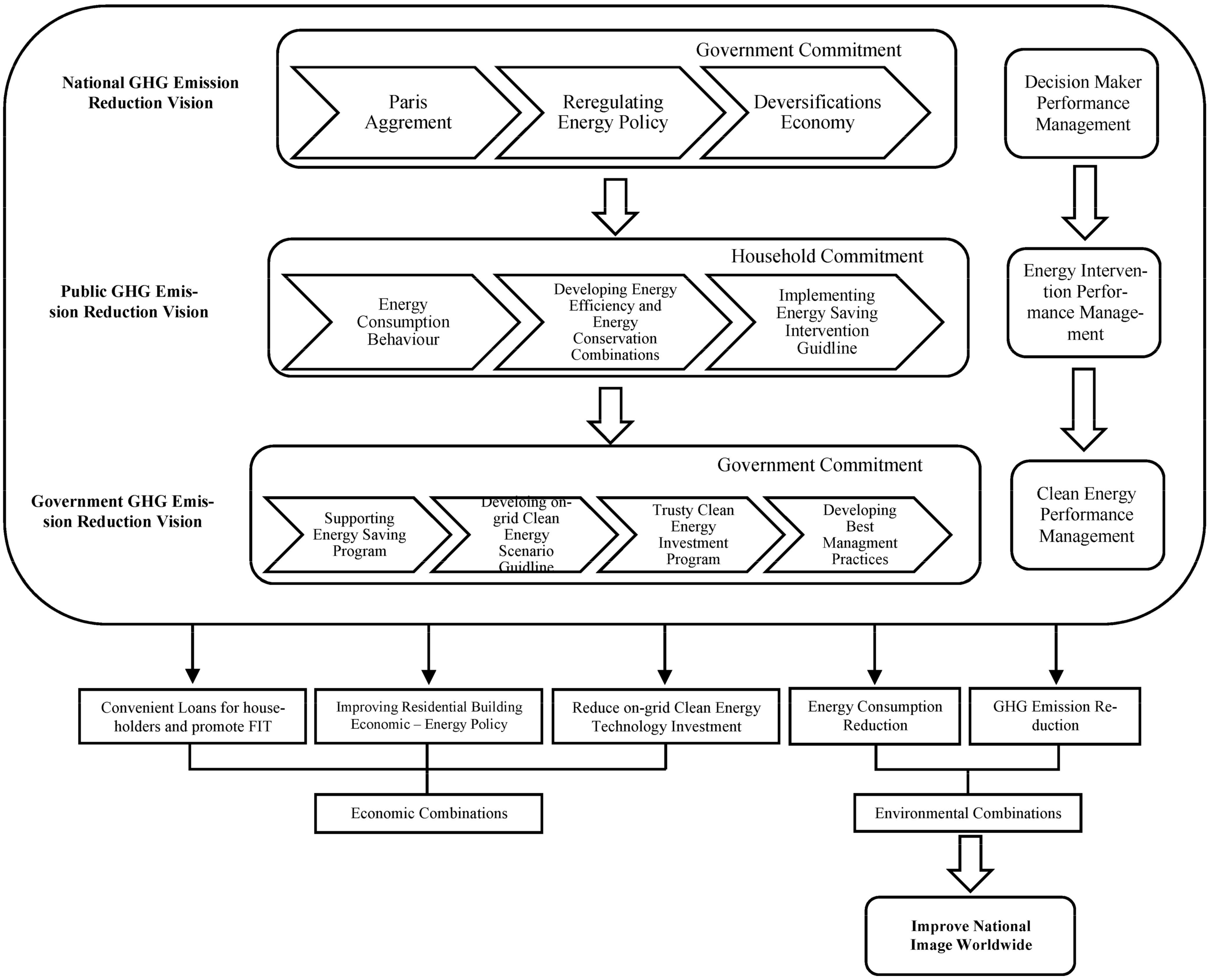


Figure 2. GHG emissions approach roadmap adapted from [11].

Building Modeling and Long-Range Energy Estimation and GHG Emissions

The following steps describe the residential building modeling for existing and newly constructed buildings:

- First step: collect required data (e.g., residential building design, geographical climate condition, population).
- Second step: develop a residential building model through Revit or another 3-D design software.
- Third step: integrate residential building modeling design into Design Builder software for comprehensive energy analysis.
- Fourth step: calculate energy consumption and GHG emissions mathematically. The Long-range Energy Alternative Planning System (LEAP) is a widely used software system for energy and environmental policy analyses in over 190 countries. LEAP software is used to calculate the energy demand based on the total activity level and energy intensity for each branch (i.e., region or country) [12].

The total energy demand can be calculated using Equation (1).

$$\boldsymbol{D}_{b,s,t} = \boldsymbol{TA}_{b,s,t} \times \boldsymbol{EI}_{b,s,t} \quad (1)$$

where:

D: Total Energy Demand;

TA: Total Activity;
EI: Energy Intensity;
b: Branch;
s: Scenario;
t: year;
Equation (2) is used to calculate the energy in each technology used:

$$UE_{b,0} = EI_{Ag,0} \times FS_{b,0} \times EFF_{b,0} \tag{2}$$

where:
b = 1,2,3, . . . , B (ranging from the base year [0] to the end year);
$EI_{Ag,0}$: final energy intensity in aggregate energy intensity branch;
***UE*:** useful energy intensity in a technology branch b;
***FS*:** fuel share;
***EFF*:** efficiency;
The useful intensity of the aggregate energy intensity branch is the sum of the suitable intensities for each technology using Equation (3)

$$UE_{Ag,0} = \sum_{b=1}^{B} UE_{b,0} \tag{3}$$

The GHG emissions are calculated using Equation (4)

$$\text{GHG} = \text{total energy consumption} \times \text{emmision factor} \tag{4}$$

For Equations (1)–(3), the literature review and energy simulation (e.g., energy consumption and GHG emissions in the residential buildings) are used over a specific period (e.g., 30 years).

Life Cycle Costing Analysis (LCCA)

LCCA is an economic assessment method that includes all related costs over the life cycle of the residence including initial cost, maintenance cost, renewal cost, and disposal cost of the residential building. This research includes direct costs such as capital (e.g., construction), operation and maintenance, and residual value. The present-worth method, (i.e., net present value (NPV)), estimates life cycle cost for each alternative in the community and government approach. The NPV of all costs and electricity use and ESO cost are estimated using Equation (5) below [13,14].

$$NPV = \sum_{t=0}^{\infty} \frac{B_t - C_t}{(1+r)^t} \tag{5}$$

where:
r is a discount rate (interest rate) of the country;
t is periods (years);
C = future expectation of energy cost;
B = present value amount for intervention cost;
The Net Present Value for Total Energy Consumption (NPV_{EC}) for future expected energy cost is explained in Equation (6) below.

$$NPV_{EC} = \sum_{t-0}^{\infty} \sum_{m-1}^{m} (1+r)^{-t} \times P_E \times z_{IER} \tag{6}$$

where:
P_E is the present energy cost;
z_{IER} is the discount rate which is increasing electricity rate per year;

The total LCC is estimated using Equation (7) [15].

$$\boldsymbol{LCC = NPV_{IC} + NPV_{OM\&RC} + NPV_{RepC} + NPV_{EC}} \quad (7)$$

where:

LCC is the total life cycle cost in present value;
(PV) dollars of a given alternative;
IC is the PV investment costs (if incurred at the base date, they need not be discounted);
RepC is the PV capital replacement costs;
EC is the PV of energy costs;
OM&RC is the PV of non-fuel operating, maintenance, and repair costs;

Multi-Criteria Decision Analysis: TOPSIS

ESOs and renewable energy selection are based on three criteria: energy, GHG emissions, and total cost. The importance of the criteria's weight is evaluated using the Analytical Hierarchy Process (AHP) based on export [16]. The criteria and the weights are aggregated using the Technique for Order of Performance by Similarity to the Ideal Solution (TOPSIS) for ESOs.

The TOPSIS method selects the best alternative that should have the shortest distance from the "positive ideal solution" and the furthest from the "negative ideal solution" in the geometrical sense. Also, this method suggests that each criterion has regularly increased or decreased utility, making it easy to target the positive ideal and negative ideal solution [17]. Moreover, the TOPSIS method calculates similarity to the positive-ideal solution by combining the distance ratio to the positive solution and the relative closeness from the negative-ideal solution for three criteria: energy, GHG emissions, and total cost as shown in the following steps:

- First Step: calculate normalized rating vector normalization using Equation (8).

$$r_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^{m} x_{ij}^2}} \quad (8)$$

$\boldsymbol{i}$ = 1, 2, . . . , $\boldsymbol{m}$,$\boldsymbol{j}$ = 1, 2, 3, . . . , n.

- Second Step: calculate weighted normalized ratings using Equation (9)

$$V_{ij} = W_j\, r_{ij} \quad (9)$$

$\boldsymbol{i}$ = 1, 2, . . . , $\boldsymbol{m}$,$\boldsymbol{j}$ = 1, 2, 3, . . . , n.

- Third Step: identify positive (A^*) and negative (A^-) ideal solutions using Equations (10) and (11).

$$\begin{aligned} A^* &= \left\{v_1^*, v_2^*, \ldots\ldots, v_j^*, \ldots\ldots, v_n^*\right\} \\ &= \left\{\left(\max V_{ij}\middle| j \in J_1\right), \left(\min V_{ij}\middle| j \in J_2\right) \middle| i = 1, \ldots\ldots, m)\right\} \end{aligned} \quad (10)$$

$$\begin{aligned} A^- &= \left\{v_1^-, v_2^-, \ldots\ldots, v_j^-, \ldots\ldots, v_n^-\right\} \\ &= \left\{\left(\min V_{ij}\middle| j \in J_1\right), \left(\max V_{ij}\middle| j \in J_2\right) \middle| i = 1, \ldots\ldots, m\right) \end{aligned} \quad (11)$$

- Fourth Step: calculate separation distances:

  Positive ideal solution A^*, shown in Equation (12).

$$S_i^* = \sqrt{\sum_{j=1}^{n} (v_{ij} - v_j^*)^2} \quad (12)$$

$\boldsymbol{i}$= 1, 2, . . . , $\boldsymbol{m}$ $\boldsymbol{j}$ = 1, 2, 3, . . . , n.

Negative ideal solution A^-, shown in Equation (13).

$$S_i^- = \sqrt{\sum_{j=1}^{n} (v_{ij} - v_j^-)^2} \tag{13}$$

$i = 1, 2, \ldots, m$ $j = 1, 2, 3, \ldots, n$.

Calculate similarities to the positive-ideal solution using Equation (14).

$$C_i^* = \frac{S_i^-}{S_i^* + S_i^-} \tag{14}$$

$i = 1, 2, \ldots, m$.

2.1.3. Clean Energy Approach (Government)

The government can develop clean energy to reduce carbon emissions of energy consumption. They can use an appropriate combination of renewable energies and the community's contribution to meet energy demands and reduce carbon emissions. The clean energy approach consists of four steps, as follows [18–20]:

First Step: review and identify the data to build a national diversification economy based on innovations to help improve product efficiencies and deregulate energy policies and initiatives.

Second Step: obtain the community's contribution using energy conservation and energy efficiency through the "building intervention" approach.

Third Step: evaluate energy performance for the country's residential sector for a long period of time and identify the best intervention combinations that suit the country through a comprehensive evaluation of clean energy management performance using the gray relational analysis technique (GRA).

Fourth Step: the clean energy systems (e.g., PV power, wind turbines) should be investigated to suit the climate and replace the on-grid traditional energy powered that use fossil fuel system with clean energy sources based on the lifecycle costing analysis that will explain the government rule to create a healthy environment.

The possible clean energy sources are solar photovoltaic (PV), wind, fuel cells, geothermal, or combinations between two or more resources in a hybrid system. The renewable energy calculation used in this research can be found in Section 2.1.3 [21]. The following sections will present the calculation for PV power and wind turbine.

V Power Structure Calculation

Solar PV Power (P_{PV}) is the annual energy output generated from the solar power plant to feed the grid. The solar energy is calculated using the following Equations (15)–(17) [22].

$$W = \frac{[(Ah_{country}/S) \times (1 + \eta_{sp}) \times (1 + \eta_i) \times (1 + \eta_b) \times E}{(1 + \eta_{cc})} \tag{15}$$

$$PV = [P - (W/1000)] \times S \tag{16}$$

$$P_{PV} = PV \times 365 \tag{17}$$

where:

W is the solar panel wattage that required for energy demand;

$Ah_{country}$ is the total daily Ampere hour based on the country national annual average in the residential sector;

S is the number of hours that is required from useful sun within a 24-h day;

η_{sp} is the solar panel losses;

η_i is the inverter losses;

η_b is the battery efficiency losses;

E is the voltage;

PV is the daily energy output generated for feeding in;

P is the annual energy output generated for feeding the grid by a photovoltaic solar power plant.

Wind Turbine Power Structure

Wind turbine power depends on the wind speed at hub height Equation (18) [21].

$$\frac{v}{v_0} = \left(\frac{h}{h_0}\right)^{\gamma} \tag{18}$$

where:

v is the wind velocity at the hub height (h);

h is the hub height;

v_0 is the measured wind velocity at the reference height (h_0);

h_0 is the measurement of the reference height;

γ is the ground surface friction coefficient;

The output power from a wind turbine is calculated using its manufacturing characteristic curve, which is expressed by adapting the curve fitting technique as shown in Equation (19).

$$P_w\,(v) = \begin{cases} 0 & for \rightarrow \quad v < v_c \\ a_1\, v^n \ \ldots\ b_1\, v^2 + c_1 v + d_1 & for \rightarrow \quad v_c \le v < v_1 \\ a_2\, v^n \ \ldots\ b_2\, v^2 + c_2 v + d_2 & for \rightarrow \quad v_1 \le v < v_2 \\ a_1\, v^n \ \ldots\ b_1\, v^2 + c_1 v + d_1 & for \rightarrow \quad v_2 \le v < v_f \\ a_1\, v^n \ \ldots\ b_1\, v^2 + c_1 v + d_1 & for \rightarrow \quad v > v_f \end{cases} \tag{19}$$

where:

$P_w\,(v)$ is the output power of the wind turbine at wind velocity;

(v_c) *and* (v_f) are the cut-in and the cut-off speeds of the wind turbine;

(v_1) *and* (v_2) are the intermediate wind speed levels used to improve the accuracy of curve fitting;

a_i, b_i, c_i, d_i are the parameters of the model;

Multi-Criteria Decision Analysis: Grey Relational Analysis

Grey relational analysis (GRA) uses the ideal alternative through evaluation alternatives based on a relative relational coefficient to determine the best alternative [23]. An analysis will be completed for each residential building scenario, inputted into the grey relational analysis method. GRA uses the relative relation coefficient to calculate the ideal option in order to determine the best alternatives [24].

Additionally, we can identify the GRA as the method to measure the degree of closeness and relative distance, which makes it capable of making a more extensive comparison between two sets of data. Moreover, the main procedure of GRA involves converting the performance of all alternative into an identical sequence [23], as described in the following steps:

First Step: Decision matrix ***D*** consists of m alternatives and n criteria: energy, GHG emissions, and total cost.

The decision matrix $\boldsymbol{D}$ is normalized to $\boldsymbol{D}$, Equation (20)

$$D = \begin{vmatrix} x_{1,1} & \cdots & x_{1,j} & \cdots & x_{1,n} \\ \vdots & \cdots & \vdots & \cdots & \vdots \\ x_{i,1} & \cdots & x_{i,j} & \cdots & x_{i,n} \\ \vdots & \cdots & \vdots & \cdots & \vdots \\ x_{m,1} & \cdots & x_{m,j} & \cdots & x_{m,n} \end{vmatrix}$$
$$D' = \begin{vmatrix} x'_{1,1} & \cdots & x'_{1,j} & \cdots & x'_{1,n} \\ \vdots & \cdots & \vdots & \cdots & \vdots \\ x'_{i,1} & \cdots & x'_{i,j} & \cdots & x'_{i,n} \\ \vdots & \cdots & \vdots & \cdots & \vdots \\ x'_{m,1} & \cdots & x'_{m,j} & \cdots & x'_{m,n} \end{vmatrix} \tag{20}$$

Second Step: Non-beneficial criteria are normalized in Equation (21)

$$\boldsymbol{x'_{i,j}} = \frac{\boldsymbol{min}\ \{\boldsymbol{x_{i,j}} \mid \boldsymbol{i = 1, 2, \ldots, m}\}}{\boldsymbol{x_{i,j}}} \tag{21}$$

$X_0 = \left\{x'_{0,j};\ j = 1, 2, 3, \ \ldots\ , \ n\right\}$.
Third Step: The grey relation coefficient in Equation (22)

$$\boldsymbol{\xi_{0i}(j)} = \frac{\boldsymbol{\Delta_{min} + \zeta \Delta_{max}}}{\boldsymbol{\Delta_{0i}(j) + \zeta \Delta_{max}}} \tag{22}$$

$\boldsymbol{\Delta_{oi}(j)} = \left|\boldsymbol{x'_{0,j} - x'_{i,j}}\right|$ is relative grey relation space;
$\boldsymbol{\Delta_{min} = min_i\left\{min_j\ \left|x'_{0,j} - x'_{i,j}\right|; j = 1,\ 2,\ \ldots,\ n\right\};\ i = 1,\ 2,\ \ldots,}\ m;$
$\boldsymbol{\Delta_{max} = max_j\left\{max_j\ \left|x'_{0,j} - x'_{i,j}\right|; j = 1,\ 2,\ \ldots,\ n\right\};\ i = 1,\ 2,\ \ldots,}\ m;$
The ζ is the distinguishing coefficient, generally set at 0.5 between $0 \leq \ \zeta \geq 1$.
Fourth Step: The grey relation grade ε from Equation (23)

$$\boldsymbol{\varepsilon = \sum_{j=1}^{n} \xi_{0i}\ (j)} \tag{23}$$

The ζ is the distinguishing coefficient; generally set at 0.5 between $0 \leq \ \zeta \geq 1$.
Fifth Step: Consider the different weights of criteria using Equation (24)

$$\boldsymbol{\varepsilon = w_j\ \sum_{j=1}^{n} \xi_{0i}\ (j)} \tag{24}$$

The ζ is the distinguishing coefficient; generally set at 0.5 between $0 \leq \ \zeta \geq 1$.

2.2. Framework Application

The community-government partnership framework for developing low-carbon energy in the residential sector has been applied to Saudi Arabia.

2.2.1. Study Area: Saudi Arabia

According to [4], the country is classified into five geographical regions: Central, Western, Southern, Northern, and Eastern. These five regions are divided into 13 administrative regions based on the government structure [25]. Where major administrative regions in the Central Region are Riyadh, Qassim, and Hail; the Western Region contains Makkah and AlMadena; the Southern Region contains Asir, Jazan, Najran, and AlBaha; the Northern

Region contains Tabouk, AlJouf, and the Northern Borders; and finally, the Eastern Region contains Dammam, Alkhouber, and Dharan. In Saudi Arabia, the temperature variation range from 27 °C to 43 °C in the inland areas and 27 °C to 38 °C in coastal areas during summer. In the winter, the temperatures in the interior parts of Saudi Arabia range between 8 °C to 20 °C, while higher temperatures 19 °C to 29 °C have been reported in the coastal areas [26–29]. According to the statistic of the Saudi Arabian Commission, it is estimated that the Saudi population will grow to 44.5 million by 2050 compared to 34 million in 2019 [25]. The population growth rate is 2.58% yearly, according to the yearly change in the population prediction from 1955 to 2020 (explained in Appendix A).

The residential building distribution in Saudi Arabia depends on the population prediction, the population distribution in each geographical region, and the average household number size. It is estimated that Saudi Arabia will have 7,135,745 residential buildings by 2050, with an average size household number of 5.97 people according to the Saudi Arabia Statistic Commission in 2018 (General Authority for Statistics, 2018a), as described in Table 1 below.

Table 1. Classified residential building distribution by geographical region in Saudi Arabia.

Geographical Region	Detached Residential Building			Attached Residential Building				Apartment
	Villa	Floor in Villa	Total	Traditional House	A Floor in Traditional House	Other	Total	
Central	560,329	329,969	890,297	191,640	67,588	122,567	381,795	991,939
Western	116,362	70,557	186,919	557,122	64,308	100,971	722,401	1,533,503
Eastern	204,060	65,676	269,736	72,907	24,071	34,175	131,153	589,694
Southern	131,216	118,556	249,771	265,445	51,684	28,350	345,479	460,359
Northern	29,809	21,169	50,977	100,767	14,747	24,458	139,972	191,746
Total	1,041,776	605,926	1,647,701	1,187,881	222,399	310,522	1,720,802	3,767,242

2.2.2. Identification of National GHG Emissions Reduction Vision

The national policies, strategies, action plans, and programs related to energy and carbon emissions were reviewed through energy programs, smart meters, and smart grids by the King Abdullah City for Atomic and Renewable Energy (KACARE), the Ministry of Energy, Industry, and Mineral Resources (MEIM), the Energy Conservation and Awareness Department in MEIM, and the Saudi ARAMCO Carbon Management Division. Based on the review, the GHG emission reduction target was identified.

2.2.3. Communities' Building Intervention Approach

Energy-Saving Options in Residential Building

The energy-saving options in the residential building are divided into three sections (i.e., design of the residential building, develop residential building energy modeling, and integration of intervention in the residential building energy modeling). The 2D design of the residential building was converted to a 3D design through Revit. The model was then developed considering the specific countries' building code, structural decision, family size, local climate, and occupant behavior [4]. Finally, the integration of intervention in the residential building in the residential building energy modeling through applying a four common intervention: LED lighting, double-glazed window, triple-glazed window, and efficient split AC unit, in this research which considers 180 combinations that have to be processed for decision making [16].

The main three criteria in this research are energy use, carbon emissions, and total cost (cost of energy use and cost of investment intervention). Using the energy model, annual energy consumption was estimated. Based on the energy use, carbon emissions were estimated as the product of energy (electricity) use and GHG emission factor of electricity for each building and confirmed through LEAP. The total cost was estimated as the sum of energy cost and capital cost of interventions. The cost of energy and intervention was expressed in terms of the net present value (NPV), considering a period of 30 years. The electricity tariffs price for the residential sector and the rate of increase of electricity, and the calculation of net present value through average interest rate for the investment in the country. The cost of the capital investment in Energy Saving Options (ESOs) in different buildings was calculated [16]. Moreover, the MCDA was applied to evaluate the combined complexity of ESOs to define the ideal solution that suites the residential building.

Ranking Energy Interventions Using TOPSIS

TOPSIS was used to evaluate the energy consumption, GHG emissions, energy cost during the operational phase, and the cost of energy intervention (EI) in each selected geographical region in Saudi Arabia. It is a widely used method of multi-criteria decision-making. It is the method to identify the best ESO/intervention combinations of existing and newly constructed residential buildings for the next 30 years, with classified Energy Saving Option with One-ESO combination referred to as ESO (A), Energy Saving Option with Two-ESO combinations referred to as ESO (B), and Energy Saving Option with Three-ESO combinations referred to as ESO (c)) as explained in Figure 3.

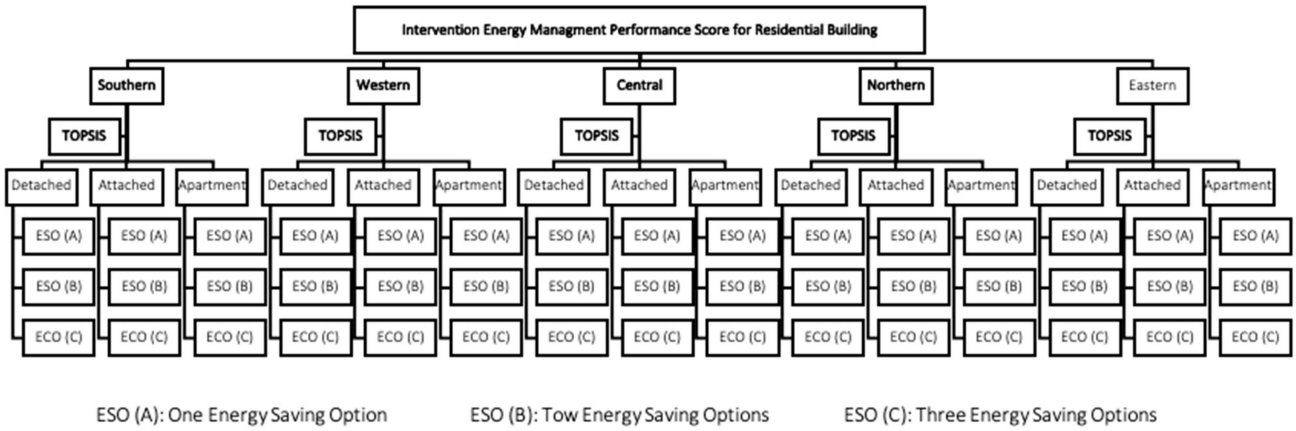


Figure 3. Evaluation of energy building interventions for residential building in Saudi Arabia.

2.2.4. Government's Clean Energy Approach

Clean Energy Options in Residential Building

The selected renewable energy systems depend on the load to be covered every hour for one year. The clean energy options should also meet cost-effectiveness (i.e., if minimum cost is considered an optimum configuration). This study has been located in five geographical regions in Saudi Arabia: the Southern, Western, Central, Northern, and Eastern regions.

In this research, the photovoltaic module is BP350 for $350 [30]. The solar panel technical specifications in terms of the solar panel wattage required for energy demand is 50. The nominal voltage of the battery in the solar panel ($V_{nominal}$) is 12 V; maximum power point (V_{mp}) is about 17.5 V; maximum power point (I_{mp}) is about 2.9 A; the open-circuit voltage (V_{oc}) is 21.8 V; and the short circuit current (I_{sc}) is 3.17 A (bp Solar, 2020). The wind turbine module is BWCXL 1000, with a power rate of 1000 W and a cost of $2500. The technical specifications of the selected wind turbine are as follows: wind turbine cut-in speed (V_{ci}) is about 2.5 m/s; and wind turbine cut-out speed (V_r) is about 11 m/s [21].

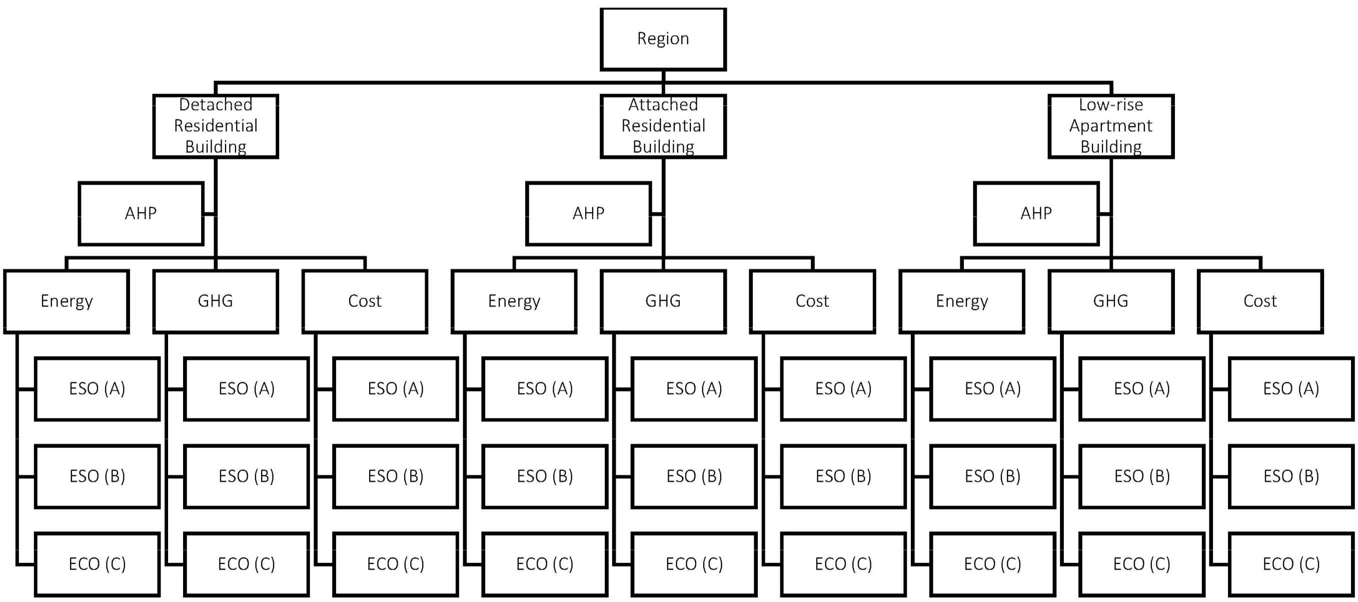
The storage system considered is either a battery bank or fuel cell and hydrogen tank. The specification of the battery is Concorde (PVX-2120L), with a cost of $465 [31]. Similarly, the initial capital cost is 3000 $/kW for fuel cells, and for hydrogen tank the initial capital cost is 1500 $/kg. The initial capital cost is 1000 $/kW required for either battery bank or fuel cell and hydrogen tank [21].

Weighting Scenarios

Two scenarios were defined: pro-economic and pro-environmental scenarios for the generation of the weights of energy consumption, GHG emissions, and cost using AHP. The pro-economic scenario considers the order of criteria importance as cost> GHG > Energy, whereas the pro-environmental scenario considers the order of criteria importance as energy > GHG > Cost. The pro-environmental scenario is in agreement with the performances of large residential buildings, where cost may not be the deciding variable in overall improvements [16]. Thus, since the comparisons are performed through export consultation or subjective judgments, some inconsistencies can be achieved. The resulting matrix (n) in the random index (RI) of AHP is 3, and RI has been calculated to be 0.58. Thus, the consistency ratio (CR) in both scenarios is <10% to ensure reasonable consistency of pairwise comparisons and ensure the judgments are consistent. Additionally, these weighting scenarios were applied to the Building Intervention Approach and Clean Energy Approach. Their specific weights were generated as shown in Table 2 and described in Figure 4.

Table 2. Environmental and economic criteria for weighting scenarios based on AHP.

Pro-Economic Scenario: Cost > GHG > Energy				**Weights**
Pair-Wise Comparison Matrix				
Criteria	**Energy**	**GHG**	**Cost**	
Energy	1	0.33	0.14	9%
GHG	3.00	1	0.33	24%
Cost	7	3	1	67%
Pro-Environmental Scenario: Energy > GHG > Cost				**Weights**
Pair-Wise Comparison Matrix				
Criteria	**Energy**	**GHG**	**Cost**	
Energy	1	5	7	73%
GHG	0.20	1	3	19%
Cost	0.14	0.33	1	8%



ESO (A): One Energy Saving Option ESO (B): Tow Energy Saving Options ESO (C): Three Energy Saving

Figure 4. Weighting scenarios based on AHP in the residential building, Saudi Arabia.

Ranking Clean Energy Alternatives Using GRA

The clean energy alternative (CEA) was ranked using GRA after obtaining the required data from the energy model. The government's clean energy approach depends on integrating ideal ESO analysis with a clean energy system chosen in this research, as shown in Figure 5. Figure 5 also describes the evaluation of energy, GHG emissions, and total cost to find the best ESO in each region and define the best clean energy technology system based on a selected set of ESO combinations and clean energy replacement investment in the gird to reach the GHG emissions target through applying the grey relation analysis technique.

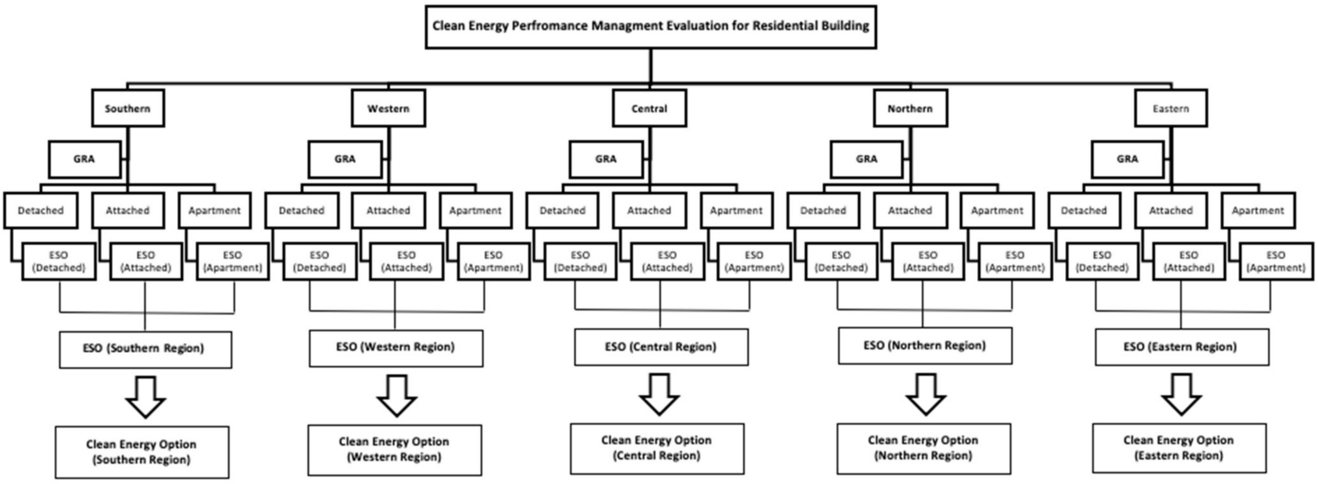


Figure 5. Clean energy option evaluation for the residential building based on GRA.

3. Results and Discussion

3.1. Saudi Arabia's GHG emissions Reduction Visions and Initiatives

3.1.1. GHG Emissions Reduction Vision

The nature of world cooperation to address climate change and its effects has been evolving since the 2015 Paris Agreement. The Paris Agreement represents a decentralized approach by embedding national carbon reduction goal visions towards an international framework to embrace collective action based on Nationally Determined Contributions (NDC) system in Saudi Arabia to identify its challenges and opportunities [32].

The NDC initiative was proposed to avoid carbon emissions by reforming energy and economic policies by supporting policy adaptation and accelerating economic diversification. Thus, the NDC department's goal is to cut 130 million tons of CO_{2e} emission by 2030. However, GHG emissions will rise by 70% with current economic and energy policies (i.e., above levels reported in 2015) [33]. Historically, the Kyoto Protocol insured 14% of global greenhouse gases (GHGs) reductions through a top-down approach [34]. This shortage falls substantially below the global GHG emissions reduction target in the Paris Agreement. After the Paris Agreement, Saudi Arabia has taken the following actions to mitigate GHG gases [35]:

- In December 2017, it was reported that the country planned to minimize the fossil fuel subsidy to enhance the economy;
- The National Renewable Energy Plan; Saudi Arabia is taking action to grow renewable electricity generation. The country has invested US$30bn to US$50bn in clean energy actions since 2017;
- In 2018, the Saudi government took actions in the free market for importing electric vehicles and regulating light-duty vehicles.

The country's GDP per capita is $52,227, which is higher by $20,790 than most G20 countries [35]. The Human development index in Saudi Arabia is 0.85, which is very high compared to G20 countries [36]. Furthermore, Saudi Arabia lags in fossil fuel subsidies by \$29.66 billion in 2016 compared to the \$7.87 billion average of other G20 countries. The country has low performance in renewable energy in power generation (almost 0% compare to the 24% with G20 countries). Additionally, the transport emission per capita (tCO_2/capita) is 4.03 comparing to 1.13 average of G20 countries [35]. In 2015 the GHG emissions almost quadrupled (276%) to reach 643 $MtCO_{2e}$. Thus, the GHG emissions per capita in Saudi Arabia are one of the highest for all G20 countries (20.1 tCO_{2e}/capita to 8 tCO_{2e}/capita G2 average) [35].

3.1.2. Energy Consumption Behavior and Energy-Saving Initiatives

According to the Carbon Dioxide Information Analysis Center, the CO_2 emissions from fossil fuels in Saudi Arabia are about 118 million metric tons [37,38]. In 1990, the carbon dioxide emissions were 172.85 million tons, increasing to 625 million tons in 2018 mainly from fossil fuel products and industrial operations [3]. Saudi Arabia's total energy consumption from fossil fuels was estimated at around 150 terawatt hour and 121 terawatt hour from natural gas [39]. Saudi Arabia aims to reduce carbon emission to 130 million tons of carbon dioxide or its equivalent [40].

The energy demand for the residential sector in Saudi Arabia is increasing, caused largely by population growth and the building of new communities. For instance, in 2017 it was reported that 70% of the total energy required for the residential sector in Saudi Arabia goes to the cooling systems (i.e., for the widespread use of air conditioning), which accounts for about 143 thousand GWh (equivalent to 30,000 M tons of CO_{2e}) [4]. Table 3 defines the current energy-saving initiatives pursued in Saudi Arabia.

Table 3. Energy saving initiatives in Saudi Arabia.

Plan/Program	Initiatives
Saudi Energy Efficiency Center (SEEC)	Establishing a national energy efficiency program. Recommended energy efficiency policies and regulations. Promote awareness about energy efficiency [41].
Saudi Energy Efficiency Program (SEEP)	SEEP is designing and implementing energy efficiency initiatives and focusing on three sectors: buildings, transport, and industry [42]. Improving Saudi Arabia's energy efficiency using a bottom-up approach. Involve all stakeholders from inception. Enhancing setting targets of the collection of data and their enforcement.
Electricity and Cogeneration Regulatory Authority (ECRA) has a detailed restructuring plan which is Electricity Industry Restructuring Plan (EIRP).	EIRP is mainly divided into three significant milestones as follows: The opening market for generation and distribution by unbundling Saudi Electric Company SEC for a vertical integration entity. Establishing a company in the generation, distribution, and retail businesses. Creating the "Parallel Market" concept for customers and suppliers based on agreed prices and conditions [43].

3.1.3. Carbon Capture, Utilization, and Storage (CCUS)

Several research and development initiatives have been considered in Saudi Arabia to reduce carbon dioxide emissions from industrial sources. The initiatives contribute to enhancing the national capacity of GHG emissions reduction trending as explained in following Table 4 and Appendix B.

Table 4. GHG emissions reduction initiatives in Saudi Arabia.

Plan/Program	Initiatives
The National Capacity	**Initiatives are described in the following areas:** Identifying and monitoring the sources of CO_2 Minimizing CO_2 formation Reducing CO_2 emissions Transportation Development Storage system Development Developing carbon capture technologies by using a metal-organic framework (MOF) Applying biological process and chemical looping combustion to develop carbon capture technologies Producing polycarbonates and polyurethanes, enhancing oil recovery by utilizing CO_2. Converting CO_2 into valuable products [12]
Saudi ARAMCO Carbon Management Division	**Some of CCUS initiatives:** Saudi Aramco's Uthmaniyah Carbon Dioxid Enhanced Oil Recovery (CO_2-EOR) in Eastern Province of Saudi Arabia; it is a pilot project to capture approximately 800 thousand ton/year CO_2 [44]. The Prototype vehicle has been presented 10% of its emissions and 20% of the second prototype in 2013 [45]. Building Ethylene Glycol plants to capture 500 thousand tons/year of CO_2 in the industrial city of Jubail [46].

3.2. Community Contribution: A Building Intervention Approach

3.2.1. Existing National Energy-Saving Regulation and Policy Actions

Initiatives have been introduced to lower energy demand through promoting and modifying energy efficiency standards and the design and structure of residential building. The table in Appendix D describes various essential aspects in regulating a framework for energy management and actions taken in the power generation sector, petroleum and petrochemical sector, and energy efficiency adaptation in the residential sector. These initiatives and their actions have limited resources (e.g., some are time consuming, use many resources, and need considerable funding, as explained in Appendix D).

3.2.2. Evaluating the Performance of ESO Combinations Performance

The total energy consumption and GHG emissions by residential buildings consist of different combinations, namely one-ESO, two-ESOs, and Three-ESO based on four interventions (which are double-glazed windows, triple-glazed windows, LED lighting, and efficient split AC units, as shown in Figure 6). These figures show that the total energy consumption is significantly reduced when applying the intervention combinations in residential buildings. The total reduction amount reaches 5–35% of baseline carbon emissions by 2050 based on the number of interventions used as the combinations. Moreover, the Figure 6a–e shows the prediction of total energy consumption, the total GHG emissions, total cost of energy used, and the cost of intervention investment in each combination that impacts each geographical region in residential buildings. The results show that the highest total energy consumption for almost 7.135 million residential buildings in the Kingdom of Saudi Arabia among the three building types (i.e., detached, attached, low-rise apartment residential building) in all regions ranging from 30 TWh/year in the northern region to 290 TWh in the central region in 2050. This is mainly due to the rapid increase in population and housing demand in these regions. This may be because of the increase in the predicted housing number. The central region has the most significant number of 2.26 million residential buildings with the highest proportion of 890 thousand detached residential buildings, representing the highest energy consumption of residential building type.

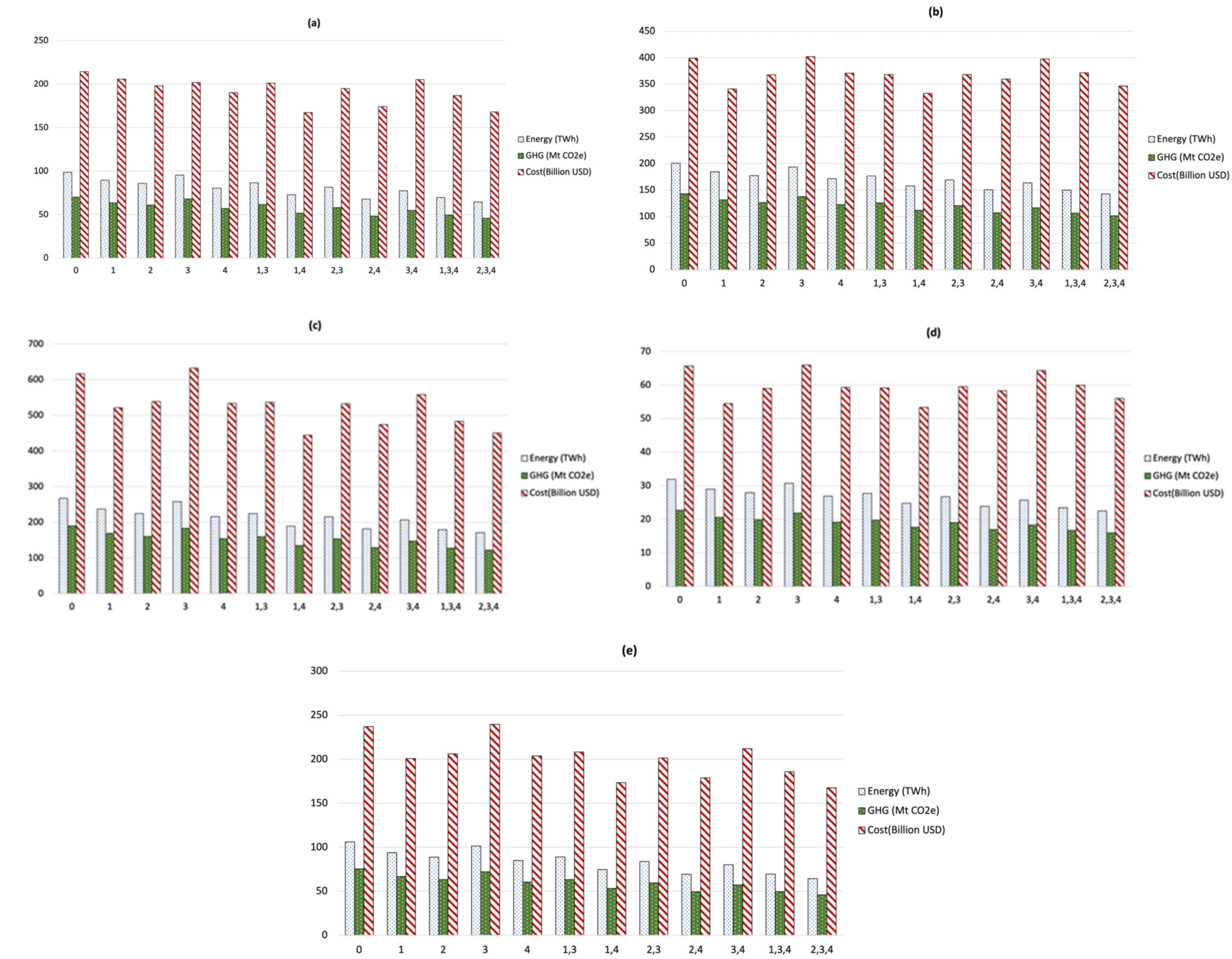


Figure 6. Energy-GHG-Cost in (**a**) southern (**b**) western (**c**) central (**d**) northern (**e**) eastern regions of Saudi Arabia.

Similarly, the GHG emissions reduction for three residential building types with different ESO combinations in each region is shown in Figure 6. The GHG emission reduction in the central region from 184 to 121 Mt CO_{2e}, 137 to 101 CO_{2e} in the western region, 72 to 46 CO_{2e} in the eastern region, 68 to 46 CO_{2e} in the southern region, and 22 to 16 CO_{2e} in the northern region. The total cost of intervention combinations and total cost of energy use in each region is defined in Figure 6a–e e.g., the highest total cost is in the central region from $632 to $450 billion, and the lowest total cost is in the northern region from $66 to $56 billion.

Furthermore, the cost of energy used and total saving energy after applying intervention is based on building intervention energy of combinations in each residential building until 2050. The findings in the saving cost in Figure 7a,b have a positive impact, parallel with the government planning initiatives such as Saudi Energy Efficiency Center, Saudi Energy Efficiency Program, and Electricity and Cogeneration Regulatory Authority [40,42,47], and government GHG emissions reduction initiatives such as The National Capacity and Saudi ARAMCO Carbon Management Division [44,48]. However, applying the interventions in Low-rise Apartment buildings is not an ideal solution based on the negativity of saving costs, as shown in Figure 7c.

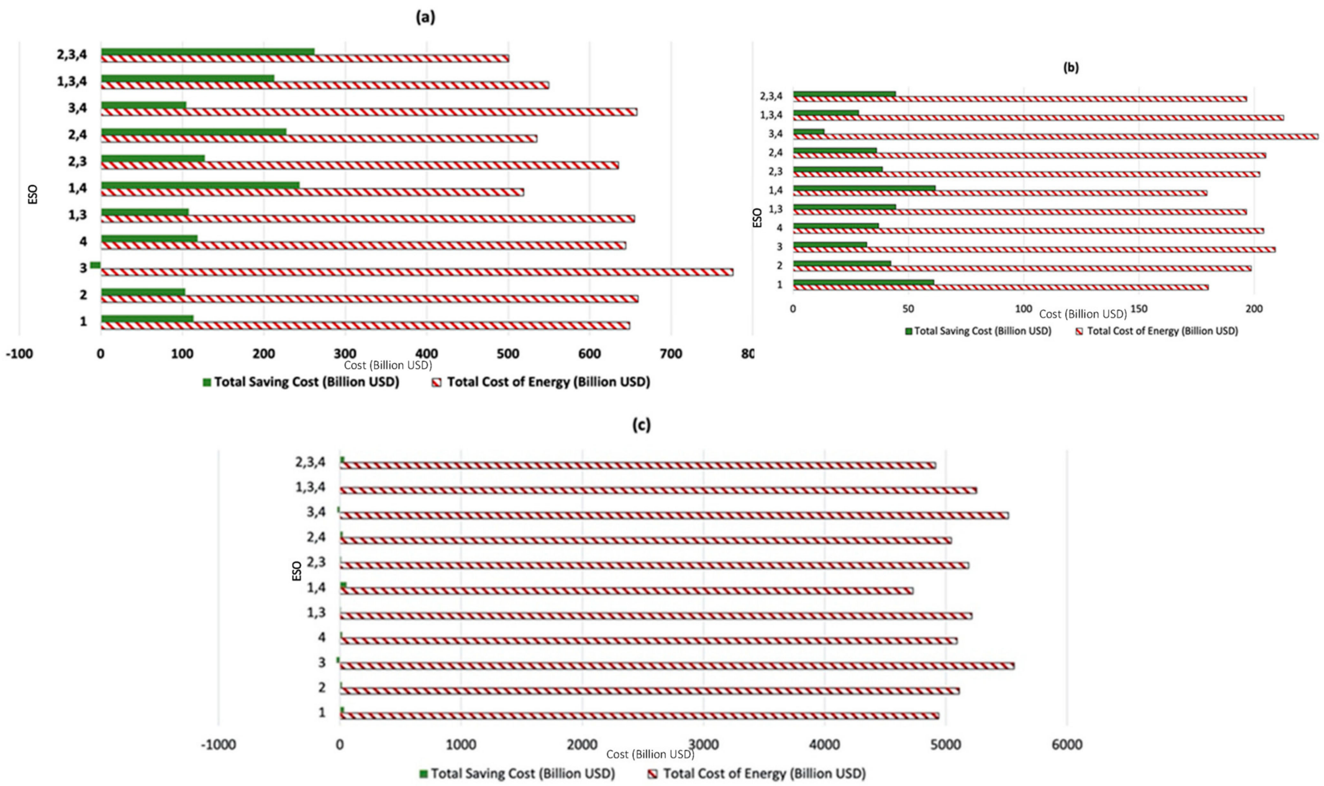


Figure 7. Comparison of cost of energy & ESO investment cost with saving cost between 2020 to 2050 in (**a**) detached residential building (**b**) attached residential building (**c**) low-rise apartment building.

3.2.3. Performance of Building Energy Use

The sustainability of building energy performance is evaluated for existing and newly constructed residential buildings. Residential buildings were classified into three categories based on the number of interventions (Energy Saving Options ESOs), namely either One-ESO, Tow-ESOs, and Three-ESOs used. The sustainability performance of building energy use is assessed by aggregating three criteria (energy, GHG emission, and cost) using the weighted sum method considering two scenarios (pro-economic and pro-environment). The priority scores of each ESO combination in each region is shown in Figure 8a–e for pro-economic scenario and in Figure 8f–j for pro-environmental scenarios. Based on Figure 8, the best ESO combination in each building type in each region under each weighting scenario. Based on the estimated priority scores, ESO_{234} is the best option among all ESO combinations in each building type in all regions under the pro-environmental scenario since ESO_{234} has sufficient energy saving and reduces GHG emissions. Thus, the ESO_{234} needs more investment in interventions, but it is sufficient for reducing the electricity bill in the long run. Under the pro-economic scenario, the same ESO_{234} is the most preferable among all ESO in each building type except in the attached residential buildings in the southern and western regions, where ESO_1 is the best option as ESO_1 has the lowest total cost in the attached residential building as shown in Figure 8a,b. From the cost perspective, the ESO_1 is the best alternative option for attached residential building caused by high electricity bill for long term and cold and humidity climates, respectively, in these particular areas [16,27,28,49].

Thus, the TOPSIS method is based on the ranking of classified ESOs combinations. The tables below show the optimal solution for each scenario based on residential building and selected geographical region and Level of Energy Sustainability in Residential Building (LESRB). TOPSIS was used to generate a score and rank them, as shown in Appendix C.

LESRB is a degree of best solution intervention in the specific existing type of residential ranked based on their value which has been divided into four levels of importance based on the number of intervention and the effectiveness of cost-benefit analysis (for both the capital investment cost of interventions and cost of energy for a period of 30-year) and the maximum number of alternatives in the category. The LESRB solution importance values are defined below in Table 5.

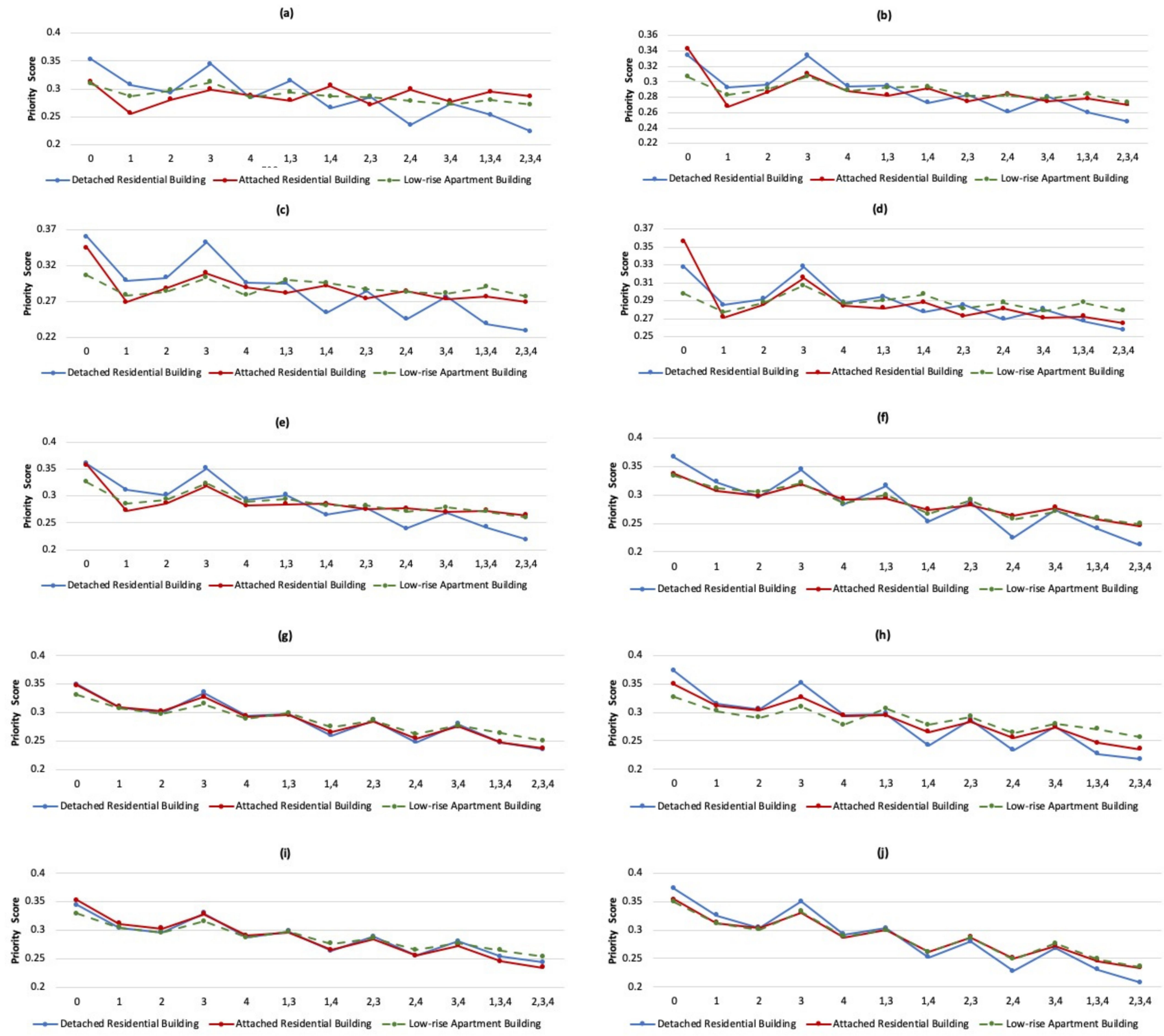


Figure 8. Priority scores of ESO combination in (**a**) southern, (**b**) western, (**c**) central, (**d**) northern, (**e**) eastern, under pro-economic; and (**f**) southern, (**g**) western, (**h**) central, (**i**) northern, (**j**) eastern under pro-environmental.

Table 5. LESRB solution definitions.

LIRRB	Definition
1	Strong important solution
2	Less strong important solution
3	Essential important solution
4	Less important solution

Precisely, the TOPSIS technique can compare ideal alternatives based on calculating a similarity to the positive-ideal solution by aggregating the proximity to the positive-ideal solution and the farness from the negative-ideal solution. This method is a selected criterion to identify the optimal solution with the maximum similarity to the positive-ideal solution. Moreover, TOPSIS is a reliable technique for finding the best alternatives in the selected criterion due to its ability to consider an unlimited number of alternatives in the decision-making process [16].

3.3. Government Contribution: Clean Energy Approach

The National Renewable Energy Program (NREP) is a program that formulates Saudi Arabia's National Transformation Program (NTP), which aims to generate 3.45 GW of renewable energy in 2020. Additionally, the country is expected to increase its total energy mix by renewable energy to reach 9.5 GW by 2023 [50]. The clean energy value chain in the Saudi economy is predicted to have a significant impact, and the government vision is to privatize a massive portion of this particular industry and developing legislation to allow the private sector to invest in the clean energy sector [50] (Ministry of Industry and Mineral Resources, 2018).

3.3.1. Existing Clean Energy Actions in Saudi Arabia

Several comprehensive studies on renewable energy options have been conducted for different parts of Saudi Arabia. These studies have been carried out by finding suitable combinations of alternative technologies that suit the country's climate conditions. The table in Appendix E shows the clean energy actions and possible studies for future projects. No single energy storage system captures all requirement energy from renewable energy systems [51].

Saudi Arabia has the potential to be leading in clean energy especially using a solar radiation source. In contrast, one of the researchers found out the daily varies of solar radiation in Saudi Arabia is between 4 to 7.5 kWh/m^2, which is 4 to 7 times counterpart in Europe by 1 kWh/m^2. Thus, Appendix E describes several clean energy actions the Kingdom has considered for last years and emphasizes enhancing the environment by adapting more clean energy projects [52–55].

3.3.2. Renewable Energy Cost in Saudi Arabia

Saudi Arabia has developed an Energy Technology Program divided into seven rank technical areas as fallowing:

(1) Renewable energy generation;
(2) Conventional energy generation;
(3) Electricity distribution and transmission;
(4) Energy conservation and management;
(5) Energy storage;
(6) Fuel cell and hydrogen;
(7) Combustion.

Thus, Saudi Arabia has supported several possible feasibility studies projects for clean energy, as described in Appendix F.

3.3.3. Identification of Clean Energy Alternatives

The clean energy approach is the process of approaching the GHG emissions reduction for the country and meeting its targets. It affirms its hold on its vision of a sustainable environmental future through the following four steps.

Thus, the first step has been addressed comprehensively in Appendix C and Section 3.3.4 and what can be summarized in this research includes:

- The total energy for the residential sector in Saudi Arabia is 143,000 GWh;
- The NDC's goal is to cut 130 million tonnes of CO_{2e} until 2030;
- CO_2 factor for fossil fuel in Saudi Arabia is 0.5454;
- CO_2 emissions of Fossil fuel in Saudi Arabia is 118 million metric tons of carbon;
- Petroleum products consumed 64.2% of fossil fuels;

- Residential building electricity tariff in Saudi Arabia is about 0.048 USD/kWh for energy consumption between 1 and 6000 kWh and 0.80 USD/kWh for energy consumption is more than 6000 kWh;
- International utility fuel production cost is estimated to be $0.1678 per kWh, and Saudi Arabia's government subsidies of the electricity tariffs are around US$0.0479, which means 19.1 billion from 128.9 billion goes toward energy subsidies.

The second step has been explained in terms of how much the public is willing to invest in the intervention and how much their contribution can reduce the GHG emissions in the residential sector, as shown in Figure 9. For instance, if the public decides to reduce the GHG emissions in the residential sector by replacing their home fluorescent lighting and other lighting with efficient LED lighting, the total cost will be around $8.5 billion. On the other hand, more GHG emissions reduction means more investment needs to be applied based on the simulation analysis and cost-benefit analysis. For example, if the public is willing to reduce the GHG emissions in the residential sector by around 50%, this means the overall public cost will be around $486 billion (which is a vast amount of investment to be considered for next 30 years). Thus, the third and fourth steps will explain the government rule to create a healthy environment that suits all nation aspects.

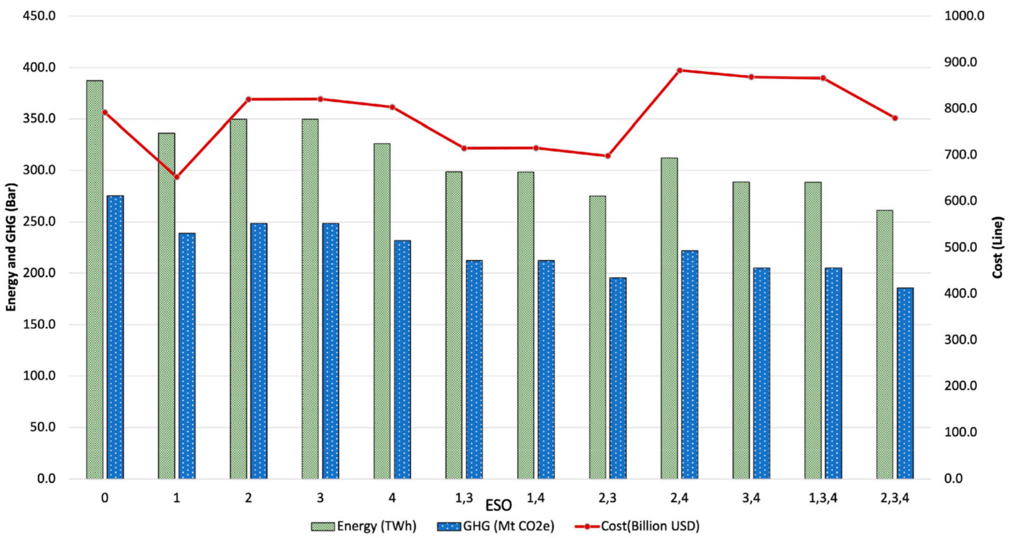


Figure 9. Total energy consumption, GHG emissions, and cost in the residential sector in Saudi Arabia in 2050.

The findings of the CEMPE are shown in Figure 10. The evaluation considers two aspects that are intertwined, the estimated GHG emissions by 2050 (after considering around 7 million residential buildings with 45 million people in the country) and the baseline GHG emissions reported level (which is around 500 Mt CO_{2e}). The Energy Saving Option Combinations that fit these aspects are ESO_1, $ESO_{2,}$ $ESO_{3,}$ ESO_4, ESO_{13}, ESO_{14}, ESO_{23}, ESO_{24} ESO_{34}, ESO_{134}, and ESO_{234}. These interventions are a grantee of GHG emissions reduction to be close to the level of GHG emissions in 2020.

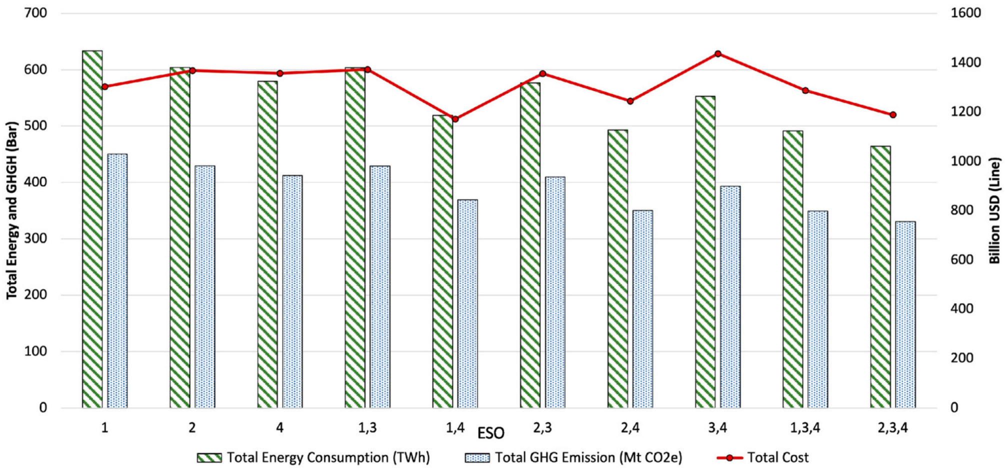


Figure 10. Energy reduction, GHG reduction, and investment required from communities by 2050 under ideal scenarios.

3.3.4. Sustainability Performance of Clean Energy Alternatives

Al-Sharafi et al. [21] studied the alternatives of the GHG emissions reduction by using renewable energy such as solar panel, wind turbine, and their hybrid systems with the storage systems (e.g., battery bank storage system and fuel cell and hydrogen tank system to suit the environment of Saudi Arabia). The study considered the simulation of six different systems which are: system (1) which is a PV array with battery bank system; system (2) which is a wind turbine with battery bank system; system (3) which is hybrid system which is PV array and wind with battery bank system; system (4) which is a PV array with a combination of an electrolyze, fuel cell and hydrogen tank system; system (5) which is a wind turbine with a combination of an electrolyze, fuel cell and hydrogen tank system; and (6) which is a hybrid system of PV and wind with a combination of an electrolyze, fuel cell, and hydrogen tank systems. Each system has been repeated in five different geographical regions in Saudi Arabia. It has been repeated into ten chosen combinations ESO_1, ESO_2, $ESO_{4,}$ ESO_{13}, ESO_{14}, ESO_{23}, ESO_{24} ESO_{34}, ESO_{134}, and ESO_{234} based on the cost-effectiveness of renewable energy need to invest.

As the fourth step of the clean energy approach, the Saudi Arabian government GHG emissions reduction target is 130 $MtCO_{2e}$ until 2030. This means that 20% of GHG emissions reach in 2015 643 $MtCO_{2e}$ (e.g., Saudi Arabia is planning to improve the networking system in smart meters and smart grids). Furthermore, the clean energy alternatives process has defined the best combinations the government needs to conclude into their consideration. At the same time, they will develop renewable energy systems that will replace the traditional energy supply (fossil fuel system) toward residential buildings in the country to meet the reduction vision.

Saudi Arabia will also fully deregulate energy efficiency in residential buildings across the country (e.g., by implementing SEEC energy efficiency standards and adapting "green building" concepts in the building sector). Applying clean energy technologies on-gird deliver the most significant CO_2 emissions reduction in the residential building sector in Saudi Arabia. For example, Saudi ARAMCO is implementing a PV solar system around 26 GWh with different projects around the Kingdom and the General Authority of Civil Aviation is applying long term clean energy approach by implementing 9.3 GWh/year of PV solar system in GACA infrastructure. This study considered lower and upper total investment cost (e.g., if the Government decide to choose system (1) which is PV array with battery bank system the total investment cost between $1.922 to $2.462 trillion, or system (4) which is PV array with fuel cell and hydrogen tank system the total investment cost between $2.066 to $3.188 trillion) while also providing a 32% to 51% of total GHG emissions reduction from estimated GHG emissions increase by 2050, creating net economic benefit ecosystems through international investment, and developing new industry opportunities as illustrated in Figures 11 and 12.

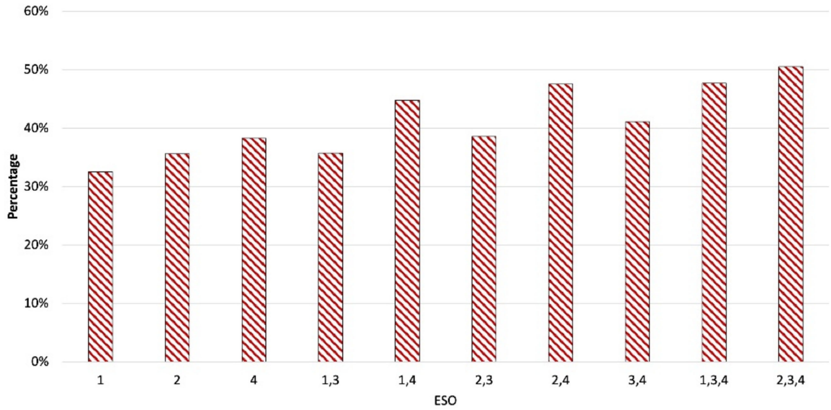


Figure 11. Total GHG emissions reduction in the residential building sector by government intervention through renewable energy.

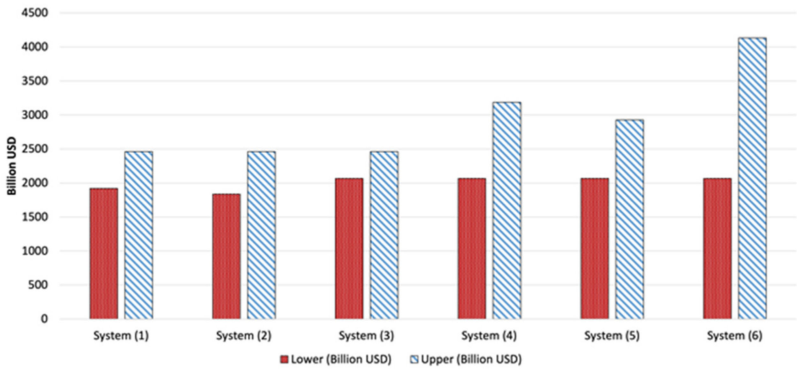


Figure 12. Total investment cost in the residential building sector in Saudi Arabia by government intervention through renewable energy.

Furthermore, system (2) has the minimum renewable energy cost need to invest from the government and private sector (e.g., the Saudi Electricity Company is allowing the private sector to participate in new power generation projects that used renewable energy). Thus, the total investment value is between $0.6 and $0.9 trillion. On the other hand, systems (1) and (3) have higher cost-effectiveness, whereas the investment value is anywhere from $0.8 to $1.2 trillion and from $0.82 to $1.2 trillion, respectively. This approach achieves an excellent reduction in CO_2 emissions. It results in favorable total saving costs while applying the chosen one-ESO and Tow-ESO classified combinations to the Saudi Arabian power generation sector. However, systems (4), (5), and (6) have the maximum renewable energy cost cause of the huge investment needed in the storage system (a combination of Electrolyzer, Fuel Cell, Hydrogen tank system). This investment is estimated to be between $1.5 and $2.2 trillion in system (4), between $1.3 and $1.9 trillion in system (5), and between $2.1 and $3.1 trillion for system (6), which is reflected in the substantial investment need in renewable energy to consider from all parties of the country for the next 30 years. This approach achieves a huge reduction in CO_2 emissions and results in a negative total saving cost to the Saudi Arabian power generation sector, as shown in Figure 13. These can be achievable through the government being willing to invest in future clean energy alternatives in the national grid and to promote the use of renewable energy.

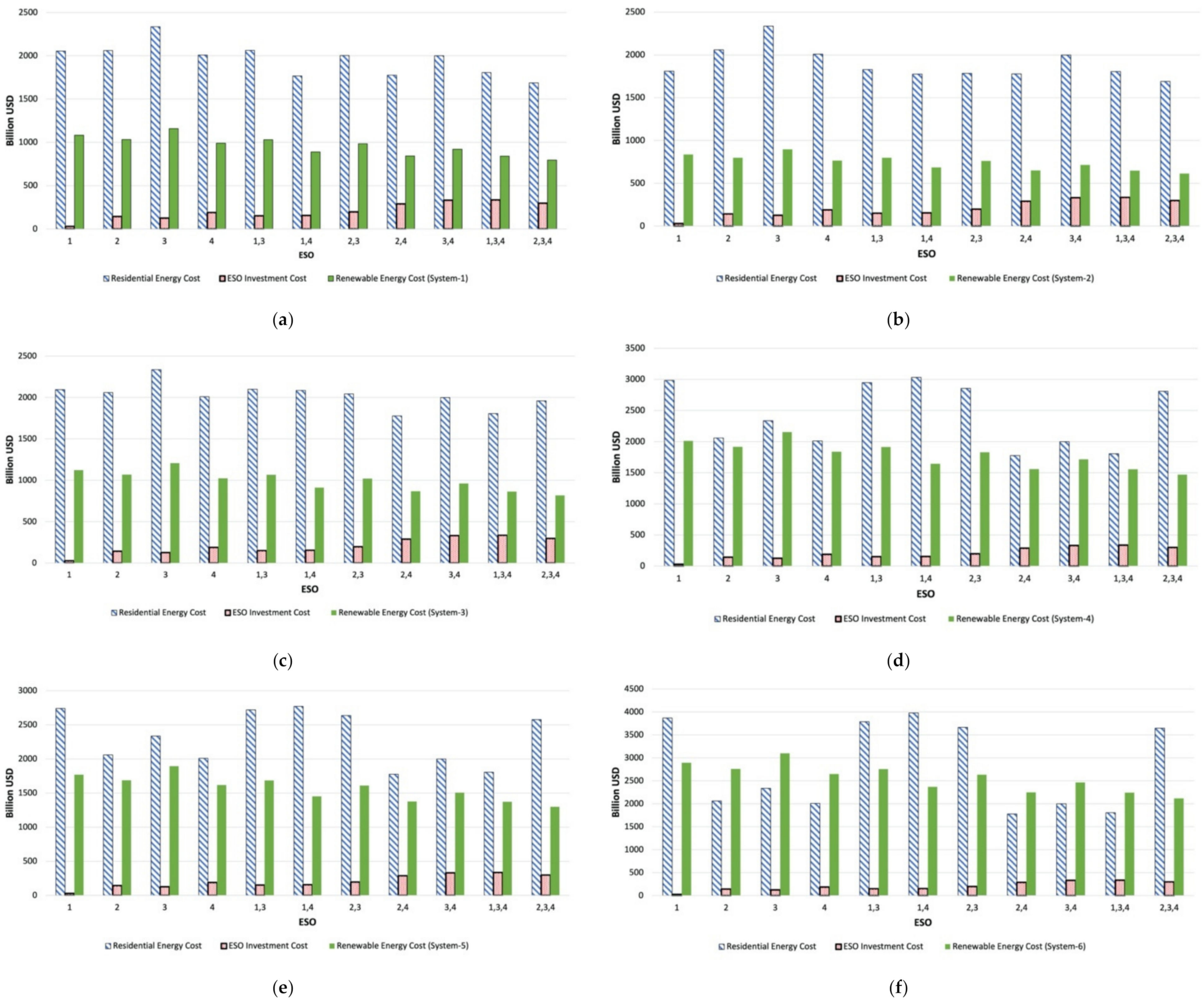


Figure 13. Cost of the system (1, 2, 3, 4, 5, and 6) as present (**a**–**f**) of clean energy in the residential building sector in Saudi Arabia.

4. Conclusions

The challenges of moving towards economic diversification and low-carbon emission in an arid climatic country involves both proposition sides and inevitable sides. Extensive reform in the low-carbon energy framework for energy performance management is required on the proposition side. On the inevitable side there is economic diversification, deregulating energy policies and initiatives, and an awareness of the public opinion on climate change and global warming. Furthermore, creating a healthy environment for the industrial base to accelerate renewable energy innovations is a necessary transformation in the energy policy system through the low-carbon energy framework for energy performance management to lower carbon capture at the macro-community level (country level) in the effort toward achieving appropriate sustainable stability. Additionally, the integration of homeowners with financial institutions for long-term clean energy investment is necessary to complete the transition.

A community-government partnership framework has been proposed for low-carbon energy use in residential buildings in hot and arid regions. The framework comprises two approaches: the building intervention approach for the community and the clean energy approach for the government. Communities' building intervention approach and the government's clean energy approach are set to identify the best combinations of buildings (retrofits) and non-building (energy source) renewable energy options to meet the country's GHG emissions reduction target. The clean energy approach considered six different renewable power generation systems (i.e., Solar PV array, wind turbine, and hybrid system with two types of storage systems (battery bank storage and a combination of electrolyzing, fuel cell, and hydrogen tank storage)). This study identified an appropriate partnership between communities and the government to meet the GHG target. This framework can lower carbon emissions at the country level by integrating micro-level (community) and macro-level (government) contributions. This framework manages a combination of different aspects used to understand energy consumption patterns and GHG emissions in residential buildings. This framework benefit is a possible way to avoid energy losses, acknowledge, execute the policies and necessity initiatives at all levels to protect the environment, and emphasize stakeholders (homeowner, developer, private sector, government) to build a better future.

The proposed framework fits technically with the current changing policies, vision, and national transformation panel toward clean energy in Saudi Arabia (e.g., the NEOM region, a future transformation area located in the northwest of Saudi Arabia). Saudi Arabia Vision sets the path toward self-economic sustainability and to enables the country to become a leading contributor to solar energy technologies worldwide (Neom, 2021). The proposed framework summarized the contribution into several systems were considered to develop and implement renewable energy replacement development. This process identified a suitable system with the best combinations that guarantee sustained improvement in the performance of the residential buildings in Saudi Arabia.

The future research in energy policy analysis concludes a possible further research through applying FIT policy that will contribute to reducing the CO_2 emissions, enhancing the Saudi Arabia economy through developing the renewable energy industry, and eliminating electricity tariffs subsidies will provide a net economic benefit by $19.1 billion annually.

However, this paper has date limitations that need detailed data on occupant behavior and building properties. The variability in human behavior was not considered, and only a limited number of energy saving options or retrofits were considered.

Furthermore, Saudi Arabia could be a place for the worldwide clean energy industry for many reasons:

- The solar radiation source is four to seven times greater than Europe;
- Expanding renewable energy programs by $30 to $50 billion including feasibility studies, actual initiatives, clean energy action, and focusing on clean technology research areas have been conducted in renewable energy. This has transformed the country into a healthy land for long-term investors
- Considering both the vertical and horizontal diversifications concepts toward renewable energy (e.g., using the vertical diversification concept) could lead to a potential development into a solar-to-renewable power generation plant in Saudi Arabia, which means utilizing the country's mineral resources to expand in local renewable energy production and manufacture (Know-how) and exporting the outcome energy production to neighboring countries and Europe.

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Appendix A. Population Prediction

Table A1. Population prediction in Saudi Arabia (1955–2050).

Year	Population	Yearly % Change	Yearly Change	Urban Pop %	Urban Population	Country's Share of World Pop	World Population	Saudi Arabia Global Rank
2050	44,562,476	0.42%	182,728	91.40%	40,708,624	0.46%	9,735,033,990	46
2045	43,648,838	0.55%	235,161	90.30%	39,396,408	0.46%	9,481,803,274	47
2040	42,473,031	0.67%	279,931	89.20%	37,878,811	0.46%	9,198,847,240	44
2035	41,073,374	0.88%	350,207	88.10%	36,170,029	0.46%	8,887,524,213	41
2030	39,322,338	1.09%	414,684	86.80%	34,142,975	0.46%	8,548,487,400	42
2025	37,248,919	1.36%	487,010	85.50%	31,842,626	0.46%	8,184,437,460	42
2020	34,813,871	1.88%	619,241	84.00%	29,255,576	0.45%	7,794,798,739	41
2019	34,268,528	1.68%	565,772	83.80%	28,700,362	0.44%	7,713,468,100	41
2018	33,702,756	1.82%	601,577	83.50%	28,133,138	0.44%	7,631,091,040	41
2017	33,101,179	2.03%	657,732	83.20%	27,543,623	0.44%	7,547,858,925	41
2016	32,443,447	2.29%	725,780	83.00%	26,918,214	0.43%	7,464,022,049	41
2015	31,717,667	2.95%	859,241	82.80%	26,249,243	0.43%	7,379,797,139	41
2010	27,421,461	2.86%	721,056	82.10%	22,512,101	0.39%	6,956,823,603	45
2005	23,816,183	2.88%	630,468	81.30%	19,358,664	0.36%	6,541,907,027	47
2000	20,663,843	2.08%	405,011	80.20%	16,579,826	0.34%	6,143,493,823	49
1995	18,638,787	2.80%	481,000	79.10%	14,739,559	0.32%	5,744,212,979	48
1990	16,233,785	4.35%	622,958	77.00%	12,503,513	0.30%	5,327,231,061	51
1985	13,118,993	6.24%	685,503	73.00%	9,581,553	0.27%	4,870,921,740	52
1980	9,691,476	5.49%	454,397	66.20%	6,415,124	0.22%	4,458,003,514	61
1975	7,419,493	4.92%	316,621	58.40%	4,334,558	0.18%	4,079,480,606	71
1970	5,836,389	3.80%	198,551	48.70%	2,840,506	0.16%	3,700,437,046	76
1965	4,843,635	3.46%	151,419	38.80%	1,877,805	0.15%	3,339,583,597	84
1960	4,086,539	2.81%	105,677	31.30%	1,277,054	0.13%	3,034,949,748	83
1955	3,558,155	2.65%	87,364	26.00%	923,917	0.13%	2,773,019,936	84

According to a 2019 estimation by the United Nations, Saudi Arabia's population is 34,140,662. The number has been growing ever since and will exceed 45 million people by 2050. Furthermore, the number of residential buildings distributed in 2018 in each administrative region are around five million houses (General Authority for Statistics, 2018b). As a result, the population distribution in each region in 2050 can be estimated based on the classified residential building, as described in the table below.

Table A2. Estimation of population prediction based on the geographical region 2050.

Geographical Region	Detached Residential Building		Attached Residential Building			Low-Rise Apartment Building	Total
	Villa	A Floor in Villa	Traditional House	A Floor in Traditional House	Other		
Central	3,499,233	2,060,644	1,196,786	422,082	765,429	6,194,623	14,138,797
Western	726,678	440,625	3,479,207	401,604	630,561	9,576,672	15,255,347
Eastern	1,274,349	410,142	455,301	150,324	213,422	3,682,621	6,186,159
Southern	819,437	740,376	1,657,696	322,766	177,045	2,874,929	6,592,249
Northern	186,155	132,197	629,285	92,096	152,741	1,197,448	2,389,923
Total	6,505,852	3,783,984	7,418,276	1,388,872	1,939,199	23,526,293	44,562,476

The figure below has described the distribution of populations in each geographical region in 2050. Whereas the population of the western region is expected to be the largest region in the country, with about 15 million people, followed by the central region with about 14.1 million. Additionally, the southern and eastern regions will be estimated to have 6.58 and 6.18 million people by 2050, respectively. Finally, the Northern Region will be expected to have more than 2.38 million people, around 23% more than the population in 2018 [25].

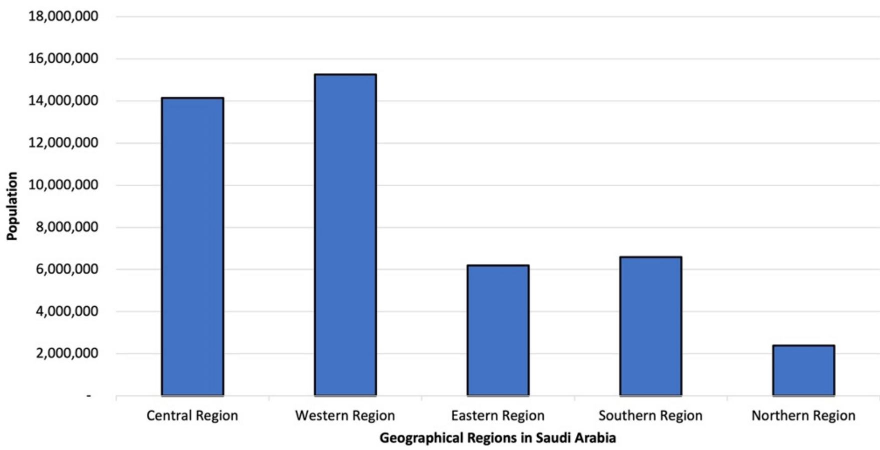

Figure A1. Geographical regions discerption of population growth in 2050 in Saudi Arabia.

Appendix B. Energy Analysis Systems Suite the Environment in Saudi Arabia

Economic Diversification in Saudi Arabia

Economic Diversification and the Tenth Development Plan in Saudi Arabia

The 10th development plan of the Kingdom of Saudi Arabia (2015–2019) advised economic diversification through three major dimensions, namely vertical, horizontal and spatial diversifications, as discussed briefly below.

Vertical diversification: vertical diversification is based on local production, processing, and manufacturing of raw mining materials (Designated National Authority, 2018). On the other hand, Saudi Arabian industries are developing production and service activities in the oil industry that lead to a possible development into a crude oil-to-chemicals plant.

Horizontal Diversification: The objectives of horizontal diversification are to [56]:

(i) Increasing production capacities of the industrial sector;
(ii) Enhancing the quality of the services sector;
(iii) Developing the non-oil based economic activities in non-oil sectors;
(iv) Encourage the private sector to invest in energy sources projects;
(v) Encourage non-oil exports;
(vi) Developing low-water-consuming agricultural products and fishing products;
(vii) Developing local and foreign strategic partnerships to introduce investment program that contributes into the economic diversification.

Spatial Diversification: The 10th development plan of the Kingdom is encouraging the provinces through boosting spatial diversification of economic activities based on the growth and development of industrial zone concepts and business-technology incubators in each region of the country. Several cities have implemented spatial economic diversification through developing industrial areas. For example, at Rabigh, Hail, Madinah, and Jazan, four new economic cities are due to be completed by 2020 with anticipated populations of 40,000, 80,000, 200,000, and 250,000, respectively [57]. Additionally, the Royal Commission of Jubail and Yanbu has approved the expansion at Jubail and Yanbu cities. Additionally, two new industrial areas have been developed in Ras Al-Khair in the Eastern Province and Waad Al-Shammal near Turaif in the country's north.

Economic Diversification and Intended Nationally Determined Contribution (INDC) of Saudi Arabia under the UNFCCC.

Intended Nationally Determined Contribution (INDC) is part of Saudi Arabia's commitment to UNFCCC principles listed in Article 3 and its specific commitment to economic diversification initiatives and adaptation measures as UNFCCC decision 24/CP.18 in Doha in 2012. Saudi Arabia will engage in actions and plans to pursue economic diversification that helps form greenhouse gas (GHG) emissions, which will assist in achieving its sustainable development objectives [58].

The steps taken by Saudi Arabia include:

(i) Economic diversification initiatives;
(ii) Climate change initiatives;
(iii) R&D activities on climate change;
(iv) Attempts to reduce impacts of international climate change policy responses.

The initiatives that mitigate co-benefits of economic diversification are [57]:

(i) Energy efficiency & renewable energy;
(ii) Carbon capture, utilization, and storage;
(iii) Utilization of gas;
(iv) Methane recovery;

The planning activities that measure the GHG emissions reduction are based on a degree of implementation and availability of funds as follows:

(i) Water and wastewater management;
(ii) Urban planning;
(iii) Marine protection;
(iv) Reduced desertification;
(v) Integrated Coastal Zone Management Plan (ICZMP);
(vi) Early Warning Systems (EWS);
(vii) Integrated Water Management Plan (IWMP)

Appendix C. Research and Development in Saudi Arabia

Clean technology and the environmental issues have been the focus of many research areas, as described in the table below.

Table A3. Research and development in clean energy in Saudi Arabia.

Responsible Source	Research Proposal	Location	Research Note
Saudi Aramco	The company established a fuel research center to develop more efficient combustion engines using modification petroleum formulations methods.	Paris, France	[59]
Saudi Aramco	The company established the Mobility Center to deploy and engage with automobile manufacturers in the USA to find suitable technological solutions to reduce the carbon emissions that cause by automobile products.	Detroit, USA	[59]
Ministry of Education	The Ministry has initiated to established centers of research excellence in clean technologies.	-	Ministry of Education
King Abdulaziz City of Science and Technology (KACST)	The center builds an infrastructure to support the scientific community through managing research grants, the availability of databases, and executing applied research.	KACST	[60]

Table A3. *Cont.*

Responsible Source	Research Proposal	Location	Research Note
King Abdulaziz City of Science and Technology (KACST)	Establishing a long-term initial program to encourage local technology projects through the National Science, Technology, and Innovation Center.	Technology Development Center, KACST	KACST
Massachusetts Institute of Technology (MIT) and KFUPM	The Center for Clean Water and Clean Energy was established to research desalination, low carbon energy, and applied research and manufacturing. The center granted achievement in the water field for more than 20 IPs and three new technologies.	MIT	KFUPM
KACST and Advance Water Technology Company (AWTC)	The institutions signed an agreement to study solar water desalination plants based on planning the design and construction. This plant production capacity of 60,000 cubic meters/day.	Al Khafaji	[57]
The center for Clean Water and Clean Energy	The center collaborates between these two academic institutions to manage research for new technology to enhance freshwater production and low carbon energy.	MIT and KFUPM	KFUPM
Center of Research Excellence in Renewable Energy	The center aims to collaborate with other institutions to enhance the science and technology related to renewable energy in significant solar cells, solar cooling, heating PV, and energy storage.	KFUPM	KFUPM

Part of Saudi Arabia's government vision is to reduce its carbon emission by 130 million tons of carbon dioxide (or something equivalent) by promoting energy efficiency and renewable energy technologies. The government has established some programs (e.g., National Energy Efficiency Program (NEEP) through King Abdulaziz City for Science and Technology (KACST)) to support research and development tasks and provide consultation related to meet the country's vision and enhance the national energy consumption patterns. The Government of Saudi Arabia also promotes another program to improve the energy efficiency for the residential sector and other sectors in 2010, Saudi Energy Efficiency Center (SEEC) [40]. However, the King Abdullah City for Atomic and Renewable Energy (KA-CARE) is planning to set a target to add 4% of renewable energy in total energy used in Saudi Arabia by 2020 [61]. According to the Climate Action Tracker, Saudi Arabia, its public investment fund is planning to locate the electric vehicle industry in Saudi Arabia by investing more than $1 billion to the United States-based electric vehicle manufacturer. Also, the government signed a memorandum with the SoftBank Group to build the most significant single solar project worldwide by the capacity of 200 GW Giga Watt in March 2018 [62].

Appendix D. Energy-Saving Regulation and Policy Actions in Saudi Arabia

Initiatives and actions for energy saving regulations that contribute from the different sectors in Saudi Arabia, as described in the table below.

Table A4. Energy, regulation, and policy actions in Saudi Arabia.

Initiative/Responsible Sector	Actions
National Strategy: smart meters and smart grids	Improving the reliability of the networking system and the quality of service. Also, increasing the efficiency of the option. Enhancing and utilizing assets, the benefits of the initiative are: Reduce complaints Reduce the cost of reading the meters Providing additional services to consumers The flexibility of renewable energy integration into the system [63]
King Abdullah City for Atomic and Renewable Energy (KACARE)	ECRA conducted a framework study for electricity generation activities, a heat recovery steam generator, and water desalination by applying atomic and renewable energy [64].
Ministry of Energy, Industry, and Mineral Resources (MEIM)	MEIM is seeking to reduce the peak demand to target the large air condition loads to incorporate thermal energy storage systems through establishing a demand-side management program [65].
Saudi Electricity Company	The private sector contributes to the new power generation projects while reorganizing the electricity sector into three main sectors: generation, transmission, and distribution.
Energy Conservation and Awareness Department in MEIM	The department implements energy conservation initiatives: Enabling commercial, governmental, agricultural, and industrial sectors to reduce energy consumption and shift peak loads. Prohibition of irrigation during peak load times in the agriculture sector. Initiate Energy Conservation and Load Management Consumers Guide. Promoting Public awareness of energy conservation throughout workshops and meetings. Promoting energy conservation procedures and load reduction tools to the primary consumers in the governmental sector [66].
Power Generation Sector	Adapting combined-cycle operation through: Can reduce the fuel consumption by converting inefficient single-cycle gas turbines to the combined- cycle [67]. Increase the electricity generation from 35 generators in 2005 to 74 generators in 2014. Thus the cogeneration entities' capacities in 2013 were 15,375 MW of electricity, 5,240,001 m3/day of water, and 14,374 ton/hour of steam [64].
Petroleum Sector	Reasonable use of energy resources: Energy conservation savings program saves 112.81 thousand barrels eq. Per day between 2000 to 2010. Also, it saved approximately 170 million cubic feet of gas per day in 2013. The energy conservation program is responsible for reducing 3% of refining energy intensity in 2014. To eliminate gas flaring and liquid hydrocarbon by using zero-discharge technology at onshore and offshore well-site, it minimized the flaring from 0.89% to 0.72% in all upstream in 2013. Resulting in a reasonable use in the operations sector by 160.85 thousand barrels of oil eq. Per day between 2002 to 2014 [68].

Table A4. *Cont.*

Initiative/Responsible Sector	Actions
Petrochemical Sector	Implementing SEEC's energy efficiency standards: Achieving reduction compare by 2010 and 2013 in GHG intensity by 2% to 5% energy consumption intensity, 5% water consumption intensity, and 10% material loss intensity [69]. Reduction in GHG emissions by 15% and 9% in energy consumption by retooling boilers and upgrading in the operational phase [69]. Reducing GHG emissions by 125,000 tonnes and saving 784,000 GJ of energy yearly by processing vent gas reutilization projects [70]. Saving 99 thousand ton/year of natural gas and 4.160 million GJ/year of energy consumption reduction and 229 thousand CO_{2e}/year of GHG emissions reduction, and 1.040 million ton/year of additional steam through high-pressure steam extraction implementation [70].
Buildings Sector	Adaptation of Green Building concept: Recently, the country has more than 300 green building projects and 20 million m^2 occupied area by green building in 2014. The country plans to build 90,000 eco-environment mosques using renewable energy sources [12].

Appendix E. Clean Energy Technology in Saudi Arabia

Clean energy technology system that have been used in different locations and variance capacity in Saudi Arabia, as described in the table below.

Table A5. Clean energy actions in Saudi Arabia.

Clean Energy System	Responsible Sector	Clean Energy Action	Location/Date	Capacity	Resource
Solar system	Energy Project Development Office (REPDO) of Kingdom's Ministry of Energy, Industry and Mineral Resources (MEIMR)	The department has licensed several companies for this project	Sakaka city, AlJouf	300 MW	Kingdom's Ministry of Energy, Industry and Mineral Resources (MEIMR)
solar thermal plant	(REPDO) in (MEIMR)	The department has qualified several companies for this project	Riyadh, 2012	25 MWh	Kingdom's Ministry of Energy, Industry and Mineral Resources (MEIMR)
Solar system	The General Authority of Civil Aviation (GACA)	GACA established ground-mounted of the solar system for long term clean energy approach	GACA, June 2013	9.3 GWh/year	The General Authority of Civil Aviation (GACA)
Solar system	Saudi Electric Company (SEC) and Showa Shell Sekiyu	Both companies commissioned a pilot	Farasan Island, Jazan, 2011	864 MWh/year	Saudi Electric Company (SEC)

Table A5. *Cont.*

Clean Energy System	Responsible Sector	Clean Energy Action	Location/Date	Capacity	Resource
Solar system	Saudi ARAMCO	The car park mounted the system in the company location	Saudi ARAMCO, 2012	17.5 GWh/year	Saudi ARAMCO
Solar system	Saudi ARAMCO	The company established the solar park and installed around 130 solars to powered lighting bollards and powered streetlight in the campus residential compound	King Abdullah University of Science & Technology (KAUST)	-	Saudi ARAMCO
Solar system	Saudi ARAMCO	The company assigned a ground-mounted solar system	King Abdullah Petroleum Studies and Research Center (KAPSARC), 2013	5.8 GWh/year	Saudi ARAMCO
Solar system	Saudi ARAMCO	The company assigned the second project the ground-mounted solar system	King Abdullah Petroleum Studies and Research Center (KAPSARC), 2014	3 GWh/year	Saudi ARAMCO
Solar system	Saudi ARAMCO	The company assigned a solar rooftop-mounted array	King Abdullah Financial District Riyadh, 2012	330 MWh/year	Saudi ARAMCO
Utility-scale solar plant	Saudi Arabia Government	The Government assign the project	Makkah, 2018	385 GWh/year	Saudi ARAMCO
Wind system	Saudi Arabia Government	The Government developed a renewable energy atlas for collecting wind resources monitoring data for developers, researchers, and stakeholder	Saudi Arabia	40 sites throughout the Kingdom	[71]
Wind system	Saudi ARAMCO	The company planned to install the system at its facility	Turaif	3.3 MW	Saudi ARAMCO
Wind system	Saudi ARAMCO	The company planned to install two wind turbines to generate power for the communication towers	Two different remote location	6 KW	Saudi ARAMCO

Table A5. *Cont.*

Clean Energy System	Responsible Sector	Clean Energy Action	Location/Date	Capacity	Resource
Wind Farm	Energy Project Development Office (REPDO) of Kingdom's Ministry of Energy, Industry and Mineral Resources (MEIMR)	The Government has qualified several companies to build the system	Midyan	400 MW	Kingdom's Ministry of Energy, Industry and Mineral Resources (MEIMR)
natural gas with solar systems	Saudi Arabian Government	The Government planned to build a power plant of natural gas-fired integrated with solar combined cycle	Saudi Arabia, 2017	550 MW + 50 MW	Saudi ARAMCO
Solar system	First Energy Bank and Vinmar International Company	The companies announced a plan to build a polysilicon plant to meet the growing demand for the system	Saudi Arabia	7500 tons/year	Saudi ARAMCO
Solar system	IDEA Polysilicon Company and Solar Wafers Company	The companies will build high purity polysilicon plant and wafers	Yanbu Industrial City	10,000 tons/year	Saudi ARAMCO
Solar system	KFUPM	A research team at the institution won the World Solar Challenge in 2011 by manufacturing a solar vehicle.	Australia	cruising speed was 80 km/h with a max speed was 140 km/h	KFUPM

Appendix F. Feasibility Study Projects for Future Clean Energy Technology in Saudi Arabia

Clean energy technology systems the county are willing to add in different locations with the expected cost estimation in Saudi Arabia, as described in the table below.

Table A6. Feasibility study projects for clean energy possibility in Saudi Arabia.

Clean Energy System	Feasibility Study Project	System Location	Cost of Energy (COE)/Unit Energy	Resources
PV	By using 2 kW convertors & 7 Batteries	Yanbu Region, Saudi Arabia	0.609 $/kWh	[72,73]
wind-photovoltaic (PV)-fuel cell (FC) (Cost of Energy)	-	Abha Region, Saudi Arabia	208 $/kWh	[74,75]
Wind-PV-FC (Cost of Hydrogen)	-	Abha Region, Saudi Arabia	43.1 $/kg	[49,76]
Wind	economic feasibility study of 600 kW wind power plants in the coastal areas	Al- Wajh, Jeddah, Yanbu and Jizan, Saudi Arabia	0.0594 $/kWh	[49,76,77]

Table A6. *Cont.*

Clean Energy System	Feasibility Study Project	System Location	Cost of Energy (COE)/Unit Energy	Resources
Wind-PV with Diesel Hybrid	economic feasibility study of 500 kW of PV and 4 Diesel generators system	North-Eastern region, Saudi Arabia	0.038 $/kWh	[78]
Wind-PV with Battery Storage	Studied the performance of loading demand of 1 kW for 12 h/day in 2 wind turbines-40PV modules-6 batteries system	Dhahran, Saudi Arabia	0.624 $/kWh	[79]
Wind-PV with Diesel	Feasibility studied of 3-wind turbines each 600 kW/1000 kW PV panels/4-Diesel Generators system	The village, Saudi Arabia	0.212 $/kWh	[73]
Wind-PV with Diesel	Studied the electrical energy demand of 15,943 MWh yearly in the remote village	Rawdhat Bin Habbas, Saudi Arabia	0.118 $/kWh	[80]
Wind-PV	The government initiate projects planning	Ten remote locations across Saudi Arabia	300 MW	[68]
Wind	Provided the data collection and in the western region through Global Wind Energy	Red Sea shore	20 MW	[81]
Geothermal	Studies show that the Jazan province characteristic of high heat flow and high geothermal gradient	Jazan province	134 × 106 kWh	[82]
Geothermal	The study conducted there is a potential of geothermal resource	Al-Kouba, Jazan	17.847 MWh	[83]
Geothermal	The location has the most potential geothermal resource	Wadi Al-Lith	1.713 × 1017 J + 26.99 MWh	[84]

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