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Article

A GIS-Based Top-Down Approach to Support Energy Retrofitting for Smart Urban Neighborhoods

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Abstract: Energy and environmental challenges are a major concern across the world and the urban residential building sector, being one of the main stakeholders in energy consumption and greenhouse gas emissions, needs to be more energy efficient and reduce carbon emissions. While it is easier to design net zero energy homes, existing home stocks are a major challenge for energy retrofitting. Two key challenges are determining the extent of retrofitting required, and developing knowledge-based effective policies that can be applied en-masse to housing stocks and neighborhoods. To overcome these challenges, it is essential to gather critical data about qualities of existing buildings including their age, geo-location, construction type, as well as electro-mechanical and occupancy parameters of each dwelling. The objective of this study was to develop a GIS-based model embedded with critical data of residential buildings to facilitate evidence-based retrofit programs for urban neighborhoods. A model based on a bottom-up approach was proposed in which information gathered from all stakeholders was inputted into one database that can be used for decision-making. A geo-located case study to validate a proposed GIS-based residential retrofitting model sample size of 74 residential buildings in the city of Riyadh was statistically analyzed and used. The results indicate behavior-based patterns, with a strong positive correlation ($r = 0.606$) between the number of occupants and number of household appliances, while regression analysis showed high occupancy rates do not necessarily result in high utility costs at the end of the month, and there is no statistical difference in the average monthly cost of gas between partial and fully occupied houses. Furthermore, neither the type of building, height, age, nor occupancy status play a significant role in the average energy consumed. Additionally, the GIS-based model was validated and found to be effective for energy-use mapping and gathering critical data for analyzing energy consumption patterns at neighborhood scale, making it useful for municipalities to develop effective policies aimed at energy efficient and smart neighborhoods, based on a recommended list of most effective energy-saving retrofit measures.

Keywords: retrofit; energy efficiency; policies; residential buildings; GIS

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1. Introduction

The global energy consumption is experiencing a rapid growth. Emission of Greenhouse Gases (GHGs) is also on a rise and the trend is set to intensify in future unless concerted efforts are made to shift away from fossil fuels. Climate change, widely attributed to the anthropogenic emissions of GHGs because of fossil fuels consumption, is regarded as one of the biggest threats facing mankind [1]. To mitigate the implications of climate change, energy systems need a radical shift to low-carbon technologies [2,3]. The building sector, owing to its extensive energy and environmental loads, must play a major role in the fight against climate change and a transformation to a sustainable energy future [4]. Particularly, electricity consumption in the residential sector needs to be significantly curtailed because the sector accounted for around 27% of the total worldwide electricity consumption in 2018 [5]. It is suggested that a reduction of 32 Gt in overall Carbon Dioxide (CO_2) emissions by 2050 is required in the global building sector to limit the earth's temperature rise to 2 °C [6].

Saudi Arabia is a country with one of the world's most energy inefficient and unsustainable residential sector and this is evident from the fact that the electricity consumption in Saudi Arabia is much worse than the global scenario with per capita electricity usage being 9140.35 KWh/person in 2014, which is around three times higher than the world average [7]. The residential sector accounts for almost 52% of the total national electricity consumption and this usage is expected to double by 2025 [8]. The sector has experienced a growth in electricity consumption of 85% from 2004 to 2014 increasing from 73,365 GWh to 135,908 GWh [9]. As a result, it is consuming the second highest amount of electricity compared to all the other sectors in Saudi Arabia. One reason for such a high percentage of increase in the residential electricity consumption is the fast growth of the housing market. The growth is expected to continue for the country to meet the needs of the constantly growing population [10]. Studies indicate that the energy consumption in Saudi Arabian residential buildings is influenced by factors like high population growth rate, harsh desert climate of the country, inefficient building stock, subsidized energy tariffs, and a lack of policies [11].

With the development of houses at such a fast pace in a wealthy country, energy efficiency seems to be overlooked, as most of the development does not consider energy efficiency strategies in the building design process. Most residential development in Saudi Arabia only considers the capital costs; however, literature dictates that the majority of energy consumption takes place during the operational phase of the building. According to a study [12], 80% of the lifecycle energy of a building is associated with its operation while less than 20% occur during the initial construction and pre-construction stages. This rapid and energy-negligent culture of residential design leads to several factors which contribute to wastage of energy. These factors include deficient insulation, leaking windows, deficient heating and cooling systems, and poor construction techniques. This obligates building users to demand high amounts of energy; hence, the resulting energy consumption in Saudi Arabian homes is higher than the global average. In the eastern province, for instance, apartments consume around 196.5 kWh/m^2/year, while traditional houses and villas consume 156.5 kWh/m^2/year and 150 kWh/m^2/year, respectively [13]. Although currently no regulations or laws exist that enforce or encourage energy retrofits for a sustainable residential sector in future, it has become imperative for the municipalities in Saudi Arabia to enforce homeowners to become more energy conscious and sustainable, which is in line with Saudi Vision 2030 [14].

Saudi Arabia is a country with a predominantly hot climate, and reducing energy demand in residential buildings by energy retrofitting has been proven to be effective in several previous studies [15–19]. For example, in their study, Krarti and Howarth identified that modifying the current inventory of outdated window units and split systems in Saudi residential buildings to meet energy efficiency standards is projected to result in a decrease in electricity usage of approximately 33 terawatt-hours per year and a reduction of 24 million tons in CO_2 emissions for the country [20]. However, energy retrofitting residential buildings have many challenges and one of the main challenges is to determine the feasibility and extent of retrofitting required. To determine the extent of retrofitting required for a particular building, all the information of a residential building is required including building characteristics and energy performance of each building. Currently, all this information is present but scattered among different stakeholders, and thus it is a challenge to utilize this information to support the energy retrofitting process [21], which would arguably be most effective if carried out at a wider scale since neighborhood buildings often share similar physical characteristics. Due to its integrative capabilities and ability to combine numerous datasets in one simple-to-use model, the Geographic Information System (GIS) has become an essential tool in sustainability planning [22]. The benefit of GIS is bringing together all the information into one database to help overcome one of the main challenges regarding sustainability planning, which is the lack of unity between different stakeholders [23]. In the case of Saudi Arabian cities, the key stakeholders include the Municipality, the Contractor, and the Energy Provider, all of whom have their different purpose/focus. Nevertheless, a GIS database can collect four categories of building attributes from four different organizations into one GIS-enabled database including the following:

1. Municipality: General information of building including age, location, owner, building type, etc.;
2. Contractor: Construction details of the buildings including envelope system, window type, etc.;
3. Energy Provider: Energy usage of the buildings including energy usage by Heating Ventilation and Air Conditioning (HVAC) and other systems, including data obtained from smart meters;
4. Homeowners: Occupancy-based behavior pattern of end users.

Currently, policies being implemented in Saudi Arabia which are compelling homeowners to reduce electricity consumption include the recent hike in electricity tariffs, which will result in homeowners having to pay almost three times the amount of electricity bill as compared to what they were previously paying. However, this policy does not necessarily reduce the demand if homeowners can afford the increase. Hence, it is in the best interest of all the stakeholders involved to energy retrofit Saudi Arabian homes to reduce energy consumption and associated carbon emissions.

With the compelling need of energy retrofitting in Saudi Arabian homes coupled with the scattered information hindering efficient decision-making, it is of utmost important that a system be placed that facilitates the process and ensures the right decisions are made. Hence, this study proposes a GIS-based system to support energy retrofitting in Saudi Arabia. The significance of a GIS-enabled database will be its ability to assist decision makers to holistically analyze the existing scenario using data from multiple sources, and then recommend or enforce an energy retrofitting solution to homeowners. GIS-enabled platforms are popular as they can provide user-friendly interfaces for decision-making [24]. Such platforms serve as a basis for selecting energy efficiency measures based on data-driven decision-making methods and ensure optimum retrofit measures are selected. In this regard, the main objectives of this study are the following:

- Develop a GIS-based model for energy retrofitting of residential buildings in Saudi Arabia;
- Apply the developed GIS-based model on selected residential buildings in a neighborhood of Riyadh City in Saudi Arabia as a case study;
- Demonstrate the benefit of the developed GIS-based model for supporting cost effective energy retrofitting policies in Saudi Arabia.

2. Application of GIS for Energy Retrofitting

The application of GIS for developing a model for existing building stock and energy retrofitting decision-making has been researched in numerous studies and their results present that there is a significant potential for minimizing energy consumption in homes. Researchers have highlighted that the application of GIS is vital to develop policies aiming at enhancing the energy consumption of buildings. In a recent study, a GIS-based urban approach was implemented to map the energy efficiency of buildings in Turin, Italy [25]. A successful dynamic GIS-based model was developed and validated as a decision-making tool to improve the energy efficiency standards in buildings. Furthermore, a study by Thornburg and Thuvander [26] highlighted that information about the energy usage of buildings can be integrated into one geo-referenced energy model and used by the municipality. They suggest that GIS applications with their visualization and analyzing possibilities have the potential to make available energy data, and that besides the common energy data and measured energy data other information on the building such as energy emissions, building energy certifications such as Leadership in Energy and Environmental Design (LEED) certificate and emissions report can be included as attributes. Similarly, Dall'O et al. [27] developed a simple and cost-effective approach based on GIS which informs about energy efficiency of different buildings as well as allows local administrators to promote energy usage reduction in buildings.

Additionally, Caputo et al. [28] in their research presented an approach which uses a GIS-based database to support stakeholders in identifying the best policies for energy retrofitting at the municipality and city levels. They also state that it is possible to evaluate the effects an introduction of a policy will have on the building stock as well as identify the pros and cons of implementing new regulations from the compliance to the national or local rules related to renewables integration. Furthermore, Buffat et al. [29] developed a web-based model for Switzerland using GIS database which allows homeowners to explore different energy retrofit scenarios. The database of the GIS required building parameter details such as the HVAC or heating system of the building, building size, and envelope details for all the buildings in Switzerland. Their aim was to develop a platform which allows building owners to make use of this easy-to-use tool and portray the ability of their building to save on energy and money without wasting too much time.

Building types other than residential buildings have also been investigated for energy retrofitting with a similar approach. For example, Fabbri et al. [30] have indicated that an energy performance certificate and minimum energy requirement policies are required for existing buildings in the case of energy retrofitting of heritage buildings. They noted that an absence of assessment on the urban level containing information of building characteristics and age is a major issue. They developed a GIS-based map projection and concluded that a database developed on GIS is the most effective model which can combine energy and other characteristics of buildings into one model and can be used as a tool to link several types of information into one database. However, implementation of GIS for energy retrofitting is most widely implemented for residential buildings.

In addition to the aforementioned studies, a GIS-based model has been presented to energy retrofit existing residential buildings in numerous studies [31–35]. A study by Cupto and Pasetti developed a GIS-based tool with the aim of improving the energy renovation rate of the private building stock in Italy [31]. Their study was based on the Municipal Energy Model (MEM) methodology that is a GIS-based method to support planning processes in different municipalities. MEM is a mapped depiction of the entirety of the municipal building stock, integrating geospatial data and providing detailed information on energy usage, generation, and characteristics at the level of individual buildings. In the study, building and energy data of buildings were obtained using a hybrid method that involved real data and estimates using statistical approaches. Such method to obtain data is necessary with GIS-based models in places where obtaining actual data is not possible or the data are not available, and this is one of the biggest challenges in GIS-based approaches.

An extensive literature review on the application of GIS on energy retrofitting has indicated that researchers believe in the capabilities of GIS as a catalyst and as the fundamental step of improving the energy consumption of buildings in cities. Research has indicated that a GIS-based map of existing building characteristics and energy consumption can assist policy makers to develop guidelines and incentives for energy retrofitting as well as highlight the areas in the city which require energy retrofitting the most. This study, in line with the other studies and the MEM method, will aim to develop a GIS-based model for Riyadh, Saudi Arabia, which will assist the municipality to make energy retrofit decisions for the old unsustainable buildings in Riyadh. The strength of the adopted case study is that actual data are used for all the buildings and this will yield accurate results.

3. Energy Retrofitting and Smart Neighborhoods

Energy retrofitting, which involves the implementation of energy-saving measures in existing buildings, is a crucial strategy for reducing energy consumption in smart neighborhoods. A variety of retrofitting measures have been investigated, including the upgrading of building envelopes, the installation of high efficiency HVAC systems, and the implementation of advanced lighting technologies [36,37]. GIS-based methods have been employed to identify areas with high retrofitting potential and to optimize the selection of retrofitting measures [38]. The integration of renewable energy sources, such as solar photovoltaic panels and wind turbines, can significantly reduce the reliance on fossil fuels and contribute to energy efficiency in smart neighborhoods [39]. GIS-based methods have been widely used to assess the potential for renewable energy generation and to optimize the placement of renewable energy infrastructure [40].

As independent communities or part of smart cities, a smart neighborhood is an urban area that leverages Information and Communication Technology (ICT) to optimize energy consumption, enhance the quality of life for its residents, and promote sustainable development [41]. The concept of a smart neighborhood encompasses various elements, such as smart grids, building automation systems, energy-efficient buildings, and electric vehicle charging infrastructure. Energy efficiency is a crucial aspect of smart neighborhoods and cities and is primarily achieved through the reduction in energy consumption, the use of renewable energy sources, and the optimization of energy management [42]. Numerous studies have demonstrated the potential for up to 15% of energy as well as reduction in carbon in smart cities compared to conventional urban areas [43]. Various methods have been employed to analyze and quantify energy efficiency in smart neighborhoods.

One popular approach is the use of GIS, which enables the spatial analysis of energy consumption patterns and the identification of areas with high potential for renewable energy [40]. GIS-based methods have been applied to other aspects of smart neighborhoods, including the assessment of renewable energy potential, and understanding energy consumption patterns [44]. In scenarios where spatially distributed data are obtained from multiple sources, and where these data are in different formats/schemas, database operations such as extract, transform, and load can be used to clean, format or translate data [45], and tools such as Building Information Modeling (BIM) are suitable for such tasks including visualization in 3D models using different Levels of Details (LODs) of buildings [46].

4. GIS-Based Model

The model is based on a bottom-up approach in which information is gathered from the homeowners and other organizations on each individual home. The information on different levels is then inputted into the model which is relayed to the regulatory authorities. Figure 1 describes the model for the database in a flow diagram.

The first step in the model is to collect data of the existing housing. A structured door-to-door survey needs to be carried out in which homeowners are surveyed and information is recorded. All the physical characteristics and electrical equipment used in the house are recorded. The energy consumption information of the house can also be collected from homeowners through electricity bills for the previous one year. However, if it is not available, the electricity data can be gathered from the electricity provider, in the case of Saudi Arabia through Saudi Electricity Company (SEC).

After all the required data are gathered, the next step is to develop the GIS database. All the recorded building attributes are inputted into the GIS database along with the geo-location of the residence. It is essential that the data are recorded and inputted correctly and referenced to the correct residence as that will determine the output of the next stage. In the next stage, an analysis is conducted to identify homes which are consuming high amounts of energy. In this regard, the Energy Use Intensity (EUI) is used to identify whether a residence is consuming high energy, after which it is then analyzed further, and all its attributes are studied to see the attribute responsible for the high consumption.

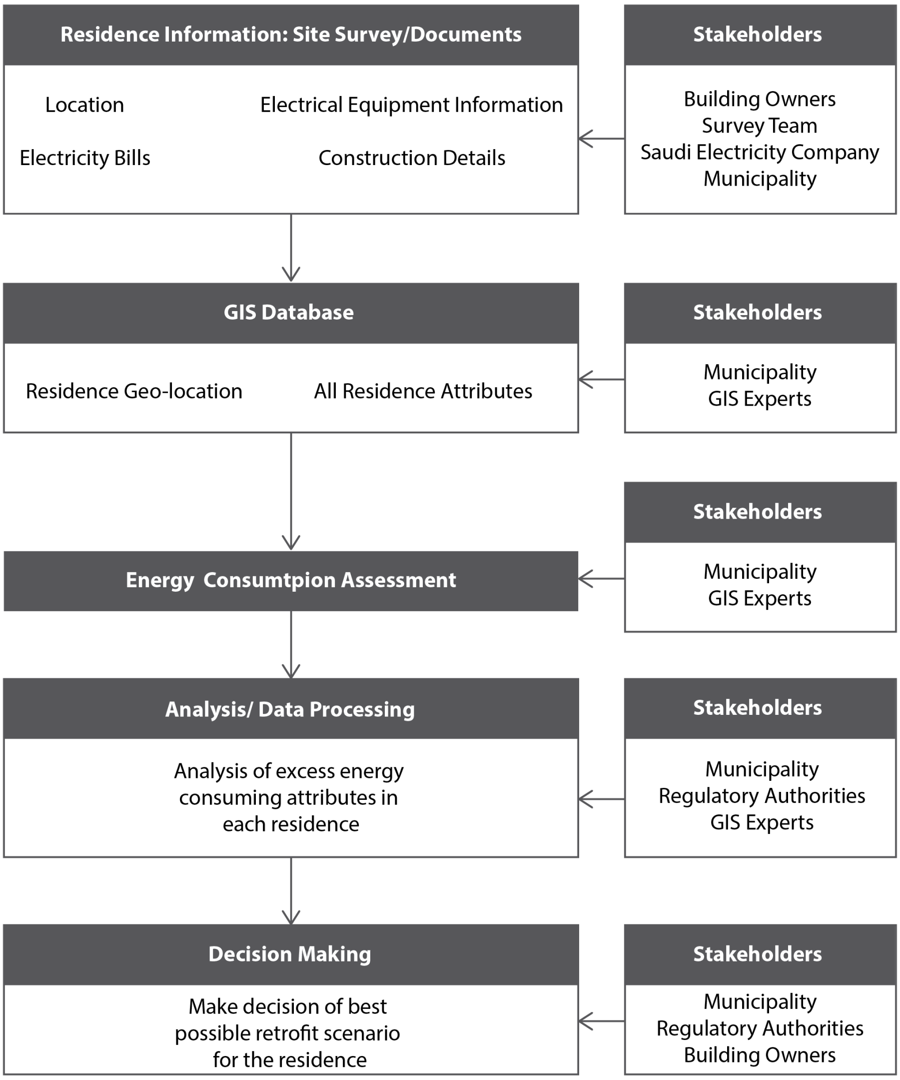

Figure 1. Database model.

The developed model ensures easy and efficient identification of residences which are consuming high amounts of electricity. Through the identification, the local governing body can regulate the level and type of energy retrofitting for each individual housing and potentially result in vast energy and economic savings.

5. Methodology

To successfully achieve the objectives of the study, a three-fold methodology based on the proposed model is used which includes the following steps:

1. Case study data collection;
2. GIS database development;
3. Analysis and proposal of best retrofit measures for case studies selected in Riyadh.

5.1. Case Study

5.1.1. Description

The selected location for the case study is the capital city of Saudi Arabia, Riyadh (Figure 2). The selected buildings are villas, which represent almost 40% of the housing type in Saudi Arabia. Most of the villas in Riyadh are unsustainable and need to be retrofitted in order to use less energy. Over the years, low energy prices have led to energy use patterns that are unsustainable. Household energy consumption is high because of the subsidized cost, which discourages investment in energy-efficient solutions and encourages consumers to use electricity without being particularly mindful of how much they use. Consequently, the per capita energy consumption in KSA is much higher than the world average. According to [47], sustainability is viewed by the local construction industry as one of the least essential concerns. It is evident from the fact that despite a harsh climate requiring extensive use of air-conditioning, the majority of the buildings lack thermal insulation [48].

Figure 2. Location of the case study.

Hence, Riyadh city, due to its unsustainable residential sector, presents an ideal case study to test the developed GIS model. Seventy-four residences were selected in various neighborhoods across Riyadh and information needed in the database was collected via a survey as described in the next section. Among the 74 residences, there were a total of 25 villas, 13 duplexes, 5 floor in villas, and 31 apartments. The selected residences represent the residential sector of Riyadh and all the residential building types in the city. The residences are all different with unique attributes which present an ideal case study for the developed model.

5.1.2. Data Collection

Information on the level of a preliminary energy audit is required to successfully build the database. Data required include complete information available on buildings from all the different stakeholders involved. Information on buildings can be obtained through municipal records or site surveys.

A survey was conducted for the 74 residences in Riyadh and information as described in Table 1 was collected for each building. The information is broadly classified into four sections including general information, construction details, electrical equipment information, and municipality bills. The general information section includes unique reference codes for each villa, the location coordinates, address, and other building information. The construction section describes the building in detail including wall construction details, glazing details, and roof information. Similarly, the electrical equipment section includes information about all the electrical equipment used including an HVAC system.

Table 1. Type of information collected for each case study in the surveys.

Category	Subcategory	Description
General Information	Reference	Number
		Type
	Coordinates	LAT
		LON
	Address	Community
		PO. Box
		PO. Code

Table 1. *Cont.*

Category	Subcategory	Description
General Information	Age	Year of Construction
		Year of Renovation
	Occupants	Total Number of Occupants
Construction Details	Dimensions/Areas	Length
		Width
		Total Built-up Area (m^2)
		Covered Area (m^2)
		Exterior Annex (Majlis), Air-Conditioned (if any)
		Area (m^2)
		Number of Floors
		Floor Height (m)
		Total Building Height (m)
	Shape	Unit Orientation (long Façade facing)
		Building Shape
	Other Areas	Basement
		Approx. Area (m^2)
		Double-Height Areas
		Approx. Area (m^2)
	Wall Details	Type of Structure
		Type of Exterior Wall
		Exterior Wall Insulation
		Type of Insulation (if known)
		North
		East
		South
		West
	Roof Details	Roof Type
		Roof Insulation
		Type of Insulation (if known)
		Parapet Wall
		Height (m)
		North
		Number
		Area
		East
		Number
		Area
		South

Table 1. *Cont.*

Category	Subcategory	Description
Construction Details	Roof Details	Number
		Area
		West
		Number
		Area
		Green Roof
		Opening in Roof—Skylights
		Approx. Area (m^2)
	Glazing Details	Type of Window Material
		Type of Glazing
		Type of Internal Shading
		External Shading
		North
		Number
		Area
		Type
		East
		Number
		Area
		Type
		South
		Number
		Area
		Type
		West
		Number
		Area
		Type
Appliances	HVAC	HVAC System
		Type of HVAC
		C-H-Both
		Number
		Fan
		Fan Type
		Number
		Heating System
		Heating System Type
		Number
	Other Equipment	Domestic Hot Water (DHW)
		DHW Type

Table 1. *Cont.*

Category	Subcategory	Description
Appliances	Other Equipment	Water Pump Type
		Dominate Lighting Type
		House Elec. Voltage
		Cooking Oven(s)
		Oven/Stove Type
		Refrigerator
		Washing Machine
		Clothes Dryer
		Dishwasher
		Microwave
		TV(s)
		Computer(s)
		Ironing
		Vacuum Cleaner
		Air Purification
		Humidifier
		Tea Kettle
		Food Blender
		Play-Station
		Others
Bills and EUI		Aver Electricity Bill/Month (SR)
		Aver Gas Bill/Month (SR)
		Energy Use Index (EUI)

5.2. GIS Database

The software to be used to develop the database is ArcGIS 10.4. ArcGIS is a geographic information system which works with maps and attributes. The software is developed by ESRI and can develop maps, analyze maps, compile information, visualize and share information and geo-reference information. The software has a multitude of applications including urban planning and others. Some of the basic tools include geo-referencing, assigning attributes, drawing shapes, editing shapes, etc. The ability of GIS to combine all information into one database and then analyze it using query tools is what makes it an ideal tool for studying existing buildings. By developing attributes which are to be displayed in the database, GIS can help monitor the performance of existing buildings and be used to make further decision-making.

5.3. Analysis Methods

Statistical analysis: Four kinds of statistical analysis were used: descriptive analysis, regression analysis, correlation analysis, and hypothesis testing. Descriptive analysis provides a very useful summary of the entire datasets from a general perspective. Linear Regression Analysis (LRA) is commonly used as an inferential statistical approach that provides a true reflection about certain characteristics in a population—the way residents use their buildings in the study area. LRA provides a measure of the extent in which the predictor (independent) variables can explain or have an impact on the dependent variable represented in the form of an equation. This is often conducted on the basis that all the variables are as a result of random occurrence. In this study, the average electricity bill per month was the dependent variable regressed against the predictors, namely, building footprint (m^2), total number of occupants, total building height (m), and total household appliances. Correlation analysis was applied to detect if there are any relationships between groups of variables, and if so, the extent/strength of such relationships. Hypothesis testing is used to ascertain the mean difference between two groups of unrelated data based on the assumption that no outliers should be present and the data are a result of independent observations.

Energy analysis: The developed database will then be used to conduct an analysis of the case study. The Energy Use Index/Intensity (EUI) will be calculated to conduct the analysis. The EUI is the amount of energy being consumed per square meter of a residence in a year. The EUI indicates whether the residence is consuming high energy or low energy. For Saudi Arabia, due to large amounts of cooling requirements, the EUI is typically high in residential buildings as compared to global standards. On average, villas in Saudi Arabia consume around 150 kWh/m^2/year [13], which is an excessive amount. For this study, energy consumption of any residence above 100 kWh/m^2/year will be considered as high. High energy consuming residences will then be analyzed for parameters which result in excessive consumption and can be retrofitted. The five retrofit parameters analyzed in this study are indicated in Table 2, and the desired parameter value for maximum energy efficiency is indicated in green. The residences which are high energy consuming will be identified and then the retrofit parameters will be analyzed, and if a residence is not up to the desired parameter value, the owners of the residence have to energy retrofit these parameters.

Table 2. Energy retrofitting parameters.

Lighting Type	Ext. Window Shading	Glazing Type	HVAC System Type	Envelope Insulation
LED	Yes	Double	Split AC	Yes
Incandescent	No	Single	Window	No
Fluorescent			Central	
CFL				

6. Results

6.1. General and Descriptive Analysis

A door-to-door survey was conducted on all the 74 residences in Riyadh city and the data for each residence were recorded. The recorded data were then used to develop the GIS database. First, a base map was developed which displays the location of each residence on a map of Riyadh city. A default map in ArcMap was used as a base map of Riyadh city. Then, all the recorded attributes from the survey are inputted into the database (Figure 3).

There were almost the same number of individuals that rented the homes as those that owned them at 49.1% and 50.9%, respectively. The rates of full-time home occupancy were approximately 70%, with around 30% using the buildings occasionally for only a few months in a year. In terms of utilities and appliances, 53.6% of residents used electric stoves and 46.4% had gas stoves. Other types of appliances commonly found in the surveyed homes include Refrigerators, Washing Machines, Clothes Dryers, Dishwashers, Microwaves, TVs, Computers, Electric Irons, Vacuum Cleaners, Air Purifiers, Humidifiers, Tea Kettles, Food Blenders, and Play-Station game consoles.

The maximum height (meters) of the building was 30 m with the minimum being 5 m high as shown in the table below. The average total height of the residential buildings was 10.527 m with the standard deviation of 3.172 meaning that most of the buildings were between 7.35 m and 13.69 m high. Although the houses had up to a maximum of 12 occupants, most of the buildings had an average of between 3 and 7 people. The mean gas consumption was 27.52 with a standard deviation of 17.94. Although some residential houses incurred no gas costs monthly due to the use of the electric stove, a maximum average gas bill/month of SR 80 was obtained. On the other hand, a maximum of SR 4000 in electricity costs with a mean of 398.41 and SD of 506.595 indicate the high reliance of electricity in the residential buildings. This can be attributed to the high number of household appliances with an average of 18 appliances per given apartment, duplex, or a villa.

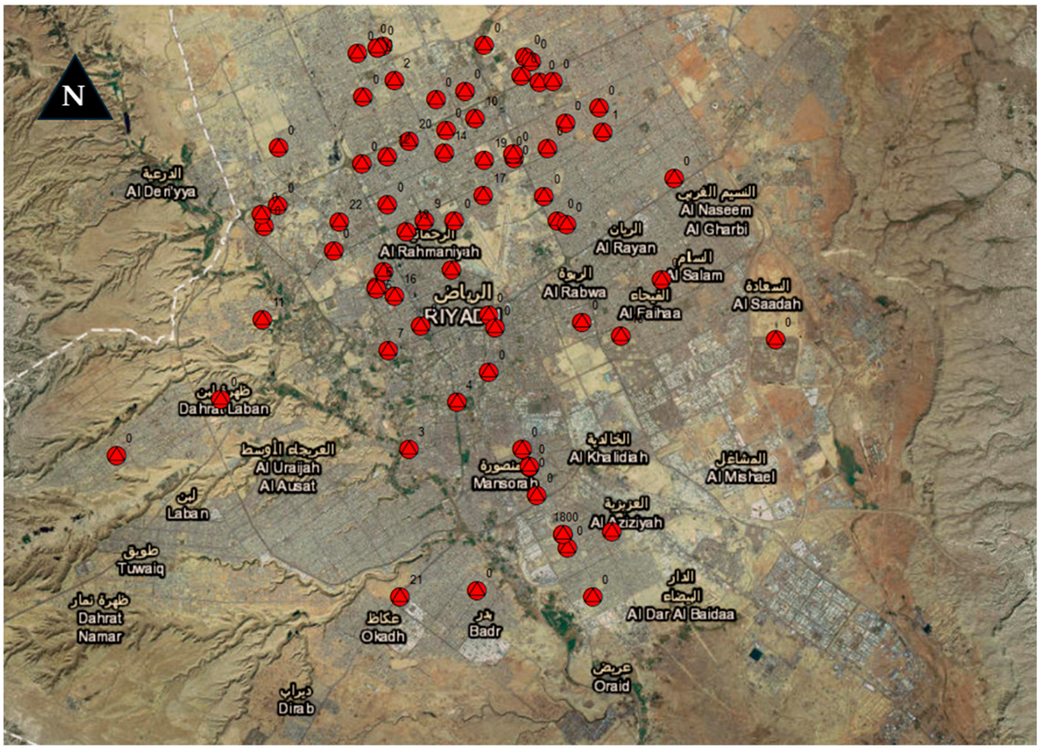

Figure 3. The location of the 74 residences in Riyadh.

6.2. GIS-Based Analysis

Several maps were then produced based on the attributes including type of residence (Figure 4), age map (Figure 5), and energy use (Figure 6). Other maps can be produced as well from the different attributes. An advantage of having maps in a GIS database over manual maps is that these maps can be updated easily by updating the attributes of each building if the building has been renovated or changed.

The application of the database is to assist policy makers in retrofit policies development and the database will allow policy makers to obtain the required information for each building. To achieve this, the ability to use attribute queries to identify specific buildings in the city will be identified. For example, if policy makers wanted to identify how many residential buildings are present which are in poor condition, they can easily develop a query and identify the buildings. Furthermore, if any energy related policy recommendation is to be introduced, policy makers can prioritize which measure and which building is to be brought in first.

The analysis of the database can be conducted using three levels of data which include the following levels:

1. House-by-house;
2. Type of house;
3. Year of construction.

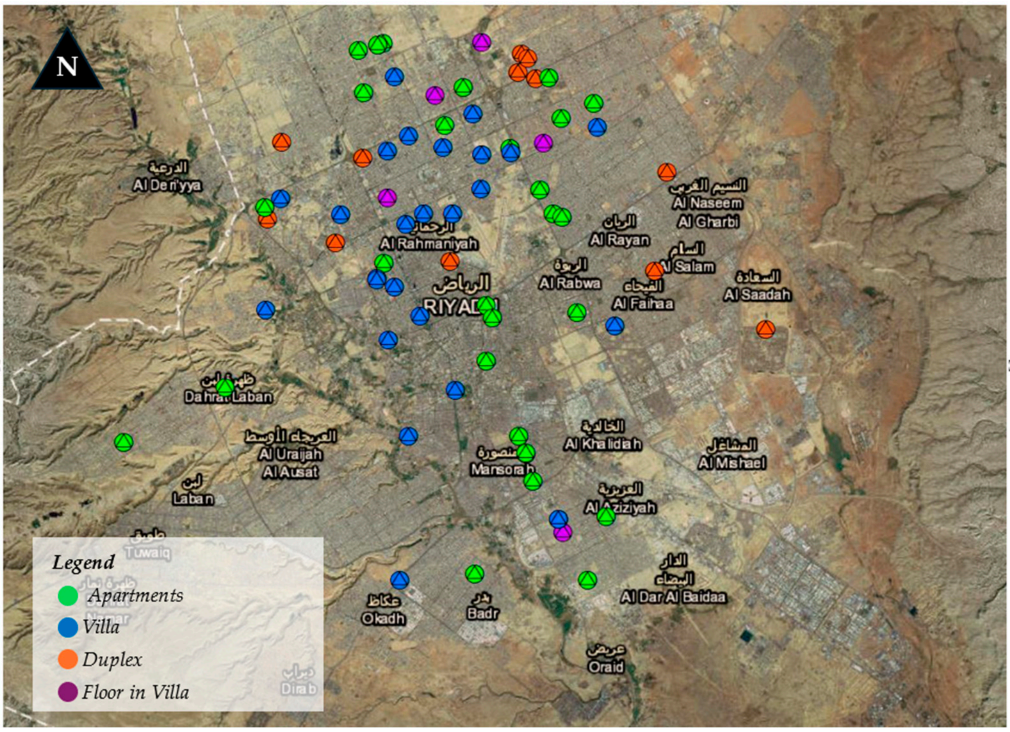

Figure 4. Type of residences.

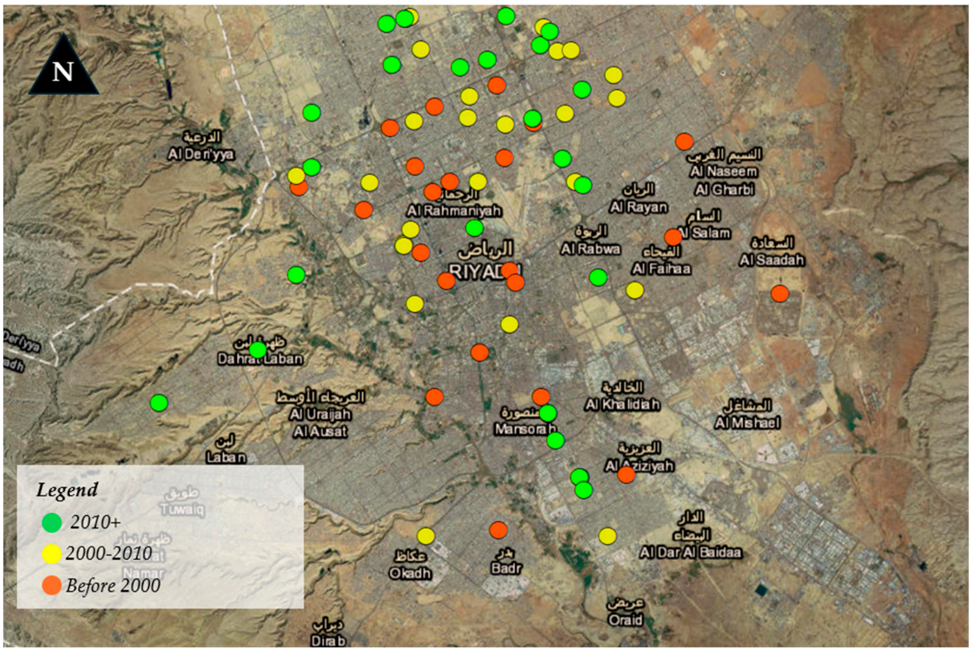

Figure 5. Age of house map.

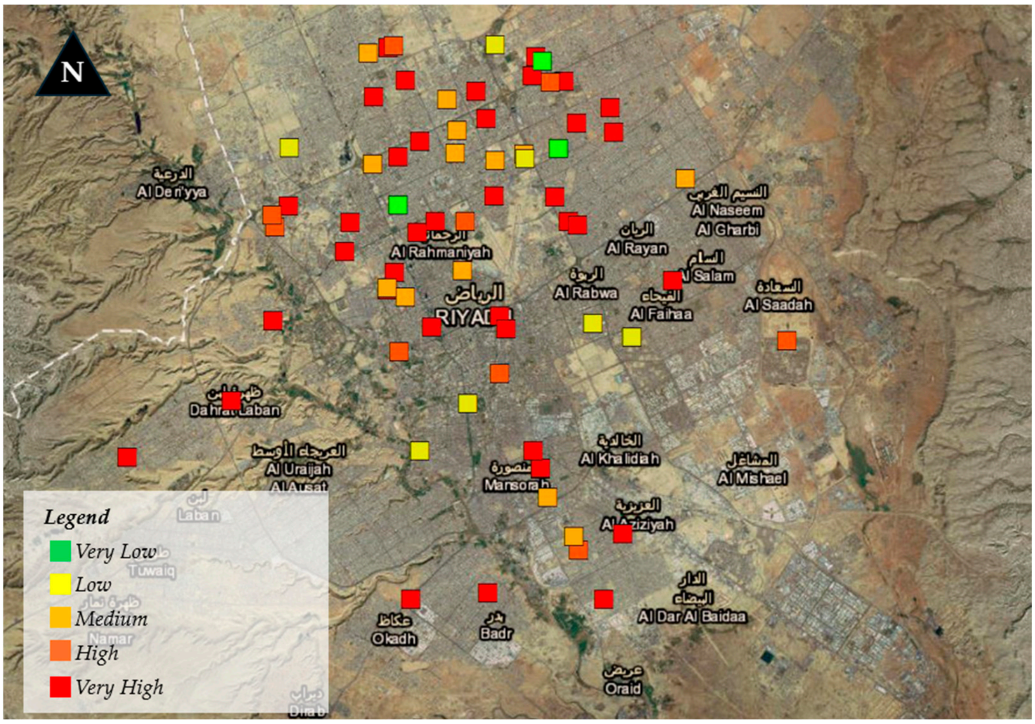

Figure 6. Energy use map.

The main difference between the three levels is the amount and type of data to be analyzed. On an urban scale, analysis on a level, such as the house-by-house level, may not be feasible as it will require dealing with huge amounts of data.

Table 3 presents the results of the house-by-house analysis. On this level, the parameters of each house are analyzed, and recommendations are given to each separately. The advantage with this type of analysis is that it ensures the maximum effectiveness in the decision-making process as each house is analyzed individually and the recommended extent of retrofitting is catered to the house. However, this type of analysis may not be feasible for the municipality due to the large number of buildings in a municipal area and analyzing and processing each one of them will be time consuming. A second type of analysis is conducted by analyzing each house type separately and introducing separate policies to each of them as presented in Figure 7. A similar analysis can be carried out based on the age of buildings (Figure 8) as buildings constructed during similar time periods are constructed with similar techniques and have the same parameters.

Table 3. House-by-house analysis results (selected). **O** = inefficient, **X** = efficient.

No.	Type	EUI (kWh/m^2/yr.)	Energy Consumption	Total No. of Occupants	Lights	External Shading	Glazing Type	HVAC	Insulation	Recommendation(s)
0	Villa	230.40	High	10	X	O	X	X	X	Construct external window shading
1	Villa	240.00	High	5	X	O	O	X	O	Construct external window shading Change glazing type to double glazing Apply envelope insulation
2	Villa	75.00	Low	10	O	O	O	X	O	Use an HVAC system with higher EER

Table 3. *Cont.*

No.	Type	EUI (kWh/m²/yr.)	Energy Consumption	Total No. of Occupants	Lights	External Shading	Glazing Type	HVAC	Insulation	Recommendation(s)
3	Villa	70.13	Low	4	O	O	O	O	O	Change lighting type to LED Construct external window shading Change glazing type to double glazing Use an HVAC system with higher EER Apply envelope insulation
4	Villa	144.00	High	12	O	O	X	X	X	Change lighting type to LED Construct external window shading
5	Villa	360.00	High	11	O	O	X	X	X	Change lighting type to LED Construct external window shading
25	Duplex	175.14	High	6	X	O	X	X	X	Change lighting type to LED Change glazing type to double glazing Use an HVAC system with higher EER Apply envelope insulation
26	Duplex	240.00	High	6	O	O	X	X	X	Change glazing type to double glazing Use an HVAC system with higher EER Apply envelope insulation
27	Duplex	447.34	High	4	O	O	O	X	O	Change lighting type to LED Construct external window shading Change glazing type to double glazing Apply envelope insulation
28	Duplex	135.00	High	8	O	O	X	X	X	Change lighting type to LED Construct external window shading
29	Duplex	225.39	High	6	O	X	O	X	O	Change lighting type to LED Change glazing type to double glazing Apply envelope insulation
38	Floor in Villa	43.20	Low	4	O	O	O	O	O	Change lighting type to LED Construct external window shading Change glazing type to double glazing Use an HVAC system with higher EER Apply envelope insulation
39	Floor in Villa	42.63	Low	3	O	O	X	X	X	Change lighting type to LED Construct external window shading
40	Floor in Villa	152.83	High	5	O	O	O	X	O	Change lighting type to LED Construct external window shading Change glazing type to double glazing Apply envelope insulation
41	Floor in Villa	101.89	High	3	X	O	X	X	X	Construct external window shading
42	Floor in Villa	54.00	Low	3	O	O	X	X	O	Change lighting type to LED Construct external window shading Apply envelope insulation
43	Apartment	216.00	High	5	O	O	O	O	O	Change lighting type to LED Construct external window shading Change glazing type to double glazing Use an HVAC system with higher EER Apply envelope insulation
44	Apartment	246.86	High	4	X	O	O	X	X	Construct external window shading Change glazing type to double glazing
45	Apartment	332.31	High	4	O	O	O	O	O	Change lighting type to LED Construct external window shading Change glazing type to double glazing Use an HVAC system with higher EER Apply envelope insulation
46	Apartment	270.00	High	6	O	O	O	O	X	Change lighting type to LED Construct external window shading Change glazing type to double glazing Use an HVAC system with higher EER

Table 3. *Cont.*

No.	Type	EUI (kWh/m^2/yr.)	Energy Consumption	Total No. of Occupants	Lights	External Shading	Glazing Type	HVAC	Insulation	Recommendation(s)
47	Apartment	144.00	High	4	O	O	O	X	X	Change lighting type to LED Construct external window shading Change glazing type to double glazing
67	Apartment	72.00	Low	2	O	O	O	X	X	Change lighting type to LED Construct external window shading Change glazing type to double glazing
68	Apartment	204.00	High	5	O	O	X	X	X	Change lighting type to LED Construct external window shading
69	Apartment	154.29	High	4	O	X	X	X	X	Change lighting type to LED

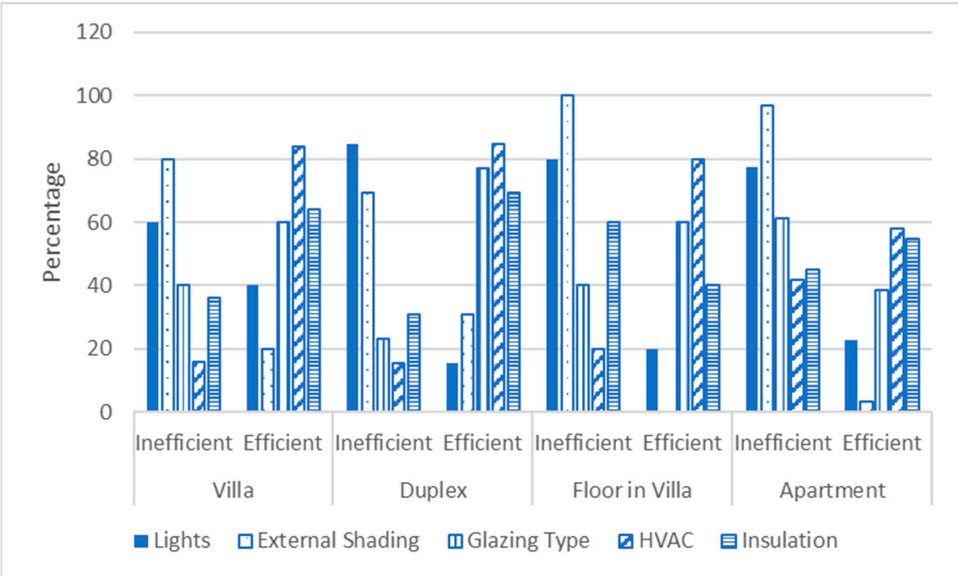

Figure 7. Type of house analysis results.

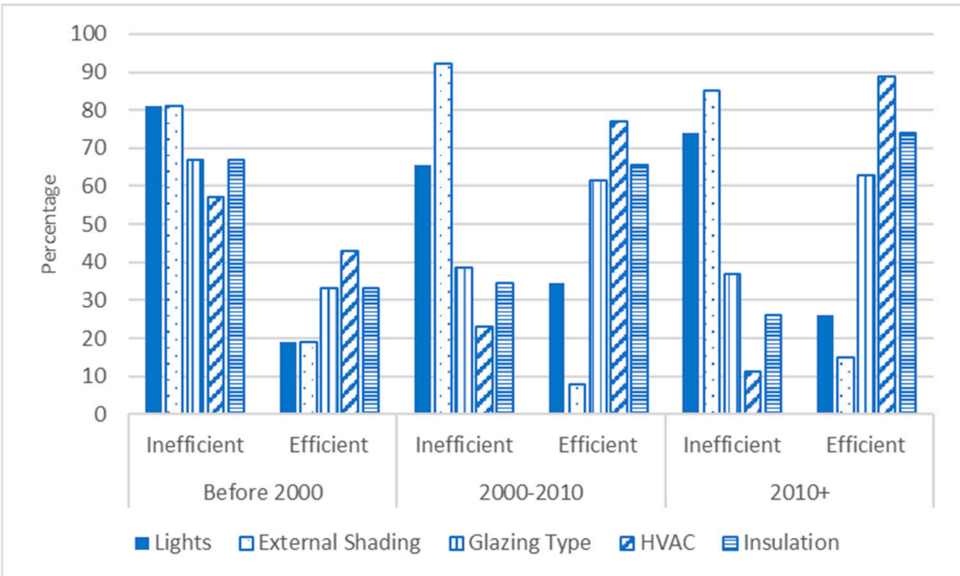

Figure 8. Year of construction analysis results.

The latter two analysis methods are not as effective and detailed as the first one because bulks of buildings are being analyzed at the same time and retrofitting recommendations are based on the majority of percentages. For example, 40% of the villas have an undesired glazing type as shown in Figure 7; however, it is not recommended to retrofit the windows in the case studies from single glazing to double glazing as 60% have a desired window type. However, this means that 40% of the villas will continue to consume high amounts of electricity due to the undesired window types. The case is similar for other attributes in the two latter analysis methods. The three types of analysis are all applicable and support decision-making for retrofitting existing residential buildings in Riyadh. The decision to select the type of analysis depends on the policy makers; however, it is recommended to analyze each resident individually.

6.3. Inferential Statistical Analysis of the Dwellings

Linear Regression: Using linear regression with model accuracy R^2 of 39.7% indicates that there is a relatively significant number of independent variables that can adequately explain the Aver Electricity Bill per month. From the table of coefficient shown below:

$$Y = aX_1 + bX_2 + cX_3 + dX_4 + eX_5 + fX_6 + gX_7 + \varepsilon$$

This translates into:

Y (aver electricity bill/month (SR)) = 1224.37 − 103.696 (type) − 0.518 (year of construction) + 12.713 (building height) + 7.05 (number of occupants) − 77.58 (average usage) + 24.214 (household appliances) + 15.04 (oven/stove type) + e.

From the equation, the total number of occupants contributes the least to the average electricity costs per month indicating that a high occupancy rate in a house does not necessarily result in high utility costs at the end of the month. On the other hand, the number of appliances and type of oven used (electric/gas) were some of the notable factors that have the most significant impact on the electricity costs including the height of the building. The higher the building, the higher the electricity costs especially on lighting and heating during winter (Table 4).

Table 4. Summary of regression variables.

Coefficients [a]						
Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	1224.373	7697.302		0.159	0.874
	Type	−103.696	49.323	−0.274	−2.102	0.038
	Year of Construction	−0.518	3.881	−0.012	−0.134	0.894
	Total Building Height (m)	**12.713**	**19.177**	**0.064**	**0.663**	**0.509**
	Total Number of Occupants	7.05	22.1	0.034	0.319	0.75
	Average Usage (m/y):	−77.577	90.006	−0.071	−0.862	0.391
	Total household Appliances	**24.214**	**7.82**	**0.394**	**3.096**	**0.003**
	Oven/Stove Type	**15.044**	**83.615**	**0.015**	**0.18**	**0.858**

[a] Dependent Variable: average electricity bill/month (SR).

Correlation Analysis: Apart from the total building height (m) of 0.396, there is no positive association between building types and other variables such as the number of occupants, household appliances, electricity as well as gas bills. A strong positive correlation of 0.606 between the number of occupants and number of household appliances indicates that the numbers are directly proportional such as the more the occupancy, the more likely the increase in the number of appliances needed. A negligible correlation between average usage of a building and average gas bill per month (r = −0.064) and average monthly electricity costs (r = −0.103) indicates the lack of association between them. Similarly, a negative correlation of −0.215 between the average gas bill per month and total building height shows no kind of relationship on the amount incurred in utility to the building type or building height (Table 5).

Table 5. Correlation matrix.

	Type	**Total Number of Occupants**	**Average Usage (m/y):**	**Total Household Appliances**	**Avg. Electricity Bill/Month (SR)**	**Aver Gas Bill/Month (SR)**	**Total Building Height (m)**
Type							
Total Number of Occupants	**−0.544** **						
Average Usage (m/y):	−0.02	0.049					
Total Household Appliances	−0.715 **	**0.606** **	−0.114				
Avg Electricity Bill/Month (SR)	**−0.547** **	**0.413** **	−0.103	**0.608** **			
Avg. Gas Bill/Month (SR)	**−0.594** **	**0.476** **	−0.064	**0.631** **	**0.643** **		
Total Building Height (m)	**0.396** **	−0.157	−0.04	−0.154	−0.135	−0.215	

** Correlation is significant at the 0.01 level (two-tailed).

Hypothesis Testing (*t*-test): Using the t-test, we sought to find out if there is any difference between the partial and full-time use of the residential house with regards to the average monthly gas bill (Table 6).

Table 6. Independent samples test.

		Levene's Test for Equality of Variances		***t*-Test for Equality of Means**						
									95% Confidence Interval of the Difference	
		F	**Sig.**	**t**	**df**	**Sig. (Two-Tailed)**	**Mean Difference**	**Std. Error Difference**	**Lower**	**Upper**
Average Gas Bill/Month (SR)	Equal variances assumed	4.828	0.031	0.535	69	0.595	2.445	4.573	−6.679	11.568
	Equal variances not assumed			0.468	32.008	0.643	2.445	5.227	−8.203	13.092

H_0. *There is no statistical difference between partial and full-time usage of the houses with respect to the average monthly gas bill incurred at the residence.*

H_1. *There is a statistical difference between partial and full-time usage of the houses with respect to the average monthly gas bill incurred at the residence.*

Based on the outcome of the analysis and assuming equal variances, the *p*-value (Sig. two-tailed) of 0.595 is quite substantial than the level of significance of 0.05 used in the analysis. Therefore, we fail to reject the null hypothesis and conclude that there is no statistical difference in the average monthly cost of gas between partial and fully occupied houses. This means that individuals living for a few months in a year effectively pay the same amount of gas bill as those that live full-time at the residency perhaps pointing out to the high use of gas in the number of months that the occupants spend in a year.

7. Discussion and Future Works

Statistical analysis of the data showed that the total number of appliances including the type of oven used is the most key factor when it comes to determining the utility consumption costs (gas and electricity) over a certain period of time. The occupancy rate of a residential building is one of the least factors that influences the total or average utility costs monthly or yearly. Neither the type of building, height, year of construction, occupancy status nor the average usage play a role in the average electricity or gas bills per month. Also, there was no statistical difference in the average monthly cost of gas between partial and full-time occupied houses.

The GIS-based model that has been presented and successfully applied on the case study also reciprocates models from other studies. A recent study in Chile applied GIS for climate sensitive planning in Santiago city [48]. The study was able to identify the most appropriate EEM for building types. Another study in Carbonia, Italy presented a web-based GIS model with the aim of sharing information of the built environment to promote the participation of stakeholders in the decision-making process [49]. They presented a case study of a public building that successfully adopts the model for sustainable facility management. Similarly, in this study, several EEMs are identified by the model and targeted for various building types in Riyadh, Saudi Arabia that will prove to be more effective than the haphazard application of EEMs.

The retrofit measures recommended in this study for Riyadh also reciprocate the EEMs presented in other studies in the country for energy retrofitting. According to several studies with a bottom-up approach, energy retrofitting has the potential to significantly reduce energy demand across a range of buildings including residential [18,21,50–52], academic [53], and office buildings [49,54]. A study, for example, demonstrated measures that can cut energy use by up to 60% in residential buildings. The range of energy efficiency measures it adopted includes adjusted cooling set point, energy-efficient appliances, window shading, low U-value windows, thermal insulation, better air tightness, and a more efficient HVAC system [20]. They evaluated a three-level energy retrofit strategy and found that deep retrofitting can reduce energy consumption in residential buildings by as much as 60%. The initial investment payback period, however, is unappealing. Another investigation conducted by Krarti et al. [50] supports these findings. They gave a thorough bottom-up analysis of Saudi Arabian residential building energy retrofitting. They suggested comparable EEMs, such as enhancing the HVAC system, switching out light fixtures, implementing control schemes, enhancing the envelope characteristics, and enhancing the energy efficiency of appliances. Their findings indicated that the residential section can potentially deliver an annual energy reduction of 100,000 GWh.

The work presented in this study lays the foundation for future works that will enhance the presented GIS model by utilizing the capabilities of Building Information Modeling (BIM). Using a BIM-GIS approach has the power to combine multiple levels of data in a single model to support and visualize energy retrofitting [54]. In addition, the BIM-GIS model can be presented to policy makers and the other stakeholders in the retrofitting process using web-based systems [49]. Future works should build on the works in this study and enhance the GIS model with BIM, particularly for Saudi Arabia and the region. Using extract, translate, and load (ETL) techniques [45], it would be helpful to develop a Unified Energy Retrofit Database (UnERD), which is 3D driven using GIS-compatible tools such as FME; hence, the integration with BIM would be easier.

8. Conclusions

Saudi Arabia is a country with one of the world's most unsustainable residential sector and the situation will not improve in the business-as-usual scenario. To satisfy the global initiatives to combat climate change and to meet the requirements of the Saudi vision 2030 which aims to transform Saudi Arabia into a more sustainable country, the residential sector of the country needs to drastically shift towards more sustainable practices. While this shift is visible in newly built residential buildings, the existing buildings built before any sustainable practice policy was enforced are continuing to consume energy at an alarmingly high rate. These existing residential buildings need to be retrofitted to reduce their energy consumption and ultimately lead to a more sustainable residential sector in Saudi Arabia.

Retrofitting the existing residential building stock of Saudi Arabia will be a challenging task and before any decisions can be made and any policies be enforced, it is essential to know the qualities of existing buildings including the geo-location, construction, electrical and demographic parameters of each individual house. Unfortunately, all this information is currently segregated and is unusable in its current form. This study successfully presents and validates a GIS-based model to support energy retrofitting decision-making. In the study, a GIS-based model was proposed and implemented in Riyadh city as a case study in which all the information of residential buildings comes together in one model. This presented GIS-based model makes it more effective for policy makers to study the current qualities of the existing building stock in Riyadh and then propose recommendations to homeowners for energy retrofitting. For Riyadh, it is recommended that all residential buildings built before the year 2000 should consider the following retrofit measures:

- Change lighting type to LED;
- Construct external window shading;
- Change glazing type to double glazing;
- Use an HVAC system with higher EER;
- Apply envelope insulation.

Buildings built after 2000 are in a better shape and only need to consider the following:

- Change lighting type to LED;
- Construct external window shading.

The presented GIS-based model in the study can be adopted for use in other municipalities of the country. Additionally, a similar approach can be adopted globally where the climate and challenge to energy retrofit the residential building stock are similar such as in Middle Eastern countries. This will greatly enhance the decision-making capabilities of the decision makers and ensure that optimum policies and measures are put into place. Additionally, the presented model can be built upon by researchers to include other data, such as BIM, that will lead to further enhancement and use of the model. Ultimately, optimum energy retrofitting decision-making will lead to energy and environmental savings in the building sector and ensure countries meet their CO_2 reduction targets.

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References

1. Asif, M. (Ed.) *Energy and Environmental Security in Developing Countries*, 1st ed.; Springer: Berlin/Heidelberg, Germany, 2021. [CrossRef]
2. Qudrat-Ullah, H.; Asif, M. (Eds.) *Dynamics of Energy, Environment, and Economy; A Sustainability Perspective*, 1st ed.; Springer: Berlin/Heidelberg, Germany, 2020. [CrossRef]
3. Shi, W.; Wang, S.; Yang, Q. Climate change and global warming. *Rev. Environ. Sci. Bio/Technol.* **2010**, *9*, 99–102. [CrossRef]

4. WGBC. The Sustainable Transition Depends on Scaling Positive Change Now! WorldGBC Announces #BuildingTheTransition for World Green Building Week. Available online: https://worldgbc.org/article/buildingthetransition-world-green-building-week-2023/ (accessed on 28 February 2024).
5. IEA. Key World Energy Statistics 2020. 2020. Available online: https://www.iea.org/reports/key-world-energy-statistics-2020 (accessed on 30 September 2021).
6. Wang, H.; Chen, W.; Shi, J. Low carbon transition of global building sector under 2- and 1.5-degree targets. *Appl. Energy* **2018**, *222*, 148–157. [CrossRef]
7. IEA. Electric Power Consumption (kWh Per Capita) | Data. 2014. Available online: https://data.worldbank.org/indicator/EG.USE.ELEC.KH.PC (accessed on 18 November 2017).
8. Alyousef, Y.; Abu-Ebid, M. *Energy Efficiency Initiatives for Saudi Arabia on Supply and Demand Sides*; INTECH: Chula Vista, CA, USA, 2012; Volume 3. Available online: http://www.intechopen.com/books/energy-efficiency-a-bridge-to-low-carbon-economy (accessed on 18 November 2017).
9. KAPSARC. Data Portal—Electricity Consumption by Sectors. 2016. Available online: https://datasource.kapsarc.org/explore/dataset/electricity-consumption-by-sectors/ (accessed on 18 November 2017).
10. Sidawi, B. Hindrances to the Financing of Affordable Housing in Kingdom of Saudi Arabia. *Emir. J. Eng. Res.* **2009**, *14*, 73–82. Available online: http://citeseerx.ist.psu.edu/viewdoc/download;jsessionid=9C038727D0D4E941224CFFF80D0C7A62?doi=10.1.1.304.5712&rep=rep1&type=pdf (accessed on 18 November 2017).
11. Ahmed, W.; Asif, M.; Alrashed, F. Application of Building Performance Simulation to Design Energy-Efficient Homes: Case Study from Saudi Arabia. *Sustainability* **2019**, *11*, 6048. [CrossRef]
12. Martinez, A. *Facade Retrofit: Enhancing Energy Performance in Existing Buildings*; University of Southern California: Los Angeles, CA, USA, 2012. Available online: http://digitallibrary.usc.edu/cdm/ref/collection/p15799coll3/id/352554 (accessed on 18 November 2017).
13. Alrashed, F.; Asif, M. Trends in Residential Energy Consumption in Saudi Arabia with Particular Reference to the Eastern Province. *J. Sustain. Dev. Energy Water Environ. Syst.* **2014**, *2*, 376–387. [CrossRef]
14. Amran, Y.A.; Amran, Y.M.; Alyousef, R.; Alabduljabbar, H. Renewable and sustainable energy production in Saudi Arabia according to Saudi Vision 2030; Current status and future prospects. *J. Clean. Prod.* **2020**, *247*, 119602. [CrossRef]
15. Jubran, A.; Peter, B. Reducing high energy demand associated with air-conditioning needs in Saudi Arabia. *Energies* **2019**, *12*, 87. [CrossRef]
16. Abd-ur-Rehman, H.M.; Al-Sulaiman, F.A.; Mehmood, A.; Shakir, S.; Umer, M. The potential of energy savings and the prospects of cleaner energy production by solar energy integration in the residential buildings of Saudi Arabia. *J. Clean. Prod.* **2018**, *183*, 1122–1130. [CrossRef]
17. Ahmed, W.; Asif, M. BIM-based techno-economic assessment of energy retrofitting residential buildings in hot humid climate. *Energy Build.* **2020**, *227*, 110406. [CrossRef]
18. Krarti, M.; Aldubyan, M.; Williams, E. Residential building stock model for evaluating energy retrofit programs in Saudi Arabia. *Energy* **2020**, *195*, 116980. [CrossRef]
19. Algarni, S. Potential for cooling load reduction in residential buildings using cool roofs in the harsh climate of Saudi Arabia. *Energy Environ.* **2019**, *30*, 235–253. [CrossRef]
20. Krarti, M.; Howarth, N. Transitioning to high efficiency air conditioning in Saudi Arabia: A benefit cost analysis for residential buildings. *J. Build. Eng.* **2020**, *31*, 101457. [CrossRef]
21. Ahmed, W.; Asif, M. A critical review of energy retrofitting trends in residential buildings with particular focus on the GCC countries. *Renew. Sustain. Energy Rev.* **2021**, *144*, 111000. [CrossRef]
22. Mason, M. Sustainability and GIS | EnvironmentalScience.org. Available online: https://www.environmentalscience.org/sustainability-gis (accessed on 13 November 2017).
23. Saretta, E.; Caputo, P.; Frontini, F. An integrated 3D GIS-based method for estimating the urban potential of BIPV retrofit of façades. *Sustain. Cities Soc.* **2020**, *62*, 102410. [CrossRef]
24. Shu, L.; Zhao, D. Decision-Making Approach to Urban Energy Retrofit—A Comprehensive Review. *Buildings* **2023**, *13*, 1425. [CrossRef]
25. Mutani, G.; Todeschi, V. GIS-based urban energy modelling and energy efficiency scenarios using the energy performance certificate database. *Energy Effic.* **2021**, *14*, 47. [CrossRef]
26. Tornberg, J.; Thuvander, L. A GIS Energy Model for the Building Stock of Goteborg. Available online: http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.594.4049&rep=rep1&type=pdf (accessed on 13 November 2017).
27. Dall'O', G.; Galante, A.; Torri, M. A methodology for the energy performance classification of residential building stock on an urban scale. *Energy Build.* **2012**, *48*, 211–219. [CrossRef]
28. Caputo, P.; Costa, G.; Ferrari, S. A supporting method for defining energy strategies in the building sector at urban scale. *Energy Policy* **2013**, *55*, 261–270. [CrossRef]
29. Buffat, R.; Schmid, L.; Heeren, N.; Froemelt, A.; Raubal, M.; Hellweg, S. GIS-based Decision Support System for Building Retrofit. *Energy Procedia* **2017**, *122*, 403–408. [CrossRef]
30. Fabbri, K.; Zuppiroli, M.; Ambrogio, K. Heritage buildings and energy performance: Mapping with GIS tools. *Energy Build.* **2012**, *48*, 137–145. [CrossRef]

31. Caputo, P.; Pasetti, G. Boosting the energy renovation rate of the private building stock in Italy: Policies and innovative GIS-based tools. *Sustain. Cities Soc.* **2017**, *34*, 394–404. [CrossRef]
32. Caputo, P.; Pasetti, G. GIS tools towards a renovation of the building heritage. *Energy Procedia* **2017**, *133*, 435–443. [CrossRef]
33. Gupta, R.; Gregg, M. Targeting and modelling urban energy retrofits using a city-scale energy mapping approach. *J. Clean. Prod.* **2018**, *174*, 401–412. [CrossRef]
34. Mastrucci, A.; Baume, O.; Stazi, F.; Leopolda, U. Estimating energy savings for the residential building stock of an entire city: A GIS-based statistical downscaling approach applied to Rotterdam. *Energy Build.* **2014**, *75*, 358–367. [CrossRef]
35. Buffat, R.; Froemelt, A.; Heeren, N.; Raubal, M.; Hellweg, S. Big data GIS analysis for novel approaches in building stock modelling. *Appl. Energy* **2017**, *208*, 277–290. [CrossRef]
36. Li, C.; Hong, T.; Yan, D. An insight into actual energy use and its drivers in high-performance buildings. *Appl. Energy* **2014**, *131*, 394–410. [CrossRef]
37. Zhou, Z.; Zhang, S.; Wang, C.; Zuo, J.; He, Q.; Rameezdeen, R. Achieving energy efficient buildings via retrofitting of existing buildings: A case study. *J. Clean. Prod.* **2016**, *112*, 3605–3615. [CrossRef]
38. Ali, U.; Shamsi, M.H.; Bohacek, M.; Purcell, K.; Hoare, C.; O'Donnell, J. GIS-based multi-scale residential building energy modeling using a data-driven approach. In *Building Simulation*; IBPSA: Las Cruces, NM, USA, 2021; Volume 17, pp. 1115–1122.
39. Paiho, S.; Kiljander, J.; Sarala, R.; Siikavirta, H.; Kilkki, O.; Bajpai, A.; Duchon, M.; Pahl, M.-O.; Wüstrich, L.; Lübben, C.; et al. Towards cross-commodity energy-sharing communities—A review of the market, regulatory, and technical situation. *Renew. Sustain. Energy Rev.* **2021**, *151*, 111568. [CrossRef]
40. Alhamwi, A.; Medjroubi, W.; Vogt, T.; Agert, C. GIS-based urban energy systems models and tools: Introducing a model for the optimisation of flexibilisation technologies in urban areas. *Appl. Energy* **2017**, *191*, 1–9. [CrossRef]
41. Lai, C.S.; Jia, Y.; Dong, Z.; Wang, D.; Tao, Y.; Lai, Q.H.; Wong, R.T.; Zobaa, A.F.; Wu, R.; Lai, L.L. A review of technical standards for smart cities. *Clean Technol.* **2020**, *2*, 290–310. [CrossRef]
42. Martins, F.; Patrão, C.; Moura, P.; de Almeida, A.T. A Review of Energy Modeling Tools for Energy Efficiency in Smart Cities. *Smart Cities* **2021**, *4*, 1420–1436. [CrossRef]
43. Mahapatra, C.; Moharana, A.K.; Leung, V.C. Energy management in smart cities based on internet of things: Peak demand reduction and energy savings. *Sensors* **2017**, *17*, 2812. [CrossRef]
44. de Santoli, L.; Mancini, F.; Garcia, D.A. A GIS-based model to assess electric energy consumptions and usable renewable energy potential in Lazio region at municipality scale. *Sustain. Cities Soc.* **2019**, *46*, 101413. [CrossRef]
45. Azeroual, O.; Saake, G.; Abuosba, M. ETL best practices for data quality checks in RIS databases. *Informatics* **2019**, *6*, 10. [CrossRef]
46. Breunig, M.; Bradley, P.E.; Jahn, M.; Kuper, P.; Mazroob, N.; Rösch, N.; Al-Doori, M.; Stefanakis, E.; Jadidi, M. Geospatial data management research: Progress and future directions. *ISPRS Int. J. Geo-Inf.* **2020**, *9*, 95. [CrossRef]
47. Mujeebu, M.; Al Shamrani, O. Prospects of energy conservation and management in buildings—The Saudi Arabian scenario versus global trends. *Renew. Sustain. Energy Rev.* **2016**, *58*, 1647–1663. [CrossRef]
48. Mutani, G.; Alehasin, M.; Yang, H.; Zhang, X.; Felmer, G. Urban Building Energy Modeling to Support Climate-Sensitive Planning in the Suburban Areas of Santiago de Chile. *Buildings* **2024**, *14*, 185. [CrossRef]
49. Congiu, E.; Desogus, G.; Frau, C.; Gatto, G.; Pili, S. Web-Based Management of Public Buildings: A Workflow Based on Integration of BIM and IoT Sensors with a Web–GIS Portal. *Buildings* **2023**, *13*, 1327. [CrossRef]
50. Krarti, M.; Dubey, K.; Howarth, N. Evaluation of Building Energy Efficiency Investment Options for the Kingdom of Saudi Arabia. *Energy* **2017**, *134*, 595–610. [CrossRef]
51. Ahmed, W.; Fardan, H.; Asif, M. Integration of Building Energy Modeling in the Design Process to Improve Sustainability Standards in the Residential Sector—Case Study of the Eastern Province of Saudi Arabia. In Proceedings of the IEEE International Conference on Smart Energy Grid Engineering (SEGE), Oshawa, ON, Canada, 14–17 August 2017; pp. 309–314.
52. Hamida, M.B.; Ahmed, W.; Asif, M.; Almaziad, F.A. Techno-Economic Assessment of Energy Retrofitting Educational Buildings: A Case Study in Saudi Arabia. *Sustainability* **2021**, *13*, 179. [CrossRef]
53. Asif, M.; Ahmed, W.; Alazazmeh, A. Energy Performance Assessment of a Post-Retrofit Office Building Using Measurement and Verification Protocol: A Case Study from KSA. *Energy Rep.* **2023**, *9*, 1366–1379. [CrossRef]
54. Graziuso, G.; Grimaldi, M.; Giordano, C. A GIS-BIM Approach for the Evaluation of Retrofit Actions in Urban Planning. In *A Methodological Proposal, Proceedings of the New Metropolitan Perspectives, Reggio Calabria, Italy, 24 May 2022*; Calabrò, F., Della Spina, L., Piñeira Mantiñán, M.J., Eds.; Springer: Cham, Switzerland, 2022; pp. 1328–1336.