SUSTAINABLE IMPACT OF BUILDING ENERGY RETROFIT MEASURES

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ABSTRACT
Energy retrofitting is argued to be the most feasible and cost-effective method for improving existing buildings' energy efficiency. As a sustainable development, building energy retrofits require the consideration and integration of all three sustainability dimensions: environmental, economic and social. The objective of this study is to estimate and compare the sustainable impact of building energy retrofits to determine the maximum sustainable benefit when implementing different energy-related measures. The proposed analysis consists of integrating three approaches for evaluating these benefits. Economic benefits are measured by estimating the payback period of energy-related measures, environmental benefits are measured by estimating the CO_2 equivalent saving per year due to the implementation of energy-related measures, and social benefits are measured by defining a "social impact index" that establishes the impact of energy-related measures on buildings' users. A case study is used to demonstrate the framework for four potential scenarios. The results show that for the case study, energy-related "controlling" and "upgrading mechanical system" measures have the highest sustainable impact among the identified energy retrofitting measures.

KEYWORDS
sustainable impact, energy improvement, energy measure, building retrofits.

1. INTRODUCTION
In the U.S., over 60 percent of the housing inventory is more than 30 years old (USCB 2013) and a large number of these homes are energy inefficient. Currently, energy retrofitting is argued to be the most feasible and cost-effective method to improve building energy efficiency (Ahn et al. 2013; Ramos et al. 2015). An energy retrofit is the physical or operational change in a building itself, its energy-consuming equipment, or its occupants' behavior to reduce the amount of energy needed and convert the building to a lower energy facility (Jafari and Valentin 2017).

As a sustainable development, building energy retrofits require the consideration and integration of all three sustainability dimensions: environmental, economic and social (Jafari et al. 2016; Santoyo-Castelazo and Azapagic 2014). Green retrofits for increasing energy efficiency can benefit the environment by reducing air emissions, can benefit a building's economy by

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reducing operating and energy consumption costs, and can benefit society and occupants by enhancing occupants' comfort and health and providing jobs (Jafari et al. 2016; USEPA).

Generally, in order to retrofit an existing building in terms of improving its energy efficiency, the following energy-related measures need to be implemented (GBA 2015; Jafari and Valentin 2017): (1) "*Controlling*" measures that provide appropriate controls for the mechanical systems; (2) "*Mechanical System Upgrade*" measures that upgrade the mechanical systems; (3) "*Insulation*" measures that insulate and air-seal the roof or ceiling, walls, and floor; (4) "*Windows & Doors Replacement*" measures that replace the windows and doors with energy-efficient models; (5) "*Fixtures & Appliances Replacement*" measures that replace fixtures, appliances, and lighting with energy-efficient models; and (6) "*Renewable Options*" measures that provide renewable-energy sources. In addition to the above energy measures, human factors such as changes of energy consumption patterns of occupants can be considered as another energy retrofit measure category (Ma et al. 2012).

The selection of a combination of retrofitting measures for a specific building is a complex process. The selection process of a retrofitting strategy is a trade-off between the capital investment (the investment required to implement that retrofitting strategy) and the benefits obtained from energy retrofitting (Ma et al. 2012). These energy retrofitting benefits can be categorized into economic, environmental, or social (Jafari et al. 2016). When choosing among a variety of sustainable benefits, the decision maker has to consider environmental, energy related, economic, and social factors to reach the optimum possible solution that satisfies the final occupant needs and requirements (Asadi et al. 2012).

The literature about the economic and environmental impacts of building energy efficiency is quite rich. There are numerous studies that highlight the impacts of building energy efficiency in terms of the environment (Dong et al. 2005; Jafari et al. 2014; Junnila and Horvath 2003; Junnila et al. 2006; Thiel et al. 2013; Wang et al. 2010; Wu et al. 2012) and the economy (Abdallah et al. 2014; Chai and Chen 2013; Jafari and Valentin 2015; Jafari et al. 2014; Jafari et al. 2016; Kansal and Kadambari 2010; Karatas and El-Rayes 2014; Kumbaroglu 2012). The measurement of social impacts of energy efficiency is under-developed (Jafari et al. 2016). While there is considerable information about energy reduction strategies for new housing buildings, there is limited knowledge about these strategies attributable to retrofitting existing buildings.

Prior research has not addressed the total sustainable impact of energy retrofits in buildings. This study integrates three approaches in terms of energy retrofitting impacts on economic benefits (Jafari et al. 2014), environmental benefits (Jafari et al. 2014), and social benefits (Jafari et al. 2016) to address this gap in the literature. The following study calculates and compares the amount of sustainable benefit that a homeowner may receive when implementing different energy-related measures for a specific home, in order to obtain the most effective sustainable level. In order to accomplish these tasks, the case study of a house, built in 1960's in Albuquerque, New Mexico, is considered to study economic and environmental impacts. In addition, a survey is used to study social impacts.

2. CASE STUDY

The house used as the case study was originally constructed in 1964 as a ranch style home (which is one of the most popular styles in the area) in Albuquerque, New Mexico. All of the repairs on the home have been intended to keep the facility habitable and no major energy conserving features have been added. The home is 150 m^2, has 3 bedrooms, 2 bathrooms, and is made of concrete block constructed on a crawlspace. The current heating is by gas furnace and cooling is provided by an evaporative cooling (swamp cooler) system. The house also uses a gas water heater and electric kitchen and laundry appliances.

In this study, data is gathered from the case study house to evaluate the effectiveness of various green remodeling techniques. The "Build Green New Mexico criteria for a Green Building" (BGNM 2012) document is used to evaluate the steps that could be taken to renovate the house. Table 1 provides a summary of the activities that could be implemented to retrofit the house.

The energy performance of the home is modeled by an energy simulation software, called eQuest v3.65. When the house was occupied by a family of three for two years, the annual utility usage had been approximately 9,000 kWh of electricity and 70 MBtu of gas. As the results show, the annual electricity and gas consumption of the study house is simulated to be 9,550 KWh and 73.42 MBtu, respectively. Therefore, the simulated energy consumption for the home is directly in line with the average actual usage of utilities. Considering the unit price of 0.113 $/KWh and 10.6 $/MBtu for electricity and natural gas during the study period, respectively, the annual utilities bill of the study house is $1,857.20.

3. METHODOLOGY

This study attempts to evaluate the sustainable impact of housing energy retrofit measures in terms of economic, environmental, and social impacts. The scope of this study focuses on

TABLE 1. Planned retrofitting activities.

Retrofitting Measures	Energy-Related Activities
Controlling	Install programmable thermostat
Mechanical System Upgrade	Tune up HVAC
	Install ground source heat exchanger
	Upgrade evaporative cooler
Insulation	Insulate Ceilings
	Insulate walls
	Insulate Attic
Windows & Doors Replacement	Replace doors with insulated core
	Replace windows with energy efficient glass
Fixtures & Appliances Replacement	Replace all lighting with CFLs
	Replace refrigerator with an energy star one
	Replace clothes washer with an energy star one
	Replace dishwasher with an energy star one
Renewable Options	Install solar thermal equipment
	Install solar electricity equipment

quantifying the sustainable benefits that an owner may receive when implementing different energy-related measures for a specific building. The aforementioned case study is used to assess economic and environmental impacts. In addition, a survey is used to evaluate the social impacts of a green energy retrofit and the results are incorporated into the analysis.

3.1. Economic Criteria Analysis

Payback period has been used as an effective tool to analyze the economic viability among available alternatives (Chidiac et al. 2011; Malatji et al. 2013; Wang et al. 2014). The payback period is the time required for an activity to recover its initial costs by considering expected savings. In this study, the time value of money is considered to accurately calculate the payback period which is used as the indicator of the economic impact for each retrofitting measure (Equation 1):

$$IIC = AECS \times \left(\frac{1-(1+d)^{-n}}{d} \right) \quad \text{or} \quad n = -\log_{(1+d)} 1 - \left(\frac{IIC}{AECS} \times d \right) \tag{1}$$

where n is payback period in years, IIC is the initial investment cost of a retrofitting measure, $AECS$ is the expected annual energy cost savings results from implementing an energy retrofit measure, and d is the discount rate. IIC refers to the cost of implementing a retrofitting measure including materials, equipment, and labor costs among others. Expected $AECS$ is the economic benefit of implementing each energy retrofitting measure in terms of utility cost savings per year. As a result of implementing each energy retrofitting measure, $AECS$ can be estimated using energy simulation tools. Only energy consumption costs and initial investment cost are considered to calculate the payback period, based on data availability for the case study. Other cost categories such as maintenance costs, operation costs, and tax rebates could be considered for more accurate results.

In this study, a PERT distribution is used to establish the estimated costs (both IIC and $AECS$). PERT distribution is a modified Beta distribution, which is typically used in construction to estimate completion time and cost based on a three point estimate (minimum, maximum, and most likely values). In this study, the estimated costs are established using three point estimates: optimistic ($x_{\min}$), most probable (x_m), and pessimistic ($x_{\max}$) expected costs. These values are then used to construct a *PERT* probability distribution for IIC and $AECS$ for each retrofitting measure.

After estimating the IIC and $AECS$, the payback period for each measure can be calculated. Using the Monte-Carlo Simulation and @Risk software, the payback period of each activity is calculated as a probability distribution.

A lower payback period is more desirable for retrofit projects. To evaluate the economic impact of each measure, a factor is defined as ECI (economic impact) for each energy retrofit measure, as shown in Equation 2.

$$ECI_i = \frac{\frac{1}{n_i}}{\sum_{i=1}^{k} \frac{1}{n_i}} \tag{2}$$

where ECI_i is the economic impact of the i^{th} energy retrofitting measure, n_i is the payback period of the i^{th} energy retrofitting measure, and k is the number of selected energy retrofitting measures (k = 6 in this case). *ECI* is equal to the multiplicative inverse of the payback period, which is normalized in a scale from 0 to 1.

3.2. Environmental Criteria Analysis

Although construction activities consume large amounts of energy, more than 80% of energy consumed by a building occurs during its operation phase, when the building is in actual occupancy and use (Menassa 2011). As such, the amount of energy consumption of a building during its operation significantly affects the environment. One of the most important environmental impacts is the amount of greenhouse gases that are released to the atmosphere through energy production, which is the focus of this study.

In the U.S., electricity is generated in many different ways, and therefore, environmental impacts vary. Electricity generation from the combustion of fossil fuels contributes towards air pollution, acid rain, and global climate change (EPA 2013). According to the U.S. Environmental Protection Agency (EPA), power emissions factors are determined based on the power grid region, and air emission rates of the electricity generated in the region are compared with those of the national average. However, burning natural gas instead of other fossil fuels emits fewer harmful pollutants, and an increased reliance on natural gas can potentially reduce the emission of many of these harmful pollutants (NaturalGas 2013). The air emissions analyzed in this study include carbon dioxide (CO_2), sulfur dioxide (SO_2), and nitrogen oxide (NO_x) (Jafari et al. 2014).

In order to describe different greenhouse gases in a common unit, the term of CO_2-equivalent reduction is used to analyze the environmental impact of energy retrofitting measures. The CO_2-equivalent reduction is the amount of CO_2-equivalent for CO_2, SO_2, and NO_x (equivalent global warming impact), that is not produced due to the energy saved by implementing a retrofitting measure. In this study, CO_2-equivalent reduction is calculated as Equation 3:

$$CO_2\text{-}Eq = \alpha\left(AES \times E_{CO_2} + AGS \times G_{CO_2}\right) + \beta\left(AES \times E_{SO_2} + AGS \times G_{SO_2}\right) + \gamma\left(AES \times E_{NO_x} + AGS \times G_{NO_x}\right) \quad (3)$$

where $CO_2\text{-}Eq$ is the CO_2-equivalent reduction per year, *AES* is the expected annual electricity saving in Kwh, *AGS* is the expected annual natural gas saving in MBtu, E_i is the amount of air emission releases for producing 1 KWh of electricity (lbs/KWh), G_i is the amount of air emission releases for consuming 1 MBtu of natural gas (lbs/MBtu), and α, β, γ are the conversion factors (in terms of global warming impact) of CO_2, SO_2, and NO_x respectively, in the CO_2-Equivalent calculation.

TABLE 1. Energy emissions factors.

Energy	Reference	Air Emissions		
		NO_x	SO_2	CO_2
Electricity (E_i)	(EPA 2013)	1.52 lbs/MWh	0.62 lbs/MWh	1,191 lbs/MWh
Natural Gas (G_i)	(NaturalGas 2013)	0.092 lbs/MBtu	0.001 lbs/MBtu	117 lbs/MBtu

Table 2 summarizes the air emissions quantities resulting from electricity and natural gas generation for the state of New Mexico (the case study location). In addition, values of 1, 1/0.005, and 1/0.0025 are suggested for the same location for α, β, and γ, respectively (ICBE 2017).

AES and *AGS* are the savings in electricity and natural gas, respectively, from implementing each energy retrofitting activity. As a result of implementing each energy retrofitting measure, *AES* and *AGS* can be estimated using energy simulation. After estimating the *AES* and *AGS*, the CO_2-*Eq* saving per year for each retrofitting measure can be calculated. Higher CO_2-*Eq* savings per year is more desirable environmentally for any retrofit project. To evaluate the environmental impact of each measure, a factor is defined as ENI (environmental impact) for each energy retrofit measure, as shown in Equation 4:

$$ENI_i = \frac{CO_2 - Eq_i}{\sum_{i=1}^{k} CO_2 - Eq_i} \tag{4}$$

where ENI_i is the environmental impact of the i^{th} energy retrofitting measure, and CO_2-Eq_i is CO_2 equivalent reduction per year for the i^{th} energy retrofitting measure. In other words, *ENI* is equal to CO_2-*Eq* saving per year, which is normalized in a scale from 0 to 1.

3.3. Social Criteria Analysis

An energy retrofit may have several social effects in a *community* and *society* levels such as improving health by decreasing air emissions, providing job opportunities, and promoting the culture of energy efficiency (Jafari and Valentin 2016). However, the social effects of energy housing retrofit practices on the building occupants (at the building level) are the primary focus of this study. Based on the characteristics of the project and prior research about positive outcomes associated with the project features and attributes, the following social benefits are identified at the building level (Jafari et al. 2016):

- *Health:* sustainable design mainly focuses on enhancing indoor air quality by improving ventilation rate, improving HVAC performance, and controlling humidity, which can have a positive effect on occupants' health (Noris et al. 2013; Sieber et al. 1996).
- *Comfort and Satisfaction:* using individual controls for temperature and ventilation as well as positive perceptions of indoor air quality associated with high ventilation rates can have a positive effect on the occupants comfort and satisfaction (Sieber et al. 1996; Wyon 2004).
- *Productivity:* controlling over temperature, air movement, and lighting are important components of an effective environment, that increases productivity (Kroner et al. 1992).
- *Security:* increasing energy-efficiency and using renewable energy sources could make security improvements more affordable: e.g., improving reliability during utility system outages by providing onsite power systems and improving thermal and optical performance by upgrading existing windows for blast resistance (Harris et al. 2002).

In this study, a survey is deployed to estimate the impact of implementing energy retrofit measures on buildings' occupants, according to the respondents' perception. The tradeoffs among these intangible benefits is not considered in this study. Opinion surveys have been used as an effective tool to assess the impact of different subjects on people, in societies where surveys are culturally appropriate (*Vanclay* et al. 2015). A questionnaire is developed, based on the features of an energy retrofitting measures and their different social benefits. The questionnaire starts with an introduction about the purpose of the study, provides a definition of the social benefits to be evaluated and asks the following questions:

- Question 1: Participants are asked to determine the level of importance of each identified social benefits of energy retrofitting. A five-point Likert scale—(1) very low importance, (2) low importance, (3) moderate importance, (4) high importance, and (5) very high importance—is adopted to calculate the relative importance of each identified social benefit; and
- Question 2: Participants are asked to estimate the level of impact that each housing energy retrofit measures has on each identified social benefit of energy retrofitting. Again, a five-point scale—(1) very low impact, (2) low impact, (3) moderate impact, (4) high impact, and (5) very high impact—is also adopted to estimate the relative impact of each retrofitting measure on each identified social area of influence.

The relative importance index (RII) method has been used to determine the relative importance of various factors is survey studies (Heravi and Jafari 2014; Sambasivan and Soon 2007). In this study, RII is used to evaluate the importance of each social building retrofit benefit based on the responses for the first question, using Equation 5:

$$RII = \frac{\sum W_1}{A \times N} \tag{5}$$

where RII is the relative importance factor for a social benefit of energy retrofitting, W_1 is the level of importance given by the respondents to each social benefit category and ranges from very low importance (1) to very high importance (5), A is the highest weight possible (i.e., 5); and N is the total number of respondents.

The responses obtained for Question 2 are used to evaluate how different retrofitting measures influence the social housing retrofit benefits through the proposed "Impact Factor" (IF) index. The IF also can be calculated using Equation 6:

$$IF = \frac{\sum W_2}{A \times N} \tag{6}$$

where IF is the impact factor of a retrofitting measure on each of the four identified social benefits of energy retrofitting, and W_2 is the level of impact given to each energy retrofitting measure by the respondents and ranges from very low impact (1) to very high impact (5).

Then, considering the social impact of a retrofitting measure as an aggregation of social benefits, a "Social Impact Index" (SII) is defined using Equation 7:

$$SII = \frac{\sum_i RII_i \times IF_i}{M} \tag{7}$$

where *SII* is the social impact index for a retrofitting measure; *i* represents the social benefits of energy retrofitting; RII_i is the relative importance index of the i^{th} social benefit; IF_i is the impact factor of the retrofitting measure for its i^{th} social benefit; and *M* is the number of social areas of influence (equal to 4 in this study).

Higher *SII* is more desirable for any retrofit project. To evaluate the social impact, a factor is defined as *SOI* (social impact) for each energy retrofit measure, using Equation 8:

$$SOI_i = \frac{SII_i}{\sum_{i=1}^{k} SII_i} \quad (8)$$

where SOI_i is the social impact of i^{th} energy retrofitting measure, and SII_i is the social impact index of the i^{th} energy retrofitting measure. In other words, *SOI* is equal to SII which is normalized in a scale from 0 to 1.

3.4. Sustainable Criteria Analysis

The sustainable impact of energy retrofit measures will be the summation of its economical (ECI), environmental (ENI), and social (SOI) impacts as shown in Equation 9:

$$SUI_i = (a \times ECI_i) + (b \times ENI_i) + (c \times SOI_i) \quad (9)$$

where SUI_i is the aggregated sustainable impact for the i^{th} energy retrofitting measure, ECI_i, is its economic impact, ENI_i is its environmental impact, SOI_i is its social impact, and *a*, *b*, and *c* are the weight of economic, environmental, and social impacts in sustainable impact analysis, respectively.

In terms of energy retrofitting, each decision-maker could choose different importance weights for ECI, ENI, and SOI. In order to demonstrate the methodology, four different potential scenarios are defined as follows:

- Equal importance to all criteria: where economic, environmental and social criteria are rated with the same importance.
- Economic scenario: where economic impact has higher importance than environmental and social criteria.

TABLE 3. Different weight factors for different scenarios.

No.	Scenario	Importance Factor		
		a	b	c
1	Equal importance to all criteria	33%	33%	33%
2	Economic scenario	80%	10%	10%
3	Environmental scenario	10%	80%	10%
4	Social scenario	10%	10%	80%

- Environmental scenario: where environmental impact has higher importance than economic and social criteria.
- Social scenario: where social impact has higher importance than environmental and economic criteria.

The importance weight factors are assumed based on the above definition for each scenario and are defined in Table 3. Using these importance factors, energy retrofitting measures are evaluated and ranked in terms of their sustainable impacts. Energy measures with higher sustainable impact would be more desirable to be implemented in a building.

4. RESULTS AND DISCUSSION

4.1. Economic Impacts

Two types of costs were required to estimate the payback period of each retrofitting measure: initial investment cost and expected annual energy cost savings.

The initial cost of each activity was estimated using available sources such as RS Means: Green Building Cost Data (RSMeans 2012), Housing and Urban Development Website: Energy Efficient Rehab Advisor (HUD 2013), and a cost estimator professional. The annual savings of each activity was estimated using the following sources: (1) eQuest (Quick Energy Simulation Tool) software (DOE2 2013), version 3.65, (2) Housing and Urban Development Website: Energy Efficient Rehab Advisor (HUD 2013), and (3) Energy Star portal (EnergyStar 2013). For each retrofitting activity, three points of cost were estimated for IIC and AECS using the aforementioned sources.

Although discount rate is not a constant term and may vary over the service life of the project, a discount rate of 2 or 3% above inflation is considered an appropriate value (Hojjat 2002). In this study, a discount rate of 3% was assumed.

Table 4 summarizes the results of each payback period distribution using Equation 1, in terms of the mean value and the interval of the payback period estimated with a 90% confidence. For example by performing “Insulate Ceiling,” the initial investment with a 90% probability will be recovered between 9.2 to 12 years; 10.2 years on average. In addition, the average payback period of each energy measure was calculated separately assuming that all energy improvement activities within that energy measure are implemented, using Equation 1.

The last column of Table 4 shows the normalized ECI for each energy retrofit measure. As the results show, the controlling measures have the highest economic impact. That is because the implementation of controlling measures is low cost; however, they can save a large amount of the energy consumed by a building. After the “controlling” measure, “fixtures and appliances replacement” and “insulation” measures have the highest economic impacts. On the other hand, “renewable options” measure has the lowest economic impact. That is because these measures have high initial costs and therefore their payback periods are usually high (however they can save a huge amount of energy).

4.2. Environmental Impacts

According to the estimated amount of electricity and gas consumption of the building, the amount of emissions that are released during the operation of the building were 21.3 lbs of NO_x, 6.0 lbs of SO_2, and 19,962 lbs of CO_2 per year. Also, the amount of CO_2 emission during

TABLE 4. Summary of the payback periods for each retrofitting activity.

Measures	Activities	Payback Period (Year)			Average Payback Period (year)	Normalized ECI
		Percentile5	Mean	Percentile95		
Controlling	Install programmable thermostat	0.4	0.6	1.0	0.6	0.835
Mechanical System Upgrade	Tune up HVAC	0.6	0.7	0.8	21.2	0.024
	Install ground source heat exchanger	30.3	35.4	41.6		
	Upgrade evaporative cooler	4.9	6.7	8.6		
Insulation	Insulate Ceilings	9.2	10.2	12.0	12.6	0.040
	Insulate walls	7.9	17.4	33.0		
	Insulate Attic	8.8	11.1	13.5		
Windows & Doors Replacement	Replace doors with insulated core	31.5	74.7	145.6	69.2	0.007
	Replace windows with energy efficient glass	43.0	63.7	97.7		
Fixtures & Appliances Replacement	Replace all lighting with CFLs	0.2	0.3	0.3	6.0	0.084
	Replace refrigerator with an energy star one	14.8	42.9	103.2		
	Replace clothes washer with an energy star one	7.9	14.5	23.5		
	Replace dishwasher with an energy star one	27.9	64.5	133.7		
Renewable Options	Install solar thermal equipment	21.5	32.4	50.1	48.4	0.010
	Install solar electricity equipment	47.6	54.4	62.4		

the operation was equal to 13.3 lbs/ft^2.year (64.9 kg/m^2.year), which can be compared to the results of prior studies which range from 13.9 kg/m^2.year in Spain (Zabalza et al. 2013) to 260 kg/m^2.year in China (Wu et al. 2012).

Considering the energy savings associated to each activity as well as energy emissions, the amount of emission savings associated with the implementation of each retrofitting activity was calculated using Equation 3. Table 5 summarizes air emission savings per year considering the implementation of each activity.

As the results show, the "mechanical system upgrade" measures and "renewable options" measure have the highest ENI and therefore the highest environmental benefits. That is, because

TABLE 5. Summary of the environmental impact for each retrofitting activity.

Measures	Activities	Average Emission Saving per year (lbs/year)			CO_2-Eq Saving (lbs/year)	Normalized ENI
		NO_x	SO_2	CO_2		
Controlling	Install programmable thermostat	0.355	0.155	297.8	471	0.009
Mechanical System Upgrade	Tune up HVAC	1.614	0.489	1572.5	20,842	0.388
	Install ground source heat exchanger	10.150	2.994	9975.0		
	Upgrade evaporative cooler	2.759	0.919	2604.9		
Insulation	Insulate Ceilings	1.194	0.333	1192.8	5,980	0.111
	Insulate walls	1.338	0.075	1640.1		
	Insulate Attic	1.388	0.348	1427.3		
Windows & Doors Replacement	Replace doors with insulated core	0.286	0.015	351.4	2,878	0.054
	Replace windows with energy efficient glass	1.578	0.301	1718.1		
Fixtures & Appliances Replacement	Replace all lighting with CFLs	2.967	1.417	2364.7	4,747	0.088
	Replace refrigerator with an energy star one	0.285	0.136	226.9		
	Replace clothes washer with an energy star one	0.285	0.136	226.9		
	Replace dishwasher with an energy star one	0.138	0.068	107.6		
Renewable Options	Install solar thermal equipment	1.914	0.021	2433.6	18,832	0.350
	Install solar electricity equipment	11.786	5.146	9885.3		

the implementation of these measures can save a large amount of energy consumed by a building. On the other hand, "controlling" measure has the lowest environmental impact because of the small amount of energy that is saved from the building's total energy consumption.

4.3. Social Impacts

In order to determine the social impact of an energy retrofit project, a survey was deployed (Jafari et al. 2016). The target population of this pilot study consists of (1) academic researchers who are experts in building sustainable developments, and (2) industrial experts who are working in sustainable areas. A group of 14 participants was involved in the pilot survey of this study.

By using the calculated RII for each identified social benefit using Equation 5 (based on survey responses for Question 1), the most important social indicators of a housing energy retrofit are calculated. The most important social area of influence for a housing retrofit project was found to be health, followed by comfort and satisfaction, security, and productivity (RII of 0.91, 0.80, 0.71, and 0.66, respectively).

To evaluate how different retrofitting measures influence the social housing retrofit benefits based on responses received for Question 2, the "Impact Factor" (IF) index is calculated, using Equation 6. Table 6 shows the relative impact of each retrofitting measure on the identified social areas of influence by calculating IF.

Table 6 shows that "mechanical system upgrade" measures has the highest impact on residents' health, followed by "controlling" measures. In addition, the retrofitting measure that has the highest impact on residents' comfort and satisfaction is "controlling" measure followed by "mechanical system upgrade" measure. The retrofitting measure that has the highest impact on residents' productivity is the "controlling" measure followed by "mechanical system upgrade" and "fixtures & appliances replacement" measures. Furthermore, the retrofitting measure that

TABLE 6. Summary of the social impact for each retrofitting activity.

	Social Impact Factor (IF)					
Measures	Health (RII = 0.91)	Comfort & Satisfaction (RII = 0.80)	Productivity (RII = 0.66)	Security (RII = 0.71)	Social Impact Index (SII)	Normalized SOI
Controlling	0.756	0.884	0.734	0.584	0.573	0.180
Mechanical System Upgrade	0.850	0.816	0.700	0.564	0.572	0.179
Insulation	0.750	0.766	0.634	0.600	0.535	0.168
Windows & Doors Replacement	0.650	0.800	0.616	0.616	0.519	0.163
Fixtures & Appliances Replacement	0.634	0.750	0.700	0.584	0.513	0.161
Renewable Options	0.666	0.650	0.516	0.634	0.479	0.150

has the highest impact on residents' security is the "renewable options" measure, followed by "windows and doors replacement" measure.

By using the calculated SII for each energy retrofit measure, their social impact is calculated and compared. The SOI results show that the "controlling" measure has the highest social impact on residents, followed by "mechanical system upgrade" measure. In addition, "renewable options" measure has the lowest social impact on residents, followed by "fixtures and appliances replacement" measure.

4.4. Sustainable Impacts

Economic, environmental and social criteria were integrated for each retrofit measure by multiplying their respective normalized factors by its associated weight them up as shown in Equation 9. As shown in Table 3, four different scenarios were considered in this study with their associated importance weights for each economic, environmental, and social criteria, as: (1) equal importance to all criteria; (2) economic scenario; (3) environmental scenario; and (4) social scenario.

The results of the sustainable index for each energy retrofit measure according to each scenario are shown in Table 7.

When equal importance is assigned to all criteria (economic, environmental, and social), the highest sustainable impact is found for "controlling" measures, followed by "mechanical system upgrade" measures. The same result is obtained when the social criteria has the highest level of importance. When the economic criteria has the highest level of importance, the highest sustainable impact is obtained by "controlling" measures, followed by "fixtures and appliances replacement" measures. Finally, when the environmental criteria has the highest level of importance, "mechanical system upgrade" measures have the highest sustainable impact, followed by renewable options measures. On the other hand, in all scenarios, "windows and doors replacement" measures have the lowest sustainable impacts and are ranked as the least effective ones.

TABLE 7. Summary of the sustainable impact for each retrofitting measure.

	Equal Importance to all Criteria		Economic Scenario		Environmental Scenario		Social Scenario	
Retrofitting Measure	Index	Rank	Index	Rank	Index	Rank	Index	Rank
Controlling	0.341	1	0.687	1	0.109	4	0.228	1
Mechanical System Upgrade	0.197	2	0.076	3	0.331	1	0.184	2
Insulation	0.106	5	0.060	4	0.110	3	0.150	4
Windows & Doors Replacement	0.075	6	0.027	6	0.060	6	0.137	6
Fixtures & Appliances Replacement	0.111	4	0.092	2	0.095	5	0.146	5
Renewable Options	0.170	3	0.058	5	0.296	2	0.156	3

5. CONCLUSION

This study integrated three approaches for evaluating and quantifying the total sustainable impacts of energy retrofitting measures in terms of economic, environmental, and social benefits. Using a case study and survey research, the study estimated and compared the amount of sustainable benefit that a homeowner may achieve when implementing different energy-related measures for a specific home in order to obtain the most effective sustainable level. The six main energy retrofitting measures considered in this study include: (1) "*Controlling*" measures; (2) "*Mechanical System Upgrade*" measures; (3) "*Insulation*" measures; (4) "*Windows & Doors Replacement*" measures; (5) "*Fixtures & Appliances Replacement*" measures; and (6) "*Renewable Options*" measures.

Four different potential scenarios were considered for establishing the weight of economic, environmental, and social benefits: (1) "Equal importance to all criteria"; (2) "Economic scenario"; (3) "Environmental scenario" and (4) "Social scenario." The results showed that "controlling" measures have consistently the highest or one of the highest impacts in each scenario, followed by "mechanical system upgrade" and "renewable option" measures. The results of this study are only applicable to the case study; however, the proposed framework could be replicated and adapted for other cases and can be used as a tool for decision-making in energy retrofitting.

Although this study tried to fill the gap in the literature about combined sustainable impact of existing buildings' energy retrofitting by developing and testing the proposed integrated approach, the study has some limitations. The study does not consider the interaction or impact of different energy retrofitting measures on each other or the tradeoffs among intangible benefits of energy retrofits. Besides, the study used investment costs and energy cost savings to calculate payback periods. Additional cost categories such as operation costs and resale value could be used for more accurate results in future research. The analysis considered environmental impacts of energy retrofitting during building operation with a focus on air emissions. Although CO_2-equivalent reduction is one of the most significant environmental benefits of energy retrofitting according to prior research, future research could consider additional impacts such as the required energy for retrofitting, and fossil fuel conservation, among others. The survey used to rank the social benefits of retrofitting had a limited number of respondents. The study could also be expanded by defining additional energy-related activities to increase generalizability of the results.

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