Energy Productivity Analysis Framework for Buildings:

A Case Study of the GCC Region

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Abstract:

A new analysis framework is developed and applied to assess the benefits of building energy efficiency policies and programs. One of the main advantages of the new energy productivity analysis is that it accounts for both economic and energy performances of energy efficiency actions using only one metric. Specifically, the approach applies the concept of energy productivity to the building sector and accounts for both value added and energy savings of energy efficiency measures. Moreover, the proposed analysis accounts for all quantifiable benefits of energy efficiency programs including economic, environmental, and social. In this paper, the general guidelines for the energy productivity analysis are first described. Then, the analysis is applied to evaluate energy efficiency renewable energy programs for both existing and new buildings in the Gulf Cooperation Council (GCC) countries. The analysis results indicate that retrofitting the existing building stock can provide significant benefits and can improve the energy productivity of the building sector in all GCC countries and free up large energy volumes and investment potentials to the development of other economic sectors. In particular, the analysis indicates that reduction in energy consumption, peak demand, and carbon emissions due to deep retrofit programs for the existing building stock can double the energy productivity of the GCC region.

Keywords: Building Energy Efficiency, Energy Productivity; GCC Region; Non-Energy Benefits; Value Added

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1. Introduction

In addition to the well-documented savings in energy use and associated costs, energy efficiency improvements of buildings deliver a range of non-energy benefits or NEBs [1-4]. The value added of NEBs, in both economic and social terms, can be substantial especially for large-scale energy efficiency programs [1-2]. Some of NEBs relevant to the buildings sector include:

- Enhanced productivity for businesses
- Increased asset value
- Improved comfort, health and safety for occupants, and
- Reduced system operation costs for electric utilities.

Currently, NEBs are often not accounted for when evaluating the benefits of energy efficiency programs specific to the building sector. The incorporation of NEBs for building energy efficiency projects, in both economic and social terms, is one important feature of the energy productivity framework analysis introduced in this paper. Specifically, this paper introduces a new analysis framework suitable to evaluate how energy efficiency programs and policies (i.e., retrofit programs, building energy codes, and building integrated solar systems) influence energy productivity of the building sector. The analysis framework integrates two main aspects of energy efficiency: a) energy consumption reduction achieved through energy efficiency programs; and b) value added from multiple non-energy benefits (NEBs) such as higher work productivity, improved occupant health, and reduced investment in energy infrastructure.

Energy productivity is gaining traction around the world as a measure of energy efficiency benefits since governments are prioritizing boosting growth and creating jobs while remaining committed to reducing emissions and environmental impacts as co-benefits [5-7]. Indeed, energy productivity or the economic output generated from one unit of energy is becoming a policy framework that governments can use to aim toward the overarching goal of increased growth, productivity and competitiveness [8-12]. For instance, governments of the US and Australia have set a target to double the energy productivity of their economy by 2030 [11-12]. The main advantage of the energy productivity is its ability to incorporate a wider range of direct and indirect benefits including the NEBs. While, several studies provide comparative analysis of energy productivity indicators based on historical macro-economic data (i.e., gross domestic product, total primary energy supply, and total final energy consumption), no analysis framework has been reported to predict the impact of any energy efficiency policy for one sector of the economy on its energy productivity [6-12]. In this paper, the energy productivity concept is applied to evaluate the benefits of energy efficiency policies and programs to the building sector. Specifically, Figure 1 presents a framework for the proposed energy productivity analysis suitable to account for the multiple and non-energy benefits of energy efficiency applied to a building stock. The building stock is often categorized into residential, commercial and industrial and public sector users. For residential users, energy is needed mainly to produce non-monetary benefits or energy services such as heating and cooling, refrigeration, and lighting. Commercial and industrial users may incorporate some of these energy services, but primarily use energy in their buildings to support their businesses whether in retail sales or office work. Public sector buildings includes government departments, museums and other spaces where the energy services support the production of community, cultural or other social benefits. The power sector includes electricity grid and distributed generation and energy storage. Electricity can flow in two directions from buildings to the grid through distributed generation and storage. The potential energy savings from energy efficiency can have multiple benefits to the grid including demand response and demand side management. The energy services by the building sector provides a wide range of benefits as outlined in Figure 1 ranging from enhancing comfort and heath of occupants to increase their productivity at work or home to lowering energy and power usage to reduce carbon emissions and investment required for new power plants. The combination of energy efficiency and the benefits from the energy services constitute the concept of energy productivity considered in this study.

While the analysis framework presented in this paper is general and is applicable to any energy policy, any sector, and any country, the study summarized in this paper targets energy efficiency programs for the building sector within the Gulf Cooperation Council (GCC) region. The GCC region consists of six Middle Eastern countries: Kingdom of Saudi Arabia (KSA), Oman, United Arab Emirates (UAE), Kuwait, Bahrain, and Qatar. The GCC region has the largest oil and natural gas reserves in the World [13]. The economies for all the GCC countries depend almost exclusively on fuel exports and therefore are significantly dependent on oil and natural gas prices that have been fluctuating significantly in the last decade. Moreover, GCC countries have the highest energy consumption per capita as illustrated in Figure 2 especially since 1990's. Indeed, the GCC region is experiencing a significant growth in energy demand over the last two decades mostly due to rapid population growth and heavy energy subsidies. Specifically, Figure 2 indicates that the residential electricity consumption per capita is significantly higher in the GCC countries than in the G-7 countries throughout the 1990-2014 period [13]. Recently, GCC governments have indicated stronger interest in reducing dependence on energy resource revenues and diversifying their economies. Linked to this interest, an emerging focus on energy productivity, which aims to maximize the economic and social benefits from each unit of energy consumed [6-7, 14].

First, the paper provides an overview of the literature on both energy productivity concept and non-energy benefits specific to building energy efficiency. Then, it outlines general principles and guidelines for energy productivity based analysis framework to quantify the impacts of energy efficiency programs. Acknowledging that existing and new building stocks have different potential to contribute to energy productivity in the buildings sector, the study summarized in this paper applies the energy productivity analysis to each building type. Specifically and using the case study of the GCC region, the energy productivity analysis is utilized to examine potential contributions of energy retrofit programs in order to reduce energy demand of the existing building stock and of more stringent standards and codes to improve the energy efficiency of new buildings. In addition to considering the entire building stock, a variation of the energy productivity analysis is applied in this paper to assess the benefits – to both owners and occupants – of improving energy efficiency for individual buildings.

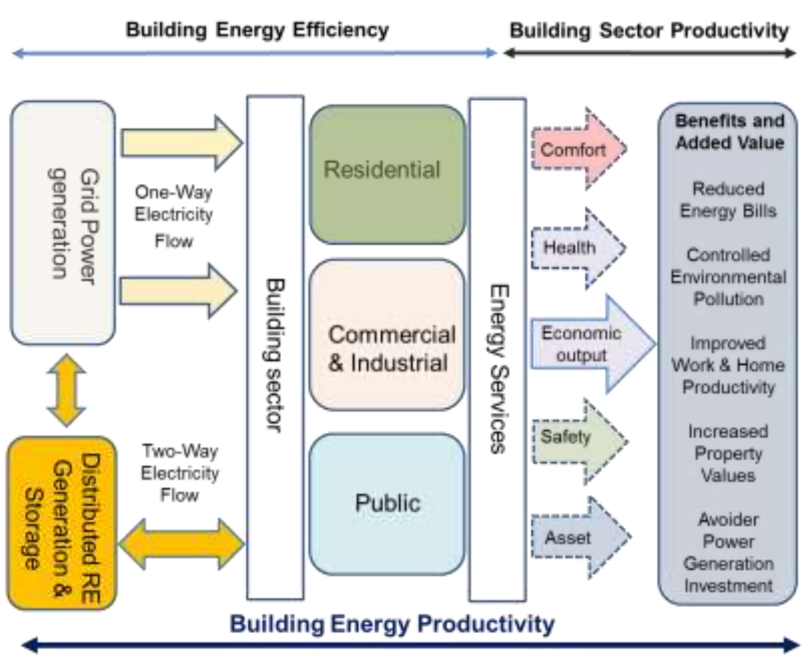


Figure 1: Flowchart for the building sector's energy productivity framework

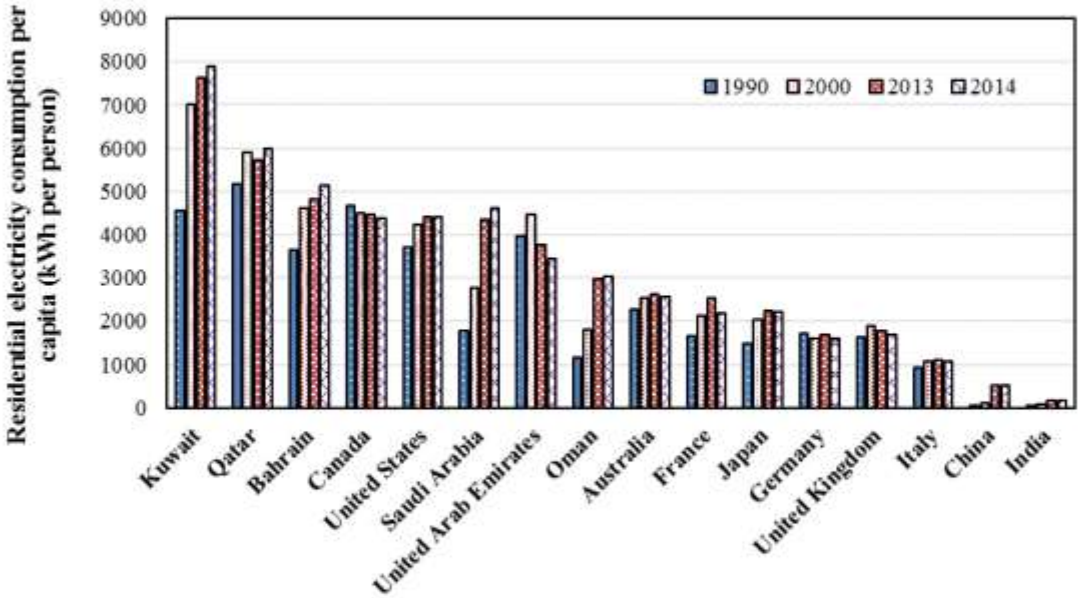


Figure 2: Electricity consumption per capita for residential buildings for GCC and G-7 countries (Source of data: IEA [13])

2. Overview of Energy Productivity

The concept of energy productivity has been introduced by several studies to assess how effectively an economy is using its energy resources to optimize economic and social development – and indeed to make more strategic decisions about the allocation of energy resources [15-16]. Generally, energy productivity is simply the inverse of energy intensity and represents the value of services and goods that an economy can produce with one unit of energy used. Thus, the energy productivity is the ratio of the value added by the energy consumed. A high ratio indicates that an economy is more effective and productive in extracting value –by generating goods and services – from the energy it consumes. While enhancing energy efficiency is at the core of the energy productivity concept, its major strength is how it can conceptually integrate a wider range of energy policies and programs including renewable energy and electricity market reform. For example, the Australian National Energy Productivity Plan has electricity sector reform and delivering lower electricity prices, especially for industry, alongside energy efficiency [17].

While the energy productivity is generally applied to evaluate the energy efficiency of an entire economy, it is can be utilized to assess the financial, social and environmental value created from energy consumption of individual economic sectors, including the buildings sector. Various studies clearly show that the service sector has inherently higher energy productivity values than other energy-intensive sectors, such industry and transport. Thus, countries with service-driven economies generally have higher energy productivity. Data for energy intensities reported annually by the International Energy Agency [13] are convenient to determine the energy productivity indices of various countries including GCC, United States (US), and United Kingdom (UK) as shown in Figure 3. The UK, with most of its economy based on services, ranks among the top in energy productivity [18]. By contrast, GCC countries show low levels of energy productivity. In fact, annual growth of energy productivity in the GCC region is low overall; in some cases, it has actually decreased since 2005. As noted earlier, the energy productivity ratio can be an indicator to assess the level of energy efficiency of a country to develop its economy. To better assess the best approaches to improve the energy productivity of a given economy, it is important to evaluate how its various sectors utilize energy resources. Reported studies have evaluated energy productivity for various economic sectors especially industries [10, 19-20]. However, very limited analyses are available on the energy productivity trends specific to the building sector especially in the GCC region. Additionally, no specific analysis framework is currently available to predict sectorial indicators of energy productivity and their relation to overall economy energy productivity.

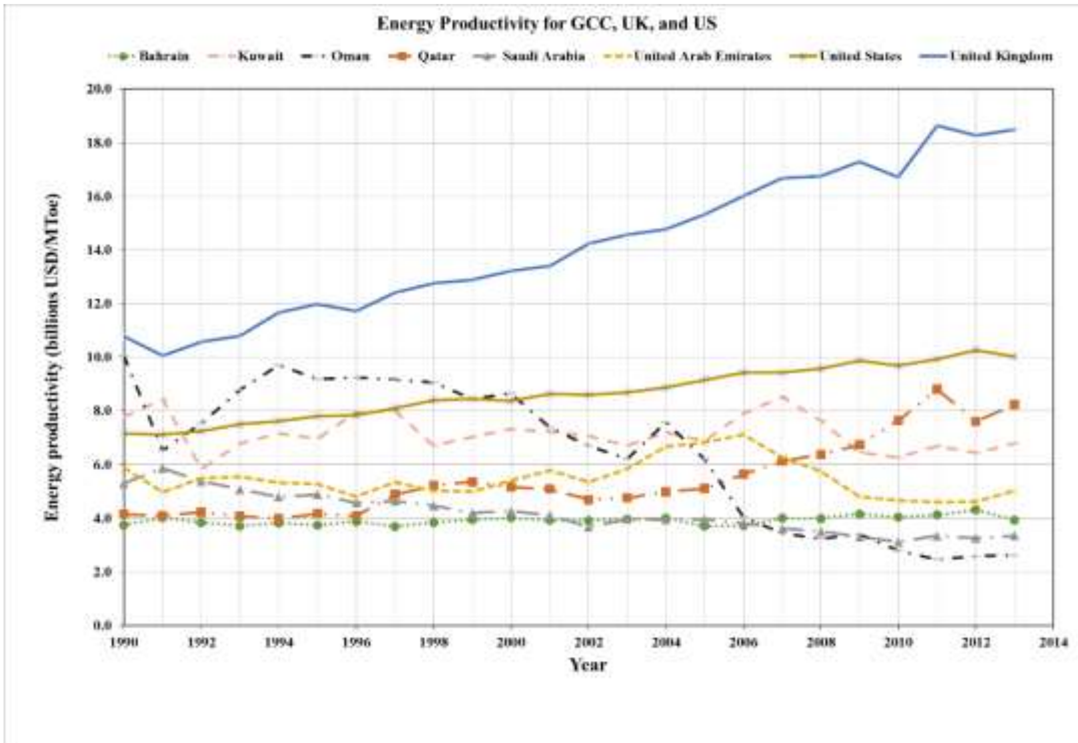


Figure 3: Annual energy productivity of GCC countries, US, and UK (Source of data: IEA [13])

Several empirical analyses have indicated that two main mechanisms can boost economy-wide energy productivity including [6-7, 14, 16]:

a) Improving energy efficiency (e.g. reducing the amount of energy consumed for each unit of GDP) primarily by promoting the adoption of new technologies and behavioral changes in various sectors; and

b) Shifting the economic structure towards less-energy intensive sectors such as financial services.

3. Benefits of Energy Efficiency for Buildings

As noted earlier, NEBs are often not considered when assessing the cost-benefit ratio of energy efficiency interventions since it is difficult to evaluate their economic impacts. In some instances, their monetary value is difficult to quantify; in other cases, financial values are associated to the non-monetary impacts (i.e., social benefits) they provide. Several studies have attempted to evaluate the economic, social, and environmental benefits of building energy efficiency programs [21-24]. Evaluation studies of energy efficiency programs are starting to recognize NEBs, and include them in measuring and assessing the cost-effectiveness of large-scale energy efficiency programs [25-26].

The impact of indoor thermal comfort on work productivity has been evaluated by several studies using specific case studies and surveys of subjects [27-30]. Improving the indoor environment in US office buildings has estimated to increase in productivity by 0.5% to 5%, delivering an economic value of $12 billion to $125 billion annually [28]. Similarly, a mere 2ºC increase of indoor air temperature above a neutral comfort temperature (typically 24ºC) can result in more than 10% work productivity loss [24]. Using data on typical salaries in US office buildings, the work productivity reduction is valued as an annual loss of approximately $200/m^2.

The asset values of sustainable buildings are found to be higher than conventional structures in several studies and analyses. Available data from several countries, including mostly LEED rated office buildings in the US, show that certified green buildings are priced up to 30% higher than non-certified buildings [4]. In addition, LEED and Green Star-rated buildings typically command rental premiums of up to 17% [4]. Energy efficient features such as daylighting in US retail stores have shown to boost floor sales by 15% to 40% per floor area [31]. By providing a better quality indoor environment, energy efficient and sustainable buildings also contribute to occupant health and well-being. Schools with optimal daylight, for instance, report increased attendance (by as much three days per year per student), 20% to 26% faster learning rates, and 5% to 14% improvement in test scores [32]. Better-ventilated buildings with outdoor air can maintain healthier indoor environment, and reduce cases of Sick Building Syndrome (SBS). Installing adequate ventilation to keep indoor carbon dioxide (CO_2) levels similar to outdoor levels can reduce SBS symptoms by 70% to 85% [33].

Several studies suggest approaches to define and estimate the monetary value of NEBs related to a wide range of energy efficiency programs [26, 34-36]. Based on reported studies and results of surveys conducted on US building energy efficiency programs, Table 1 summarizes some of the main NEBs and their value estimates (as a percentage of the overall energy cost savings) for various stakeholders [4, 26]. It should be noted that some studies have documented lower impacts from high performance and sustainable buildings than those indicated in Table 1 [37-38].

For the energy productivity analysis framework outlined in the following section, the value added of NEBs can be included in assessing the effectiveness of energy efficiency programs for buildings.

Table 1: Select NEBs for energy efficiency programs for various stakeholders

Owners/Occupants of Residential Buildings		**Operators/Occupants of Commercial Buildings**		**Power Generators and Utility Companies**	
Impact/Benefits	**Value (%)***	**Impact/Benefit**	**Value**	**Impact/Benefit**	**Value**
Lighting Maintenance Reduction	28%	Improved Productivity	Up to 10% increase in worker productivity	Avoided Costs of T&D Capacity	$0 - $200 per kW-year
Increase Durability	10%	Reduced maintenance costs	7% of energy use savings	Avoided Costs of Generating Capacity	$22 - $434 per kW-year
Increase of Marketability of Rental Units	8%	Increased sales	Up to 17% relative to conventional buildings	Avoided Costs of Energy	$0.02-$0.19 per kWh
Increased Safety, Comfort, and Respect from Community	18%	Enhanced public image	Increased attendance 3 days/year	Demand Reduction Induced Price Effects	$0-$0.024 per kWh and $0.62-$34 per kW-year

Note (*) percent of the energy cost savings

4. Energy productivity analysis framework

The main features of the energy productivity analysis specific to the building sector are presented in this section for both macro and micro levels. First, the analysis targeting building stocks is described to evaluate on the benefits of large-scale energy programs. Moreover, the energy productivity analysis for individual buildings is presented to assess the impact of targeted energy efficiency projects. Then, variations in energy productivity due to the implementation of energy programs or projects are outlined. Finally, calculation methods are summarized to estimate value added associated with energy efficiency benefits that vary uniformly or gradually over time.

4.1 Analysis Approach for Building Stocks

The macroeconomic value of energy productivity (EP) at the level of a given economy can be estimated using the gross domestic product (GDP) and the total final energy consumption (TFC) [7-8]:

$$EP = \frac{GDP}{TFC} \tag{1}$$

This energy productivity across the economy as a whole can be decomposed using the economy's sectorial energy productivity values, as indicated in Eq (2):

$$EP = \sum_{i=1}^{S} \frac{GDP_i}{TFC} = \sum_{i=1}^{S} \left(\frac{TFC_i}{TFC}\right)\left(\frac{GDP_i}{TFC_i}\right) = \sum_{i=1}^{S} f_i \, EP_i \tag{2}$$

Where,

- S is the total number of sectors contributing to the total economy GDP
- GDP_i is the contribution of the GDP of sector i
- TFC_i is the total final energy consumed by sector i
- EP_i is the energy productivity for sector, *i*.
- f_i is the contribution (in percent) of a particular sector (*i*) to TFC.

Analysis of reported data indicates that the share of various sectors in TFC varies dramatically between countries. For instance, Figure 4 shows the share of the building, industry, and transport sectors in final energy consumption for the US, the UK and GCC during the period 1990-2013 [13].

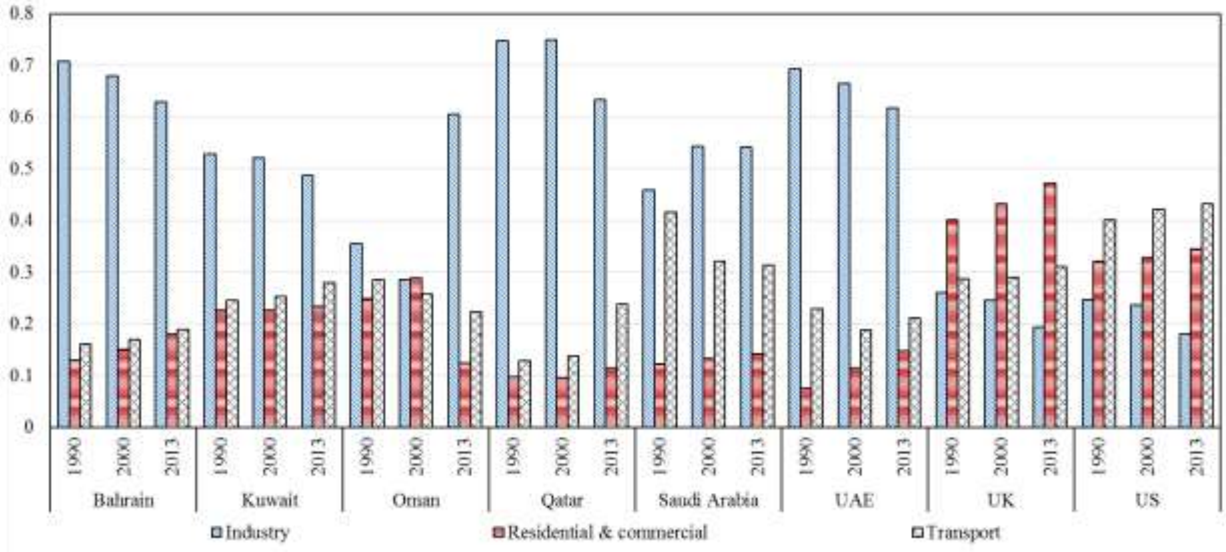


Figure 4: Share of building, industry, and transport sectors in final energy consumption of GCC countries, US, and UK (source of data: IEA [13])

Eq. (2) clearly shows that the energy productivity values of energy-intensive sectors have a strong effect on the energy productivity of the economy as a whole. Moreover, Eq. (2) indicates that there are two main options to increase an economy's energy productivity: (i) improve energy productivity, particularly of energy-intensive sectors, through energy efficiency actions (i.e., by increasing their EP_i values); or (ii) shift the economy to less energy-intensive sectors (i.e., by increasing their f_i values) even though this option may not be feasible for some countries.

As noted in Figure 4, the buildings sector share in TFC is rather low for most GCC countries compared with that of UK and to lesser extent that of US. Industry dominates in all GCC countries (except Oman), representing as high as 70% of TFC. As a result, the potential impact of energy policies specific to the building sector for the GCC countries is low on overall economy energy productivity by comparison to the case of UK or even the US. To illustrate this observation, Eq. (2) can be used to decompose each country economy-wide energy productivity (EP) and determine how improving EP for the building sector would affect the global economy EP for GCC countries and for the US as illustrated in Figure 5. When building EP is doubled (i.e., 100% improvement), the global EP increases by 14% for KSA, by 50% for UK, and by 35% for the US.

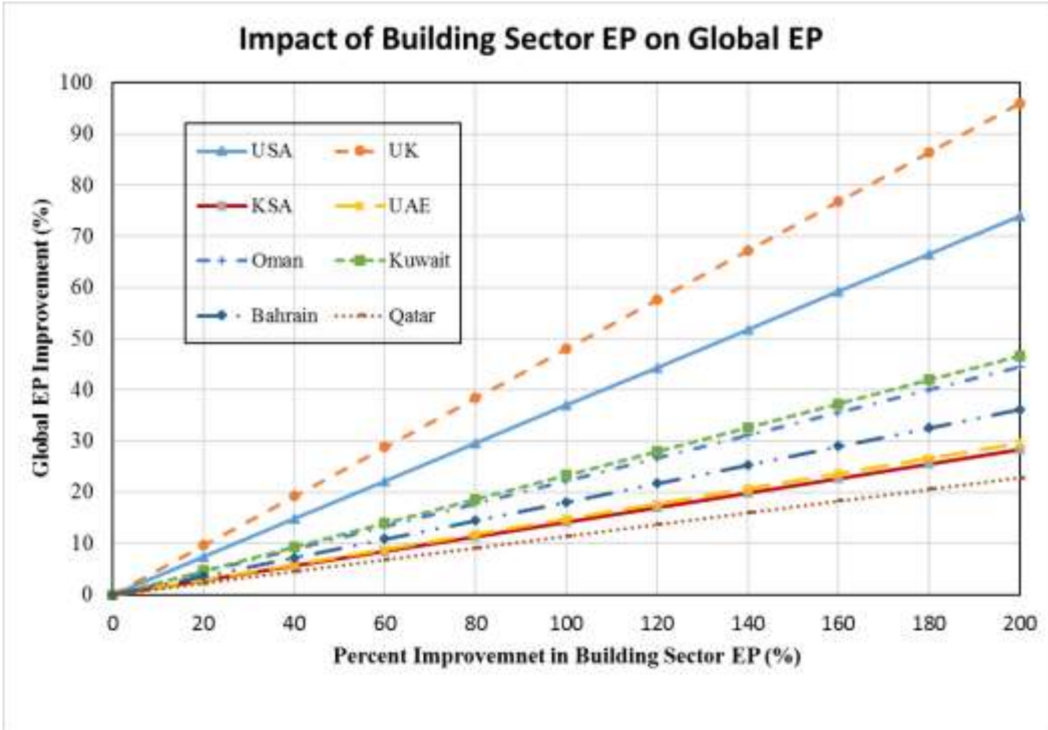


Figure 5: Impact of building sector EP Improvements on national EP changes for the GCC countries, US, and UK

The energy productivity at the sector level such as the building sector, EP_B, is the ratio of value added (VA_B) and total final energy consumption (TFC_B):

$$\mathrm{EP_B} = \frac{VA_B}{TFC_B} \tag{3}$$

Within the GCC countries, the energy productivity values for building sector show substantial annual variation as noted in Figure 6 [13]. In almost all the GCC countries, energy productivity for the building sector has been declining since 1990 with the exception of Qatar and to a lesser extend KSA that showed a slight improvement since 2005.

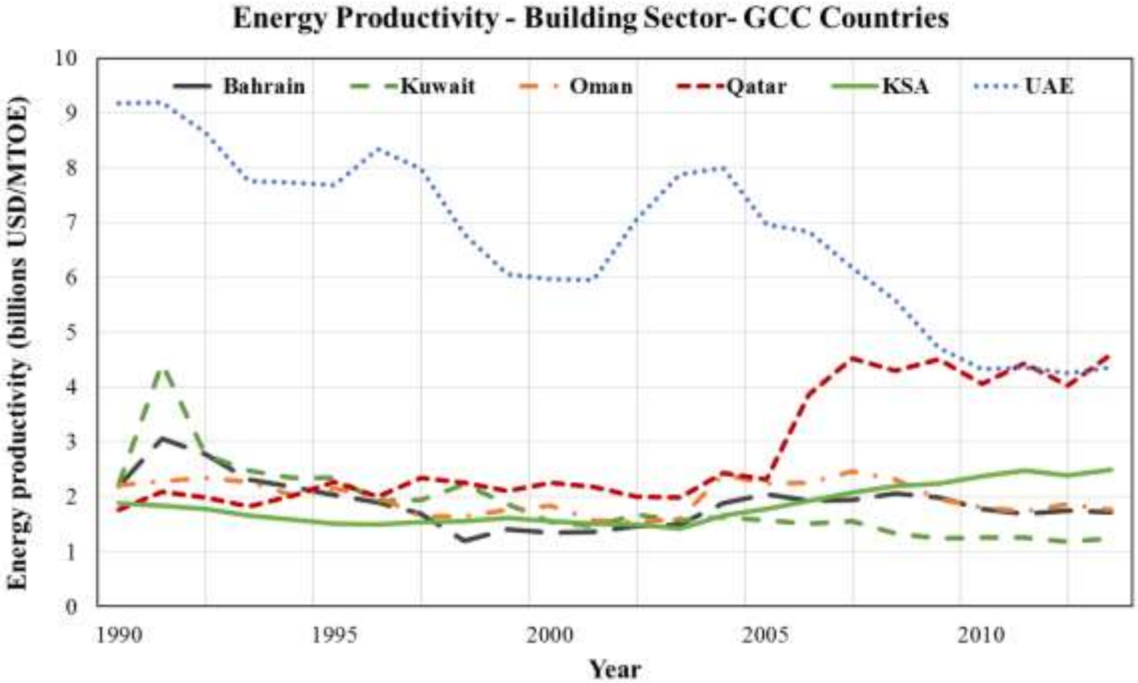


Figure 6: Annual variation of Energy Productivity for the building sector for GCC countries (Data Source: IEA [13])

The energy efficiency level for a building is, generally, estimated using the energy use intensity or index, EUI_B, defined as ratio of the TFC of the building, TFC_B, and the total usable or useful floor area, $TUFA_B$, as noted in Eq. (4):

$$\mathrm{EUI_B} = \frac{TFC_B}{TUFA_B} \tag{4}$$

This indicator can be introduced for the entire building sector in order to determine an economy's energy productivity by reformulating Eq. (3):

$$\mathrm{EP_B} = \left(\frac{VA_B}{TUFA_B}\right).\left(\frac{TUFA_B}{TFC_B}\right) = \left(\frac{VA_B}{TUFA_B}\right)\frac{1}{EUI_B} \tag{5}$$

The formulation of Eq. (5) establishes that building energy productivity is function of two indicators:

- The economic productivity indicator (as the ratio $VA_B/TUFA_B$) that represents the economic output per a building unit area. The VA for the building sector is rather difficult to estimate (in contrast to the industry and transport sectors). Different value added estimates can be considered for buildings including their asset value, their rental value, the work productivity value (office buildings), or the sale value (retail stores). For macroeconomic analysis, the value added for the buildings sector is estimated from reported sectorial data [13].
- The energy efficiency indicator (calculated as the reciprocal of the energy use intensity, $1/EUI_B$) that represents the building useful area that can be served by one unit of energy. This indicator, referred to as the energy affordability index, is sometimes used to assess the energy performance of individual buildings.

Figure 1, illustrating the concept for the buildings sector energy productivity, indicates the two indicators outlined above and given by Eq. (5): economic productivity and energy efficiency. It is important that the energy productivity analysis for the building sector can conceptually include the entire building stock and all energy efficiency benefits including NEBs.

To improve the buildings sector energy productivity, EP_B provided by Eq. (5), two main actions are possible:

- Increase the economic output per unit floor area – either by fostering more energy productive economic activities and/or by enhancing effective use of building spaces.
- Reduce the energy use index, EUI_B, – either by implementing energy efficiency measures or integrating renewable energy technologies within buildings.

Since the buildings sector includes several building types such as housing, offices, hotels, banks, retail stores, and schools, the energy productivity for the building sector can further be decomposed to determine the share of each building type. One decomposition option is through the energy use index, EUI_B, as follows:

$$\frac{1}{\mathrm{EUI_B}} = \frac{TUFA_B}{TSEC_B} = \sum_{k=1}^{N} \left(\frac{TUFA_{B,k}}{TSEC_{B,k}} \right) . \left(\frac{TSEC_{B,k}}{TSEC_B} \right) . = \sum_{k=1}^{N} r_k \cdot \frac{1}{EUI_k} \tag{6}$$

Where,

- N is the total number of building types that are considered in the building stock;
- r_k is the fraction of the building type k relative of the entire building stock in terms of usable total floor area;
- EUI_k is the energy use index specific to each building type k.

The fraction r_k can be estimated using available data for energy consumption and floor area. In the GCC region, floor area for housing is significant compared with other building types. Thus, efforts to reduce the energy efficiency for residential buildings can have a large positive effect on the overall energy use index and thus energy productivity of the building sector. As stated above and described in Section 5, the approaches to boost energy productivity are different for existing and new building stocks.

4.2 Analysis Approach for Individual Buildings

The same analysis, presented for large-scale energy efficiency programs specific to an entire building stock, can apply to individual buildings. Indeed, an energy productivity, $\mathrm{EP_b}$, can be defined for an individual building or even an energy system within a building (such as lighting, air conditioning, or appliances) using an expression similar to that of Eq. (3):

$$EP_b = \frac{VA_b}{EU_b} \tag{7}$$

Where,

- VA_b is the average annual value provided by the building, including any combination of any value added such as asset value (housing), rental value (office building), and sale value (retail).
- EU_b is the annual energy used by the building or building energy system.

A decomposition of Eq. (7) allows the estimation of the individual building energy productivity as a function of its energy use intensity value, EUI_b:

$$EP_b = \left(\frac{VA_b}{FA_b}\right)\cdot\left(\frac{FA_b}{EU_b}\right) = \left(\frac{VA_b}{FA_b}\right)\cdot\frac{1}{EUI_b} \tag{8}$$

As noted earlier, the term $1/EUI_b$ (expressing the floor area served by a unit of energy) is considered as a measure of energy affordability, EA_b:

$$EA_b = \frac{1}{EUI_b} = \frac{FA_b}{EU_b} \tag{9}$$

As noted in Figure 7 for a villa located in Riyadh and Abha, various EEMs, including installing wall and/or roof insulation, low-e glazing, LED lighting, and a high-efficiency AC system, have diverse effects on energy affordability, EA_b, expressed in terms of the potential building floor area served by per 10,000 kWh/year to maintain acceptable indoor environment quality. The data shown in Figure 7 are based on results of the analysis carried out by Alaidroos and Krarti [39]. As expected, measures that increase energy efficiency also enhance energy affordability – and thus energy productivity.

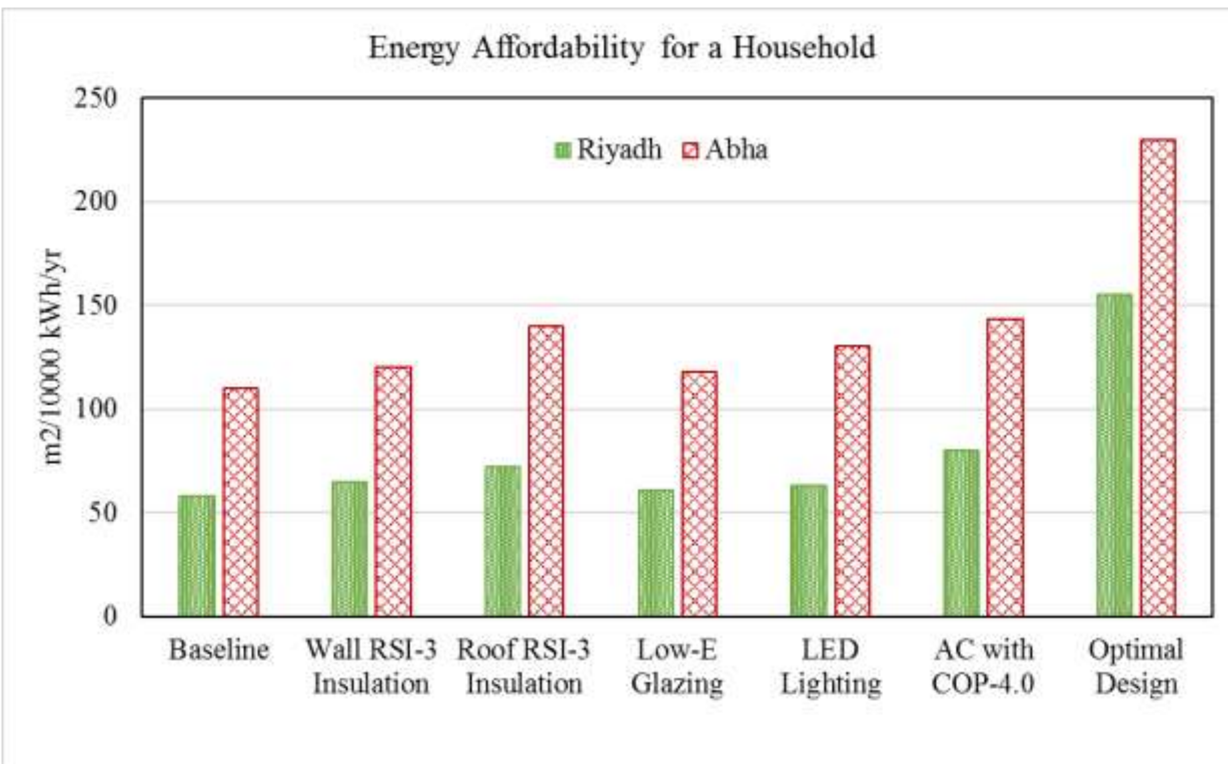


Figure 7: Household energy affordability expressed in floor area covered by 10000kWh/year electricity consumption in Riyadh and Abha, KSA

The energy productivity metric, proposed for an individual building or for a building sub-system, incorporates two indicators as illustrated in Figure 8: the energy efficiency and the value added productivity. In addition, quantifiable and measurable indicators for NEBs can contribute to value added, such as rental rates (residential, commercial) or sale levels (retail). It should be noted that the impact of any energy efficiency measure on an individual building energy productivity can be determined using the same analysis outlined in section 4.3.

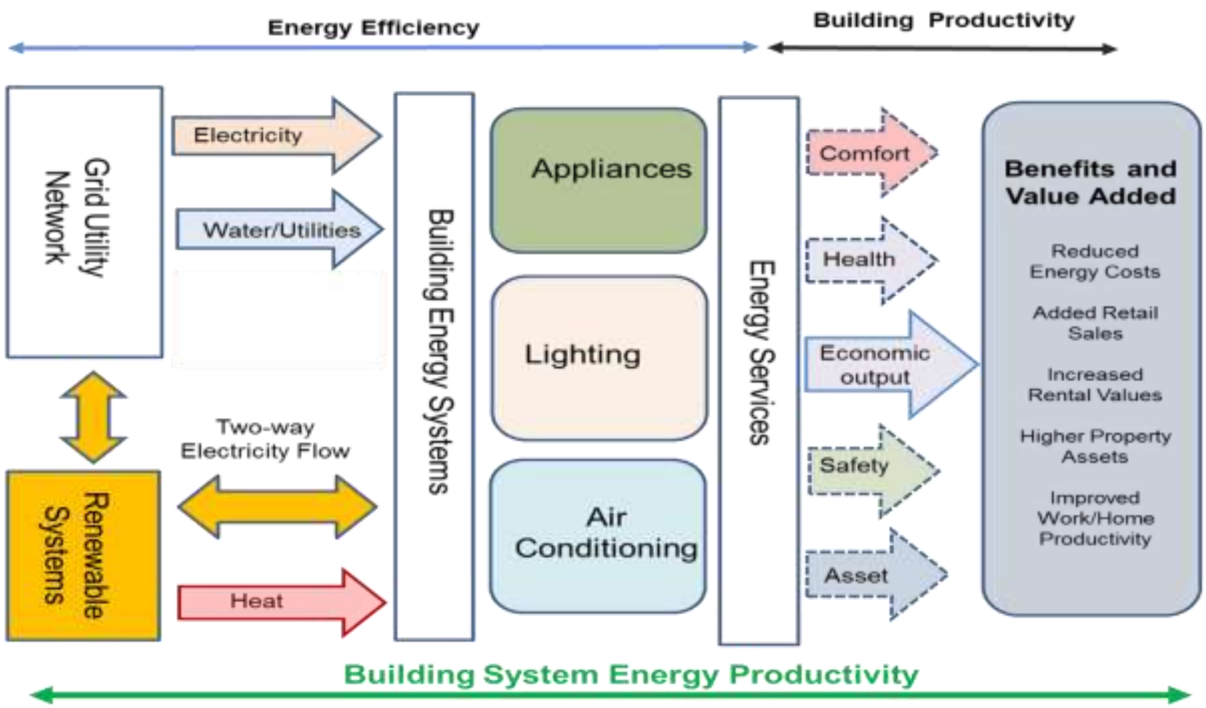


Figure 8: Basic concept of individual building energy productivity

4.3 Evaluation of Impact for Energy Efficiency Measures

The change in energy productivity, $\Delta EP_{B,}$ associated with any energy efficiency measure (EEM) targeting a building stock or an individual building can be estimated as noted in Eq. (10):

$$\Delta EP_B = EP_{B,n} - EP_{B,e} = \frac{VA_{B,n}}{TFC_{B,n}} - \frac{VA_{B,e}}{TFC_{B,e}} \tag{10}$$

Where,

- $EP_{B,r}$ and $EP_{B,e}$ are energy productivity values for, respectively, retrofitted and existing buildings.
- $VA_{B,r}$ and $VA_{B,e}$ are the value-added values for, respectively, retrofitted and existing buildings.
- $TFC_{B,r}$ and $TFC_{B,e}$ are the TFC values for, respectively, retrofitted and existing buildings.

Any EEM may change both the VA and the TFC, depending on the quantifiable resulting benefits, ΔVA_{EE}, and energy savings, ΔTFC_{EE}. As noted earlier, the benefits can encompass both benefits from reduced energy demands (including the avoided costs for energy generation and distribution as well as reduced carbon and other greenhouse gas emissions) and a wide range of NEBs (such as increased worker productivity due to improved indoor air quality and thermal comfort).

The new value added, ΔVA_{EE}, can be determined by estimating the monetary value of the benefits arising from the EEM:

$$VA_{B,r} = VA_{B,e} + \Delta VA_{EE} \tag{11}$$

The retrofitted TFC can be determined from the energy use savings, ΔTFC_{EE}:

$$TFC_{B,r} = TFC_{B,e} - \Delta TFC_{EE} \tag{12}$$

Thus, the change in energy productivity can then be expressed as:

$$\Delta EP_B = \frac{VA_{B,e} + \Delta VA_{EE}}{TFC_{B,e} - \Delta TFC_{EE}} - \frac{VA_{B,e}}{TFC_{B,e}} \tag{13}$$

The percent increase in energy productivity in the building sector can then be determined simply as a function of percent changes in both value added and energy consumption:

$$\Delta EP_B(\%) = \frac{1 + \Delta VA_{EE}(\%)}{1 - \Delta TFC_{EE}(\%)} - 1 \tag{14}$$

Figure 9 illustrates the percent increase of energy productivity in the buildings sector as a function of how any EEM stimulates relative changes in both value added and energy consumption. Based on the profiles shown in Figure 9 and the expression of Eq. (14), two basic principles can be formulated to assess the impact of any EEM on the buildings sector energy productivity:

1- Any EEM that saves energy consumption and increases the value added boosts energy productivity. In other terms, any cost-effective energy efficiency measure increases energy productivity.
2- Any EEM that reduces the value added, even if it reduces energy consumption, may lower energy productivity. Such is the case of an EEM that is not cost-effective.

The threshold of value-added reduction, after which energy productivity starts to decrease, due to any EEM is estimated using Eq. (15):

$$\Delta VA_{EE}(\%) \leq \Delta TFC_{EE}(\%) \tag{15}$$

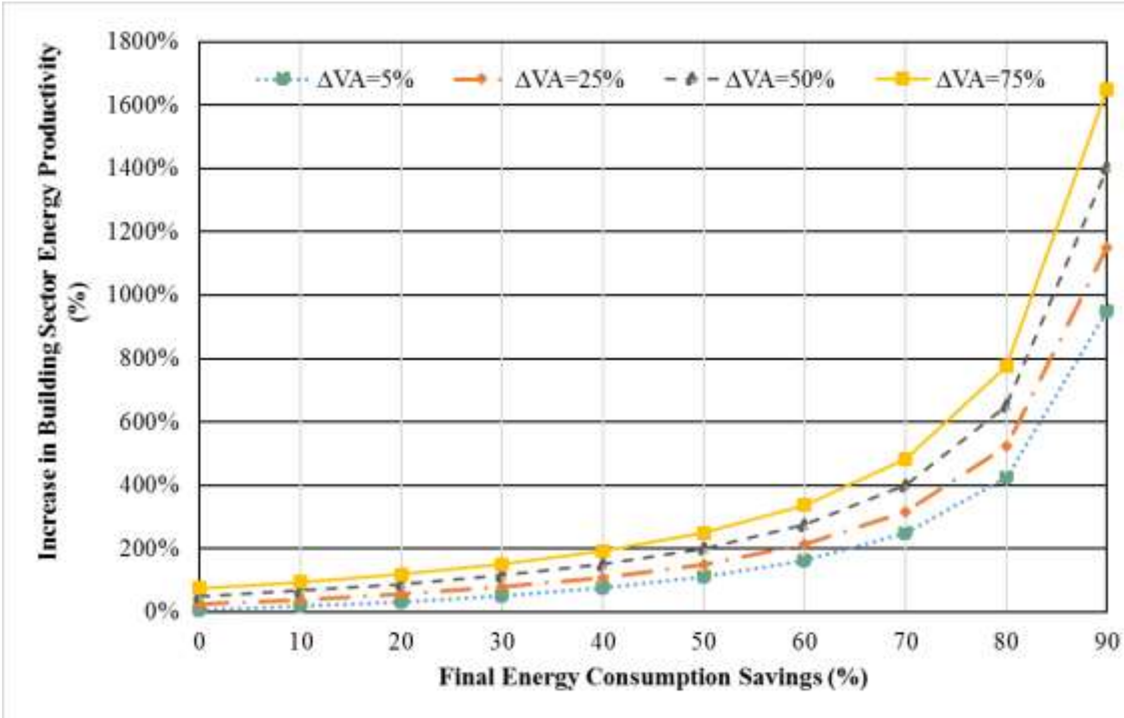


Figure 9: Variation of energy productivity as a function of energy use savings and change in value added for the building sector

4.4 Estimation of Value Added Change

The change in value added resulting from any EEM, whether applied to the entire building sector or an individual building energy system, can be estimated using net present value (NPV) analysis to account for implementation costs, *IC*, initial monetary benefits, B_0, and annual cash flows from the action [40-41]:

$$NPV = -(IC - B_0) + \sum_{n=1}^{N} CF_n . SPPW(r_d, n) \tag{16}$$

Where,

- CF_n are the annual cash flows, which typically include potential energy cost savings, ΔEC_n, operation and maintenance costs, OM_n, NEBs (such as emissions reduction, enhanced work productivity and increased sales), B_n, and other costs (such as replacement and resale costs), O_n:

$$CF_n = \Delta EC_n + B_n + OM_n + O_n \tag{17}$$

- SPPW is the single present payment worth factor, which depends on the annual average discount rate, r_d, and the lifetime, *N*, expressed by the number of year for the EEM:

$$SPPW(r_d, n) = (1 + r_d)^{-n} \tag{18}$$

It should be noted that the discount rate, r_d, encompasses various economic rates including nominal interest rate, inflation rate, energy escalation rate, and if applicable tax rate [40-41]. The annual change of value added can be estimated using the annualized costs, *AC*, of the energy project (i.e., EEM) obtained from the present worth value, *NPW*, and the uniform series present worth factor, *USPW* [40]:

$$\Delta VA = AC = \frac{NPV}{USPW(r_d, N)} \tag{19}$$

The *USPW* depends on the life cycle period *N* and discount rate, r_d, of an economy [40]:

$$USPW(r_d, N) = \frac{1-(1+r_d)^{-N}}{r_d} \tag{20}$$

The concept of uniform series, when all annual cash flows are identical, is illustrated in Figure 10(a).

The lifetime avoided energy (i.e., electricity or fuel) consumption, U_{tot}, from an EEM that results in uniform annual savings, A, can be expressed using Eq. (21):

$$U_{tot} = N.A \tag{21}$$

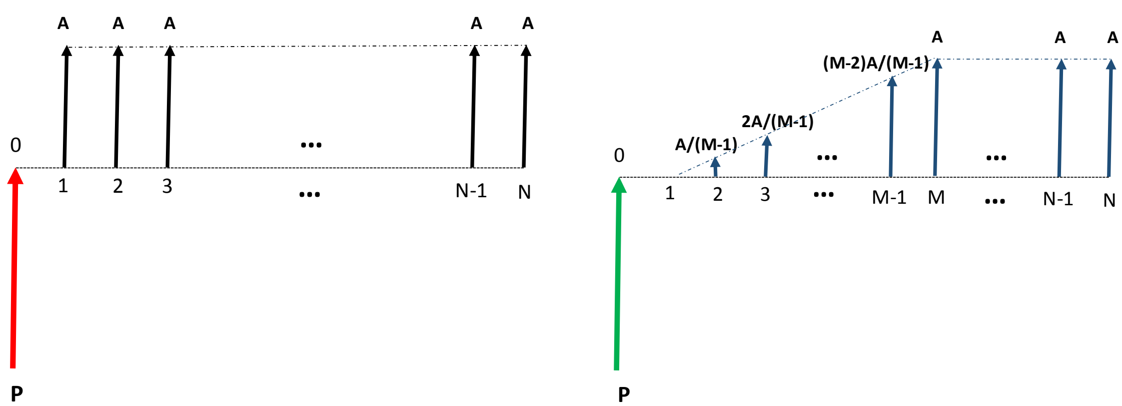
When, by contrast, a large-scale energy efficiency program is implemented incrementally, the annual cash flows are not uniform but follow a gradient after the initial phase of M years. Such a series is illustrated in Figure 11(b). In this case, the gradient series present worth, GSPW, is used to convert the annual cash flows to the present [41]:

$$GSPW(r_d, N, M) = \frac{1-(1+Mr_d)(1+r_d)^{-M}}{r_d^2} + \frac{(1+r_d)^{-M}(1+r_d)^{-N}}{r_d} \tag{22}$$

Additionally, the lifetime avoided energy consumption follows a gradient, G_{tot}, which can be computed from the final annual energy savings, A, as follows:

$$G_{tot} = \left(N + \frac{M}{2}\right).A \tag{23}$$

It should be noted that both *NPV* and *AC* can be used to assess the cost-effectiveness of the EEM. In the following section, various applications of the energy productivity analysis are outlined to evaluate the benefits of energy efficiency actions for both individual building sand entire building stock in the GCC region.



(a) Uniform Series (b) Gradient and Uniform Series

Figure 10: Uniform series and gradient series for estimation of the present values

5. Applications of Energy Productivity Analysis

5.1 Energy Retrofit of an individual building

To illustrate, at the microeconomic level, the distinction between energy productivity and energy efficiency, consider a small retail store of 500 m^2 and the impact of investing in an energy-efficient air conditioning system compared to a standard system. The analysis is carried out for a life cycle of 15 years, with an average discount rate of 5% so that USPW=10.4 years using Eq. (20). The cost of electricity is set to \$0.04/kWh based on the recent KSA energy rate increases and the annual sales set constant at \$600/m^2 even though the literature suggests that the sales may increase due to better comfort [42]. In this analysis, the potential benefit of thermal comfort is assumed to be offset by the small increase in annual expenses associated with the higher cost of the energy-efficient air conditioning system.

Table 2 summarizes various indicators considered in estimating energy productivity and annualized cost for both the baseline and the installation of the energy efficient air-conditioning system. Using the cost-effectiveness analysis, the energy-efficient system has lower annualized cost (i.e., \$4,741/year) than the baseline cost (i.e., \$4,922/year), resulting in annual savings of \$181/year. When evaluating the two options using the energy productivity analysis, the high efficient AC provides more benefits with higher EP value (\$4.80/kWh) than the baseline system (with an EP value of \$3.49/kWh), delivering an additional EP value of \$1.31/kWh. Installing the high efficiency air conditioning system is cost-effective since it has lower annualized costs and boosts productivity of the retail store, using the sales value and added income from energy use cost savings as the measurable economic output.

Table 2: Estimation of Energy Productivity and Annualized Cost for installing energy-efficient air conditioning for a retail store

Indicator	**Baseline**	**Improved Air-Conditioner**
Energy Use Intensity (kWh/m^2/year)	172	125
Annual Energy Use (kWh/year)	86000	62500
Initial Cost (\$)	5,000	6,500
Annual Cost (\$/year)	**4,922**	**4,751**
Value Added (\$/year)	300,000	300,181
Energy Productivity (\$/kWh)	**3.49**	**4.80**

5.2 Evaluation of Improved Designs for Villas

With the adoption of proven energy efficiency and renewable energy technologies, buildings can have low energy use intensity and even be net-zero energy. Residential buildings in KSA, for example, can be designed to consume less than 60% of current consumption levels [42]. Table 3 summarizes four design options for a 500-m^2 villa including:

- Baseline design with no energy efficiency design features.
- Baseline design incorporating thermal insulation (RSI= 3.0 m^2.K/W) for both exterior walls and roof. This case represents the current mandatory energy conservation regulations for KSA buildings.
- Low-energy building design incorporating a set of optimal energy efficiency features [45].

- Baseline design with a 20-kW PV roof-mounted panel that can generate electricity to offset part of the villa energy needs using either a storage system or a smart meter connected with the grid.

Table 3: Annual energy consumption and life cycle costs for four villa designs in Riyadh, KSA

Villa design option	Annual Energy Use (kWh)	PV Size (kW)	Energy Cost (USD)	Implementation Costs (USD)	PV Cost (USD)	Life Cycle Cost (USD)
Baseline	153,594	0	7,924	0	0	121,811
Insulation in walls and roof	115,196	0	5,193	3,500	0	83,329
Low energy design	57,444	0	1,653	21,000	0	46,411
Baseline with PV	118,694	20	5,407	0	60,000	143,119

Table 3 provides the annual electricity consumption for each design as well as the cost of the energy efficiency and PV systems. It also shows the life-cycle cost for each design using a lifetime of 30 years and a discount rate of 5%. The capital cost of the PV system is estimated to be $3,000/kW. Using the current electricity rate structure, the life-cycle cost indicates the cost-effectiveness to the owner of each design relative to the baseline option. The low-energy design is the most cost-effective due to lower energy consumption and to lower energy prices being applied to low energy consumers. The addition of the PV system is not cost-effective relative to the baseline due to the low electricity prices from the grid (only $0.04/kWh).

The energy productivity analysis of the four design options is summarized in Table 4, considering the total construction and operating costs as an indicator of the value added for the baseline design. For the other designs, the annualized costs of various additional energy efficiency and renewable energy features are evaluated using whole-building analysis [45]. As shown in Table 4, the low-energy design has the highest energy productivity value while the baseline has the lowest value. The installation of the PV system would increase the building energy productivity more than the addition of thermal insulation.

Table 4: Estimation of Energy Productivity and Energy Intensity for various villa design in Riyadh, KSA

Villa design option	Net Present Value (USD)	Value Added (USD/year)	Annual Energy Use (kWh)	Energy productivity (USD/kwh)	Energy Intensity (kWh/USD)
Baseline	0	32,525	153,594	0.212	4.72
Insulation in walls and roof	38,482	30,022	115,196	0.261	3.84
Low energy design	75,401	27,620	57,444	0.481	2.08
Baseline with PV	21,308	33,911	118,694	0.286	3.50

5.3 Analysis of retrofit programs for existing buildings

To assess the potential for the existing building stock to contribute to energy productivity in the GCC, three options of energy retrofits are considered using ASHRAE energy audit levels [43]:

- **Level-1** applies low-cost EEMs such installing programmable thermostat, use of LED lighting, and weatherization of building shell to reduce air infiltration.
- **Level-2** improves the building envelope components to meet any energy efficiency code requirements for new buildings, including use of energy efficient cooling systems and appliances.
- **Level-3** applies a wide range of EEMs, including replacing windows and/or cooling systems, using variable speed drives, and installing daylighting control systems. To minimize implementation costs, this type of energy retrofit is typically linked with architectural refits and is often called deep retrofit.

The impacts of these energy retrofit levels on the building sector for the GCC region have been evaluated comprehensively in reported studies [42, 44-47]. Specifically, the reported analyses provided, for all six GCC countries, estimates of both the annual energy use savings (from using less fuel to generate electricity) from the three energy retrofit levels as well as the investments needed to implement these programs for the existing building stocks [14, 42, 44-47]. The reported analyses also estimated other quantifiable benefits, including reductions in electricity peak demands (associated with avoided demand for new power plants and new T&D infrastructure) and in CO_2 emissions. Tables 5 through 8 summarize reported results for each of the GCC countries, reflecting retrofits of the entire existing building stocks and of the residential buildings.

Using the results provided in Tables 5 through 8 and the NPV analysis outlined by Eq.(10) through Eq.(23) to estimate changes in value added arising from various retrofit programs, energy productivity values have been estimated for all GCC countries, covering energy retrofits applied to both the entire building stocks and only to residential buildings.

Table 5: Estimations of required investments and potential primary energy savings from large-scale energy retrofit programs for the entire existing GCC building stock [42, 44-47]

Country	Energy Retrofit Level for Existing Building Stock								
	Level 1			Level 2			Level 3		
	Investment Required (USD Billion)	Potential Primary Energy Savings (MBOE/yr)	Potential Available Economic Value Released to Gov't (USD Million/yr)	Investment Required (USD Billion)	Potential Primary Energy Savings (MBOE/yr)	Potential Available Economic Value Released to Gov't (USD Million/yr	Investment Required (USD Billion)	Potential Primary Energy Savings (MBOE/year)	Potential Available Economic Value Released to Gov't (USD Million/yr
Bahrain	0.6	1.8	56.9	3.2	5.4	172.0	6.5	11.8	374.0
Kuwait	0.9	2.4	75.8	5.4	7.1	253.2	10.8	15.5	550.5
Qatar	0.3	2.5	79.0	1.7	7.3	243.5	3.4	15.9	529.3
Oman	1.6	2.6	82.2	8.8	7.9	273.1	17.6	17.1	593.7
KSA	10.4	28.7	906.9	103.7	85.1	2980.1	207.4	185.1	6478.5

UAE	2.0	12.9	407.6	10.7	37.6	1281.3	21.4	81.7	2785.3
Total GCC	**15.8**	**51**	**1608**	**134.5**	**1501**	**5203**	**267.1**	**327**	**11311**

Table 6: Benefits from energy retrofit programs applied to the entire existing GCC building stock [42, 44-47]

Country	**Energy Retrofit Level for Existing Building Stock**								
	Level 1			**Level 2**			**Level 3**		
	Avoided Electrical Power Generation Capacity (MW)	Total Lifetime Barrels Avoided (MBOE)	Annual Carbon Emissions Reduction (kton/yr)	Avoided Electrical Power Generation Capacity (MW)	Total Lifetime Barrels Avoided (MBOE)	Annual Carbon Emissions Reduction (kton/yr)	Avoided Electrical Power Generation Capacity (MW)	Total Lifetime Barrels Avoided (MBOE)	Annual Carbon Emissions Reduction (kton/yr))
Bahrain	204	47	662	588	136	1903	1278	296	4138
Kuwait	817	62	1244	2348	178	3575	5105	387	7773
Qatar	414	64	878	1191	183	2524	2590	399	5487
Oman	370	68	1003	1063	197	2885	2311	428	6271
KSA	3668	740	12192	10546	2129	35051	22926	4627	76199
UAE	1408	327	4568	4049	939	13134	8802	2042	28553
Total GCC	**6881**	**1308**	**20547**	**19785**	**3762**	**59072**	**43012**	**8178**	**128421**

Table 7: Estimations of required investments and potential primary energy savings from energy retrofit programs for the existing GCC residential building stock [42, 44-47]

Country	**Energy Retrofit Level for Existing Building Stock**								
	Level 1			**Level 2**			**Level 3**		
	Investment Required (USD Billion)	Potential Primary Energy Savings (MBOE/yr)	Potential Available Economic Value Released to Gov't (USD Million/yr)	Investment Required (USD Billion)	Potential Primary Energy Savings (MBE/yr)	Potential Available Economic Value Released to Gov't (USD Million/yr	Investment Required (USD Billion)	Potential Primary Energy Savings (MBOE/year)	Potential Available Economic Value Released to Gov't (USD Million/yr

Bahrain	0.103	0.3	9.2	1.027	0.8	26.4	2.053	1.8	57.5
Kuwait	0.195	1.3	45.5	1.951	3.7	130.8	3.902	8.0	284.3
Qatar	0.071	1.5	50.8	0.707	4.4	146.0	1.413	9.6	317.3
Oman	0.174	1.6	55.0	1.739	4.6	158.2	3.477	9.9	344.0
KSA	2.836	18.5	647.1	28.365	53.2	1860.4	47.569	115.6	4044.4
UAE	0.126	4.6	157.2	1.255	13.3	451.9	2.511	28.8	982.4
Total GCC	**4**	**28**	**965**	**35**	**80**	**2774**	**61**	**174**	**6030**

Table 8: Benefits from energy retrofit programs applied to the existing GCC residential building stock [42, 44-47]

Country	**Energy Retrofit Level for Existing Building Stock**								
	Level 1			**Level 2**			**Level 3**		
	Avoided Electrical Power Generation Capacity (MW)	Total Lifetime Barrels Avoided (MBOE)	Annual Carbon Emissions Reduction (kton/yr)	Avoided Electrical Power Generation Capacity (MW)	Total Lifetime Barrels Avoided (MBOE)	Annual Carbon Emissions Reduction (kton/yr)	Avoided Electrical Power Generation Capacity (MW)	Total Lifetime Barrels Avoided (MBOE)	Annual Carbon Emissions Reduction (kton/yr)
Bahrain	116	7	377	335	21	1083	727	45	2053
Kuwait	422	32	642	1213	92	1847	2637	200	4014
Qatar	248	38	526	714	110	1513	1553	239	3290
Oman	214	40	660	616	114	1898	1339	248	4126
KSA	2290	462	7611	6583	1329	21882	14312	2889	47569
UAE	497	115	1611	1428	331	4633	3105	720	10071
Total GCC	**3787**	**695**	**11427**	**10889**	**1997**	**32856**	**23673**	**4341**	**71123**

Energy productivity gains in the buildings sector resulting from large-scale energy retrofit programs in all GCC countries are shown when the entire building stock is targeted as shown in Figure 11. The results of Figure 11 are obtained using the following assumptions:

- Monetary value for avoided CO_2 emissions using either a carbon tax fee or a cap-and-trade value. A conservative added value of $10/ton is considered in this analysis [27, 48],
- Oil price of $45/BOE paired against oil production cost in each GCC country, as summarized in Table 9 [49],
- Electricity generation power plant of $1,700/kW [50], and
- Average power plant efficiency as noted in Table 9 [13].

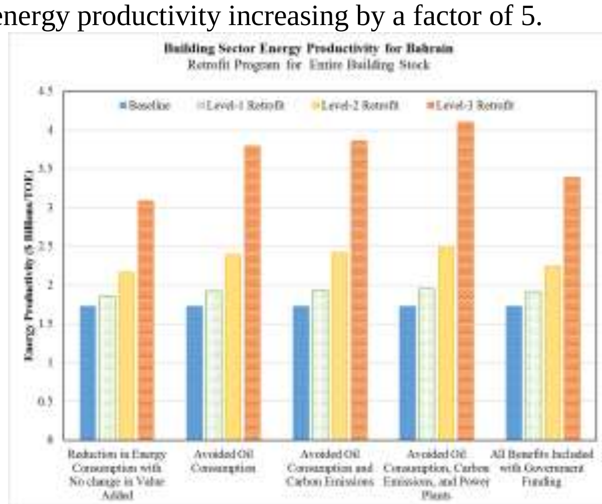
Moreover, data from 2013 for building sector value added and TFC are used to estimate the baseline energy productivity indicators for the GCC countries [13, 51].

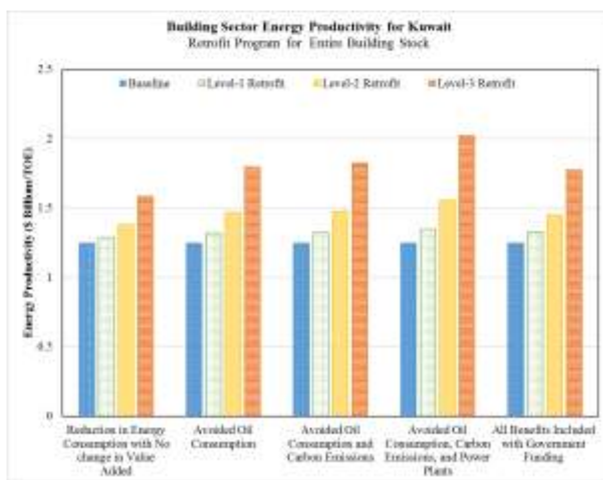
Table 9: Summary of oil production costs and thermal efficiency of power plants in GCC

GCC Countries	Oil Production Costs (USD/BOE)[1]	Average Electrical Power Plant Efficiency[2] (%)	Building Sector Value Added for 2013[3] (USD Billion/year)	Building Sector Final Energy Consumption for 2013[2] (MTOE/year)
Bahrain	8.4	27	1.83	1.06
Kuwait	4.4	34	4.50	3.61
Oman	5.3	36	4.10	2.32
Qatar	6.8	41	8.54	1.86
KSA	5.0	32	47.23	18.48
UAE	5.9	34	32.20	7.39

(Data sources: 1- Knoema [49], 2- IEA [13], 3- IMF [51])

Based on the analysis framework outlined in Section 4.3, the three energy retrofit levels applied to the entire existing building stock show positive impact on energy productivity for each GCC country as indicated in Figure 11. As summarized in Table 5 through Table 8, the impacts are evaluated and quantified for the three retrofit levels when different benefits are gradually considered in the analysis [44]. Specifically, the benefits considered in the analysis shown in Figure 11 include (i) energy use reduction, (ii) income from avoided oil consumption, (iii) value of avoided carbon emissions, and (iv) avoided investment in new power plants. The scenario when the costs of the energy retrofit programs are totally funded by the governments instead of the private sector is also considered in the analysis results presented in Figure 11. As shown in Figure 11, Level-3 retrofit programs provide the highest impact on building sector energy productivity for the GCC region even when accounting only for the avoided energy consumption benefit. For all the GCC countries, the building sector's energy productivity can be substantially increased even when the government finances the entire retrofit programs. When all benefits are considered and the private sector provides the investment needed, energy productivity can be increased significantly. In the case of KSA, retrofitting the entire building stock can double the energy productivity. The impact is even more pronounced for UAE, with energy productivity increasing by a factor of 5.





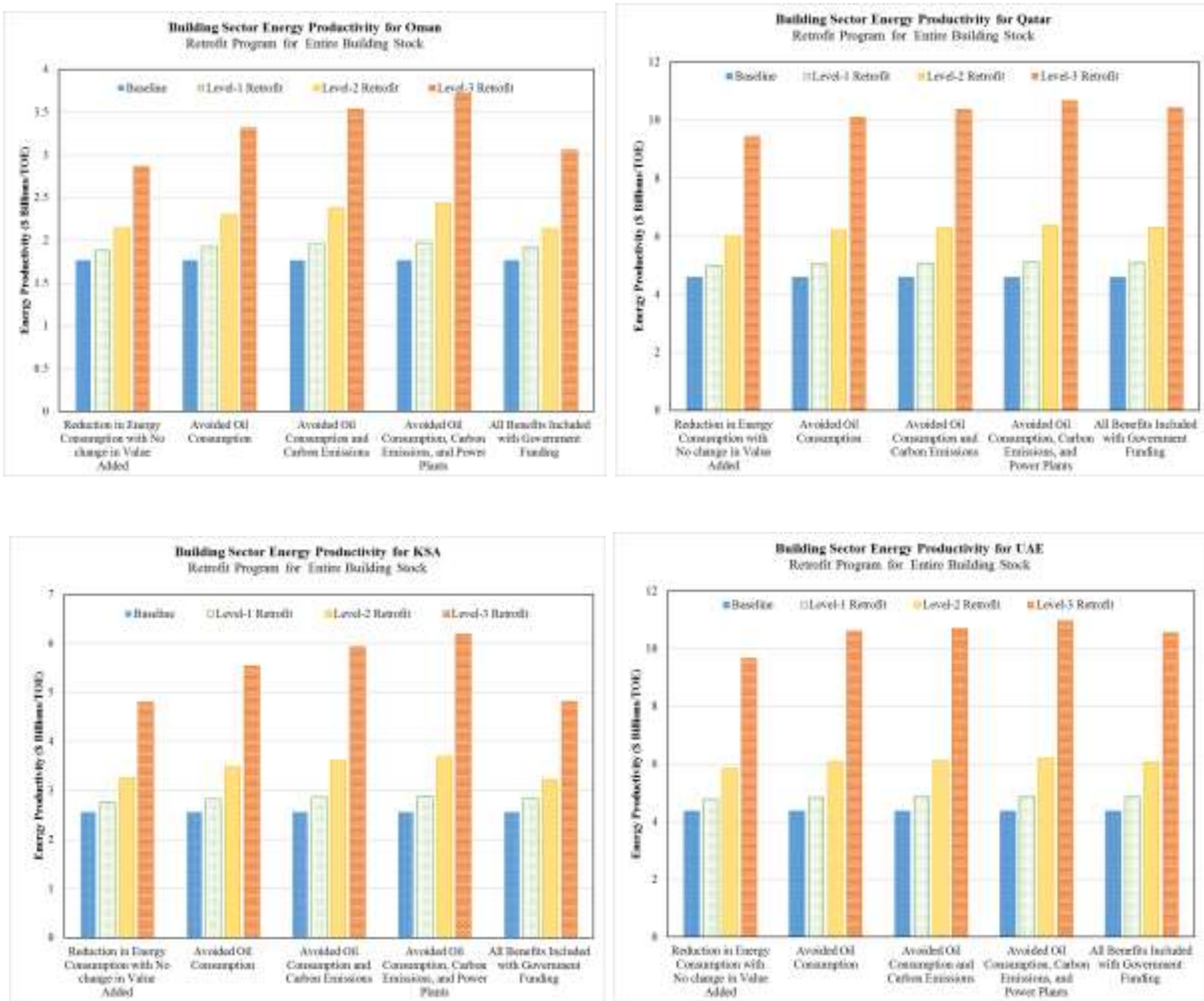


Figure 11: Impact of Energy Retrofit Programs for Entire Existing Buildings in GCC countries

Using Eq. (14), an uncertainty analysis is carried out to estimate the uncertainty level in the change in building energy productivity based on the uncertainties associated with changes of value added and total final energy consumption. Specifically, based on propagation of error analysis, the uncertainty in ΔEP, $U_{\Delta EP}$, can be expressed based on the uncertainty levels of ΔVA and ΔTFC, $U_{\Delta VA}$ and $U_{\Delta TFC}$ as follows:

$$U_{\Delta EP} = \sqrt{A^2 U_{\Delta TFC}{}^2 + B^2 U_{\Delta VA}{}^2} \tag{24}$$

With the coefficients A and B defined as:

$$\mathrm{A} = \frac{\partial U_{\Delta EP}}{\partial U_{\Delta TFC}} = \frac{1}{(1 - \Delta\mathrm{TFC})^2}$$

$$B = \frac{\partial U_{\Delta EP}}{\partial U_{\Delta VA}} = \frac{1}{(1 - \Delta \mathrm{TFC})}$$

Using Eq. (24), the uncertainty $U_{\Delta EP}$ can be determined for various uncertainty levels $U_{\Delta VA}$ and $U_{\Delta TFC}$ as illustrated in Figures 12 and Figure 13 for the existing KSA building stock retrofit Level 1 and Level 3, respectively. As noted in both Figures 12 and 13, the uncertainty level in change of the building energy productivity is highly affected by the uncertainty level for estimating the change in final energy consumption, that is, the actual energy savings associated with the retrofit programs. The uncertainty level for the change in value added is rather limited in estimating the change in building energy productivity. Thus, it is important to have a high confidence in estimating the energy savings associated with the building retrofit programs especially when deep retrofits are considered (i.e., Level 3 program). For instance, when the uncertainty for determining both ΔVA and ΔTFC is 5%, the uncertainty in estimating ΔEP is 8% for Level 1 and 20% for Level 3 retrofit programs. However, when both ΔVA and ΔTFC are computed with 10% uncertainty, ΔEP can only be estimated at 16% and 40% for respectively, Level 1 and Level 3 retrofit programs.

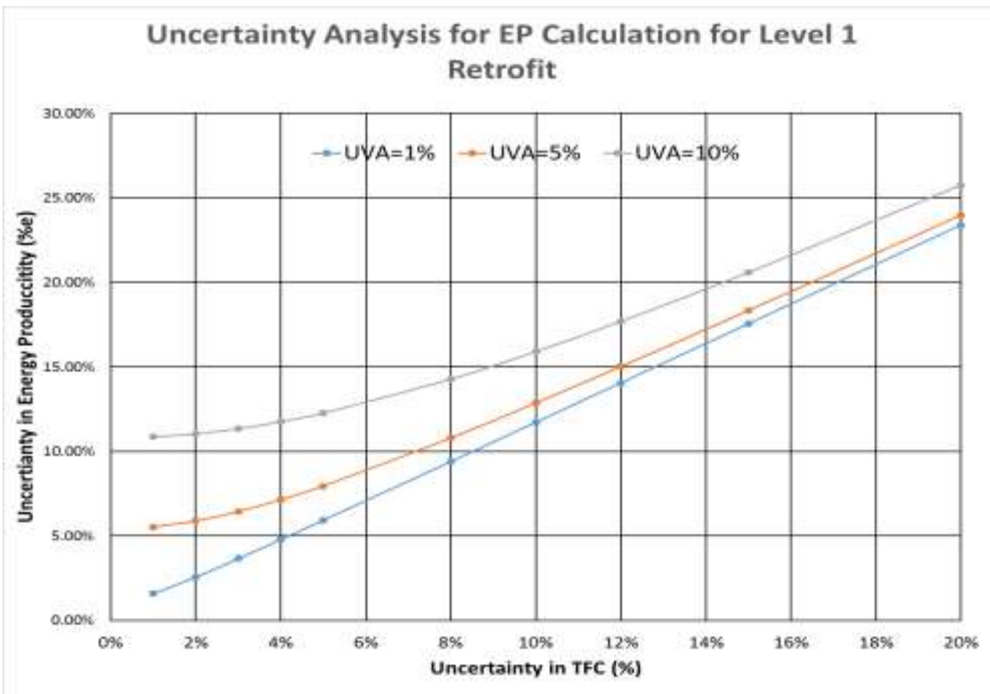


Figure 12: Variation of Uncertainty of ΔEP with the Uncertainties ΔTFC and ΔVA for Level 1 Building Energy Retrofit Program in KSA

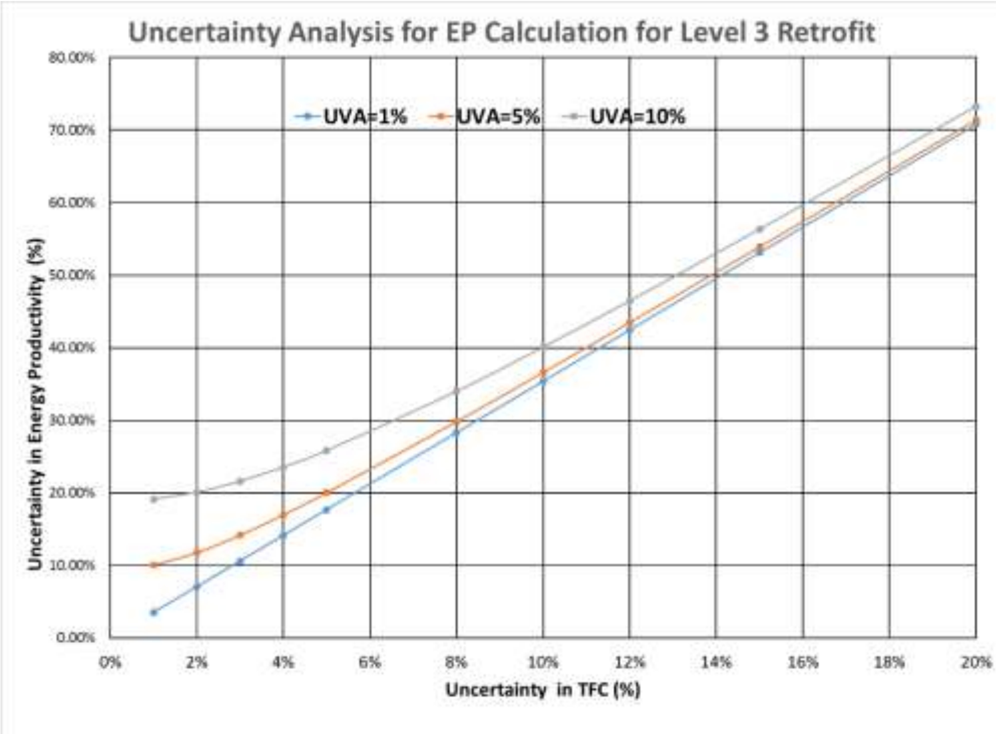


Figure 13: Variation of Uncertainty of ΔEP with the Uncertainties ΔTFC and ΔVA for Level 3 Building Energy Retrofit Program in KSA

5.4 Evaluation of energy efficiency programs for new buildings

Considering energy efficiency potential in new buildings for the GCC countries, a series of reported analyses for a wide range of energy efficiency technologies and control techniques quantified the potential benefits each country could achieve through two levels of energy efficiency requirements for new buildings as summarized in Table 10 [14, 42, 44-47]. The first level of building energy efficiency requirement includes thermal insulation for walls and roofs for all buildings. The second level focuses on comprehensive EEMs, based on performance compliance, covering all building energy systems including the envelope, appliances, lighting, office equipment, controls, and air-conditioning systems. Three countries (Kuwait, KSA, and UAE) have already set thermal insulation requirements for all new buildings; the others are expected to introduce mandatory building energy efficiency requirements in the next few years. Only Kuwait has a comprehensive building energy efficiency code.

Table 10: Benefits from energy efficiency codes for new buildings in GCC

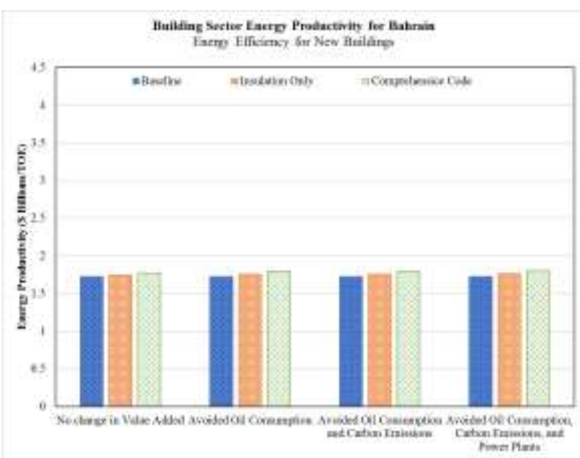
Country	**Insulation Requirements Only**			**Comprehensive Code**		
	Avoided Electrical Power Generation Capacity (MW)	Total Electricity Consumption Avoided (GWh/yr)	Avoided Electrical Power Generation Capacity (MW)	Total Electricity Consumption Avoided (GWh/yr)	Avoided Electrical Power Generation Capacity (MW)	Total Electricity Consumption Avoided (GWh/yr)
Bahrain	32	136	103	87	320	242
Kuwait*	-	-	-	-	-	-
Qatar	73	311	154	145	624	309

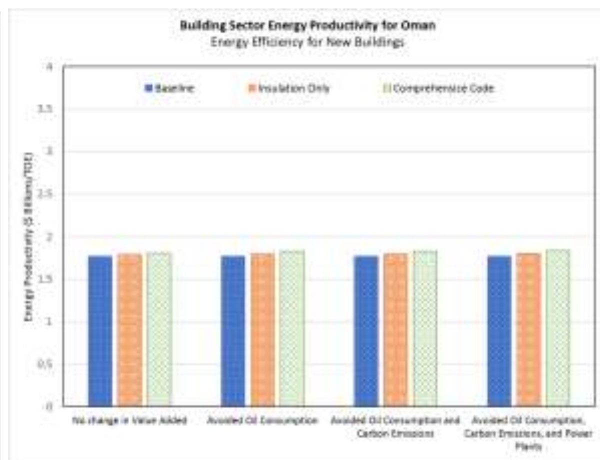
Oman	69	310	188	139	620	377
KSA*	-	-	-	468	1751	1326
UAE*	-	-	-	423	2265	1371
GCC	174	757	445	1262	5580	3625

Note *: These countries have already building codes that require thermal insulation. Kuwait has also a mandatory comprehensive building energy code.

Implementing the two levels of energy efficiency requirements on new buildings for three GCC countries has a marked effect as shown in Table 10 for those countries with no mandatory codes. Applying the same energy productivity analysis considered for the retrofit programs to new buildings is substantially different in that no investments from the government is required. Indeed, it is expected that the requirements would be mandatory for any new building and thus additional cost associated to energy efficiency features would be absorbed mainly by the households and the private sector (e.g. contractors).

However, since new buildings represent a rather small fraction of the entire building stock, such energy efficiency requirements have a relatively small impact on energy productivity in the buildings sector as a whole: the range of increase is just 3% to 8%. This is true for all countries in the GCC as indicated in Figure 14. Over at least 40 years as the building stock is renewed and refurbished, the impact would increase substantially eventually having the same order of magnitude as the large-scale energy retrofit programs applied to the existing building stock. Developing and implementing more stringent energy efficiency codes – and updating them regularly – is vitally important in all the GCC countries to ensure that the building stock continually advances towards and remains aligned with state-of-the-art energy efficiency practices for buildings.





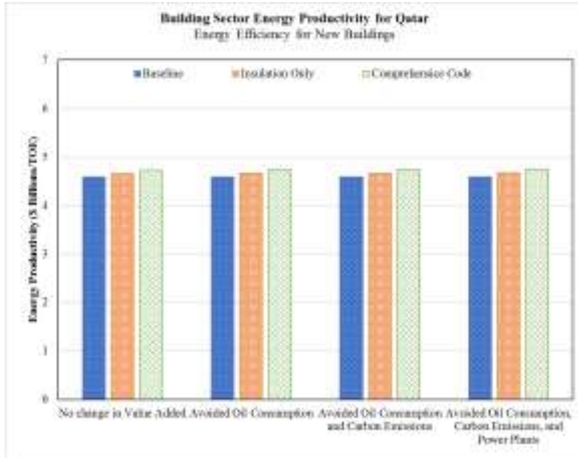


Figure 14: Impact of Energy Efficiency Requirements for New Buildings in three GCC countries

5.4 Evaluation of the impacts of non-energy benefits

In this section, the framework outlined in this paper for the energy productivity analysis is utilized to evaluate the impacts of some NEBs associated with energy retrofit programs as well as to compare the benefits of promoting energy efficiency to those specific to installing rooftop PV systems. Figure 15 illustrates the increase in energy productivity for the KSA building sector due to two indirect benefits of retrofitting buildings: increase in real estate value and improvement in work productivity. For KSA, the value added for real estate represents $60 billion, or 9.2 percent of its GDP, based on compiled data for 2014 [52]. Using reported findings of value added of energy retrofits [53-54], real estate value added for improving the energy efficiency of existing buildings is set to increase by 1%, 2%, and 5% for respectively, Level-1, Level-2, and Level-3 retrofit programs described in Section 5.3. Similarly, the work productivity increases due to energy efficiency improvements of buildings can be significant as summarized in Table 1 and as quantified by several studies [55-56]. For this study, the monetary value associated with the increase in work productivity –due to better thermal and visual comfort as well as heathier indoor environment- is set conservatively to be 1%, 5%, and 10% of the value added by the KSA services sector for respectively Level-1, Level-2, and Level 3 retrofits. As shown in Figure 15, the energy productivity for the KSA building sector associated with Level-3 retrofit can further increase by 7% and 12% when the non-energy benefits of respectively higher value added for real estate and better work productivity are considered.

Recent studies have assessed the implementation costs and benefits of installing PV systems on roofs of existing KSA housing stock [57]. In particular, it is estimated that there is a potential of installing 38-GW capacity of PV panels on the available roofs of existing residential building stock within KSA. These PV systems could generate 51.0 TWh of electricity annually, representing about the third of current electricity needs for the residential buildings in KSA. Considering that the government would subsidize the cost of these PV systems estimated at $2.5 per Watt in this study, the energy productivity of the building sector, as summarized in Figure 16, would increase by 40%, a slightly lower impact than that achieved by Level-3 retrofit applied to all KSA households. However, when PV and Level-3 retrofit are combined and applied to the KSA existing housing stock, the energy productivity can double resulting in more impact than Level-3 retrofit program applied to the entire existing building stock.

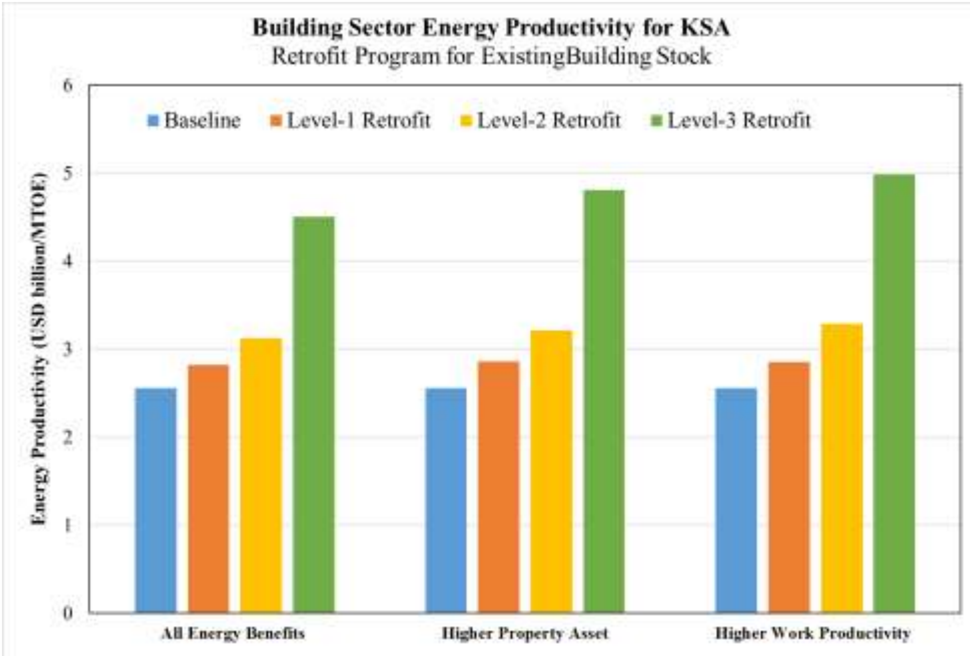


Figure 15: Impact of NEBs of Energy Retrofit Programs on Building Sector Energy Productivity for KSA

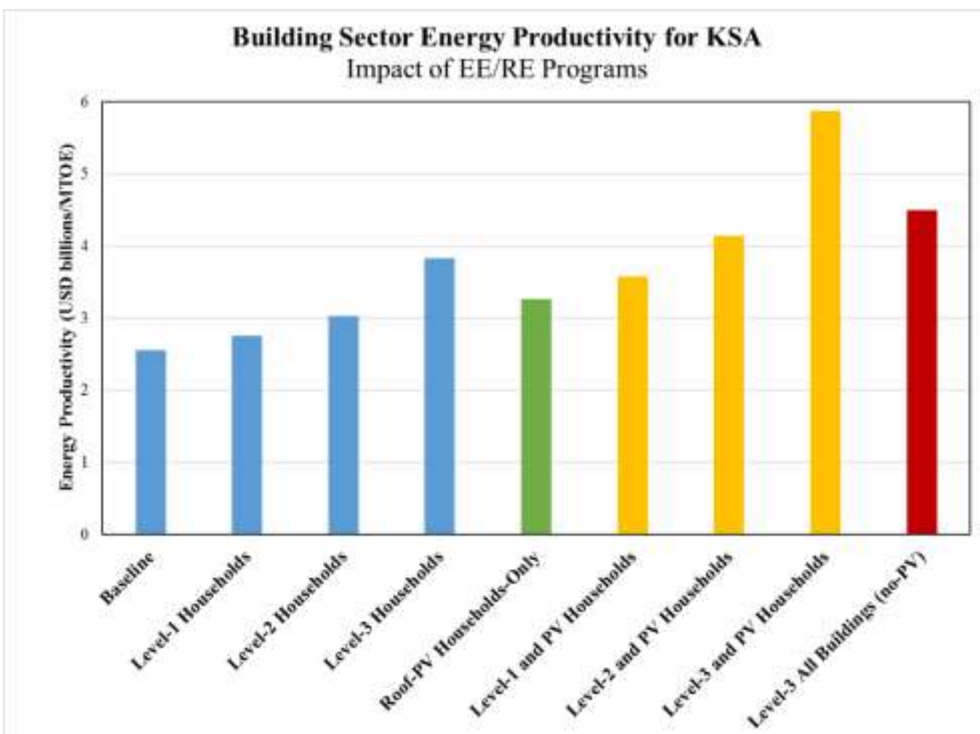


Figure 16: Impacts of Rooftop PV Installations and Retrofit Programs on Building Sector Energy Productivity for KSA

6. Summary and Conclusions

A new analysis approach is developed and applied to assess the benefits of energy efficiency programs. The approach is based the energy productivity concept and combine the energy and economic performances of energy efficiency actions using a single metric. Unlike empirical approaches based on historical data, the developed analysis approach can predict the effectiveness of various energy efficiency programs and measures in improving the energy productivity of the entire building sector or a single building. In particular, the energy productivity indicator can inform decision making on the merit of any energy efficiency program, identifying how to maximize economic benefits while minimizing energy consumption.

In this paper, the generalized analysis framework is applied to assess the benefits of large-scale energy retrofits for the existing building stock as well as benefits associated with implementing energy efficiency requirements for new buildings within the GCC region. As shown, improving the existing building stock through retrofits offers an effective option to extract economic value by reducing national energy consumption. Other benefits from the retrofit programs proposed include additional income from avoided fuel used to generate electricity and reduced costs for power generation and distribution. The programs proposed would also reduce CO_2 emissions and create demand for high skilled jobs. Clearly, such programs carry a substantial cost. The analysis shows, however, the potential to double the energy productivity of the buildings sector, even when governments provide the entire investments needed to implement the large-scale energy efficiency programs for both new and existing building stocks. The analysis has indicated that renewable energy systems can also improve significantly the energy productivity of buildings especially when combined with energy efficiency programs. When considered, non-energy benefits of energy efficiency programs such as increased real estate value and occupant work output enhance the energy productivity of the building sector.

Future work will use the energy productivity analysis presented in this paper to compare the benefits of a wide range of energy efficiency and renewable energy projects for the GCC region, accounting for both economic value added and energy savings at the national scale and/or the individual building scale.

7. References

[1] Kats, G., 2010, Greening Our Built World: Costs, Benefits and Strategies, Island Press, Washington D.C.

[2] Bernstein, H.M. and Russo, M.A, 2011, Business Case for Energy Efficient Building Retrofit and Renovation. McGraw Hill Construction SmartMarket Reports

[3] Yu, S., Yong, T., and Chenxi, L., 2011, Green Retrofitting Costs and Benefits: A New Research Agenda, IRES Working Paper Series. Singapore: National University of Singapore, Institute of Real Estate Studies.

[4] WGBC, 2013, The Business Case for Green Buildings: A Review of the Costs and Benefits for Developers, Investors and Occupants, a report by World Green Building Council, accessed on March 26, 2017: http://www.worldgbc.org.

[5] McKinsey, 2008, The Case for Investing in Energy Productivity. McKinsey Global Institute Report. https://www.mckinsey.com/business-functions/sustainability-and-resource-productivity/our-insights/the-case-for-investing-in-energy-productivity

[6] KAPSARC, 2014, The case of energy productivity: It's not just semantics, KAPSARC discussion paper, The King Abdullah Petroleum Studies and Research Center, Riyadh, http://www.kapsarc.org.

[7] KAPSARC, 2015, Global Shift: The energy productivity transformation, KAPSRAC Energy Workshop Series, The King Abdullah Petroleum Studies and Research Center, Riyadh, http://www.kapsarc.org.

[8] IEA, 2017, Energy Efficiency 2017, Report from International Energy Agency, Accessed June 25, 2018. http://www.iea.org/pblublications/freepublications/publication/Energy_efficiency_2017.pdf.

[9] Howarth, N., Galeotti, M., lanza, A., and Dubey, K., 2017, Economic development and energy consumption in the GCC: An international sectoral analysis. Energy Transitions. 1:6.

[10] Morrow, W.R., Carpenter, A., Cresko, J., Das, S., Graziano, D.J., Hanes, R., Supekar, S.D., Nimbalkar, S., Riddle, M., and Shehabi, A., 2017, US Industrial Sector Energy Productivity Improvement Pathways, Proceedings of ACEEE Summer Study on Energy Efficiency in Industry, August 15-18, Denver, CO.

[11] Global Alliance for Energy Productivity, 2018, Accessed on June 16, 2018. http://www.globalproductivity.org/

[12] Australian Alliance for Energy Productivity, 2018, Accessed on June 17, 2018. https://a2se.org.au/

[13] IEA, 2017, IEA Statistics: Energy Balance, data accessed on November 2017. http://www.iea.org/statistics, Paris, France.

[14] Krarti M. and Dubey, K., 2017, Energy productivity evaluation of large scale building energy efficiency programs for Oman, Sustainable Cities and Society, 29, 12-22.

[15] Dimitropoulos, J., 2007, Energy productivity improvements and the rebound effect: An overview of the state of knowledge, Energy Policy, 35(12), 6354-6363.

[16] Burke, P.J., and Csereklyei, Z., 2016, Understanding the energy-GDP elasticity: A sectoral approach, Energy Economics, 58, 199-210.

[17] COAG, 2016, National Energy Productivity Plan 2015-2030. Boosting competitive, managing costs and reducing emissions. Australian Government, Canberra.

[18] Block, K., Hofheinz, P., and Kerkhoven, J., 2015, The 2015 Energy Productivity and Economic Prosperity Index: How Efficiency Will Drive growth, Create Jobs, and Speed Wellbeing Throughout Society, Report by Ecofys, Quintel Intelligence, and the Lisobon Council.

[19] MGA, 2012, Industrial Energy Productivity, Manufacturing Sector in the Midwest, Midwestern Governors Association, accessed March 14, 2018: http://www.midwesterngovernors.org/Publications/IEPManufacturing.pdf.

[20] Wang, Z.H., Zeng, H.L., Wei, Y.M., Yi-Xiang Zhang, Y.X., 2012, Regional total factor energy efficiency: An empirical analysis of industrial sector in China, Applied Energy, 97, 115–123.

[21] Kuckshinrichs, W., Kronenberg, T., and Hansen P., 2010, The social return on investment in the energy efficiency of buildings in Germany, Energy Policy, 38(8), 4317-4329.

[22] Tuominen, P., Forsström, J. and Honkatukia, J., 2013, Economic effects of energy efficiency improvements in the Finnish building stock, Energy Policy, 52, 181-189.

[23] Miniaci, R., Scarpa, C., and Valbonesi,P., 2014, Energy affordability and the benefits system in Italy, Energy Policy, 75, 289-300.

[24] Mikulić, D. , Rašić Bakarić, I., and Slijepčević, S., 2016, The economic impact of energy saving retrofits of residential and public buildings in Croatia, Energy Policy, 96, 630-644.

[25] Morrissey, J., Meyrick, B., Sivaraman, D., Horne, R.E., and Berry, M., 2013, Cost-benefit assessment of energy efficiency investments: Accounting for future resources, savings and risks in the Australian residential sector, Energy Policy, 54, 148-159.

[26] Russell, C., Baatz, B., Cluett, R., and Amann, J., 2015, Recognizing the value of energy efficiency's multiple benefits. American Council for an Energy-Efficient Economy, Washington, DC.

[27] Wyon, D.P., 1996, Indoor environmental effects on productivity. IAQ 96 Paths to better building environments/Keynote address, Y. Kevin. Atlanta, ASHRAE Transactions, pp. 5–15.

[28] Kosonena, R., and Tan, F., 2004, Assessment of productivity loss in air-conditioned buildings using PMV index, Energy and Buildings, 36, 987–993.

[29] Romm, J.J., W. D. Browning, W.D., 2004, Greening the Building and the Bottom Line, a report by Rocky Mountain Institute, Boulder, CO.

[30] Colliers International, 2012, Building Choice Crucial to Attracting Retaining Quality Office Staff. Available at: http://geelong.colliers.com.au/News. Accessed March 26, 2017.

[31] Montgomery, J., Heubach, J., Weimer, W. and Heerwagen, J., 1994, Impacts on Satisfaction and Productivity in a Laboratory Renovation. Internal Report by Pacific Northwest National Laboratory, PNNL.

[32] Wargocki, P. and Wyon, D.P., 2017, Ten questions concerning thermal and indoor air quality effects on the performance of office work and schoolwork. Building Environment, 112, 359–366.

[33] Apte, M.G; Fisk, W. and Daisey, J.M., 2000, Associations between Indoor CO2 Concentration and Sick Building Syndrome Symptoms in US Office Buildings: An Analysis of the 1994-1996 Base Study Data, Indoor Air, 10(4), 246-57.

[34] Amann, J., 2006, From valuation of no-energy benefits to determine cost-effectiveness of whole-house retrofits program: A literature review, American Council for an Energy-Efficient Economy, Washington, DC.

[35] LeBaron, R., 2011, Getting to fair cost-effectiveness testing using the PACT, best practices for the TRC and Beyond, national Home Performance Council, September.

[36] Skumatz, L.A., 2014, Non-energy benefits/Non-energy impacts (NEBs/NEIs) and their role and values in cost-effectiveness tests: State of Maryland, Final Report, Skumatz Economic Research Associates, Inc., Superior, CO.

[37] Diamond, R. Berkeley, L., Opitz, M., Hicks, T., Von Neida, B., and Herrera, S., 2006, Evaluating the Energy Performance of the First Generation of LEED-Certified Commercial Buildings. Proceedings of the 2006 American Council for an Energy-Efficient Economy Summer Study on Energy Efficiency in Buildings. Berkeley, CA.

[38] Menezes, A. C., Cripps, A., Bouchlaghem, D., and Buswell, R., 2012, Predicted vs. actual energy performance of non-domestic buildings: using post-occupancy evaluation data to reduce the performance gap. Applied Energy, 97, 355–364.

[39] Alaidroos, A., and Krarti, M., 2015, Optimal design of residential building envelope systems in the Kingdom of Saudi Arabia., Energy and Buildings, 86, 104-117.

[40] Krarti, M. 2012. Weatherization of Residential Buildings, textbook, Taylor and Francis Publishing, New York, NY.

[41] Fuller, S.K., and Petersen, S.R., 1995, Life-Cycle Costing Manual, NIST Handbook 135, National Institute of Standards and Technology, US Department of Commerce, Washington D.C.

[42] Krarti, M., Dubey, K., and Howarth, N., 2017, Evaluation of building energy efficiency investment options for the Kingdom of Saudi Arabia, Energy 134, 595–610.

[43] ASHRAE, 2011, Procedures for commercial building energy audits, American Society for Heating, Refrigerating, and Air Conditioning Engineers, Atlanta, GA.

[44] Krarti, M., 2015, Evaluation of large scale building energy efficiency retrofit program in Kuwait, Renewable and Sustainable Energy Reviews, 50, 1069-1080.

[45] Krarti, M., and Dubey, K., 2018, Review Analysis of Economic and Environmental Benefits of Improving Energy Efficiency for UAE Building Stock, Renewable and Sustainable Energy Reviews, 82(1), 14-24.

[46] Krarti, M., Ali, F., Alaidroos, A., and Houchati, M., 2018, Macro-economic benefit analysis of large-scale building energy efficiency programs in Qatar, International Journal of Sustainable Built Environment, https://doi.org/10.1016/j.ijsbe.2017.12.006.

[47] Krarti, M., and Dubey, K., 2018, Evaluation of High Performance of Residential Buildings in Bahrain, Accepted for publication in Journal of Building Engineering.

[48] EPA, 2016, The social cost of carbon, Climate Change, accessed on April 21, 2017, http:www3.epa.org.

[49] Knoema, 2016, Cost of Oil Production by Country, accessed April 20, 2017, http://www.knoema.org.

[50] ECRA, 2015, Electricity and Cogeneration Regulatory Authority, Activities and Achievements of the Authority in 2014, Kingdom of Saudi Arabia, August.

[51] IMF, 2016, World Economic Outlook, International Monetary Fund, accessed April 18, 2017, http://www.imf.org, Washington, DC.

[52] JLL, 2016, Riyadh Real Estate Market Overview 2014 [cited March 25, 2016]. Available from http://www.jll.com.

[53] IMT, 2018, Green Building and Property Value. Institute for Market Transformation, Downloaded on 8 march, 2018 from https://www.appraisalinstitute.org/assets/1/7/Green-Building-and-Property-Value.pdf

[54] Kok, Nils, Norman G. Miller, and Peter Morris. 2012. The Economics of Green Retrofits, Journal of Sustainable Real Estate, 4.1 (2012): 4-22. http://www.CoStar.com/uploadedFiles/JOSRE/JournalPdfs/01_4-22-J4_The_Economics_of_Green_Retrofits.pdf

[55] Seppänen, O. and Fisk, W.J., 2006, Some Quantitative Relations between Indoor Environmental Quality and Work Performance or Health, Int. J. HVAC and R Research, 12, 957–973.

[56] Roelofsen, P., 2001, The design of the workplace as a strategy for productivity enhancement. In Proceedings of the 7th World Congress Clima 2000, Naples, Italy, 15–18 September 2001.

[57] Wargocki, P., Wyon, D.P., Sundell, J., Clausen, G., and Fanger, O., 2000, The Effects of Outdoor Air Supply Rate in an Office on Perceived Air Quality, Sick Building Syndrome (SBS) Symptoms and Productivity. Indoor Air, 10, 222–236.

[58] Khan, M.M.A, Asif, M., and Stach, E., 2017, Rooftop PV Potential in the Residential Sector of the Kingdom of Saudi Arabia, Buildings 2017, 7(2), 46; doi:10.3390/buildings7020046.