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King Abdullah Petroleum Studies and Research Center

Evaluating Building Energy Efficiency Investment Options for Saudi Arabia

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About KAPSARC

The King Abdullah Petroleum Studies and Research Center (KAPSARC) is a non-profit global institution dedicated to independent research into energy economics, policy, technology and the environment across all types of energy. KAPSARC's mandate is to advance the understanding of energy challenges and opportunities facing the world today and tomorrow, through unbiased, independent, and high-caliber research for the benefit of society. KAPSARC is located in Riyadh, Saudi Arabia.

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Key Points

This study suggests that energy efficiency programs in buildings can provide up to a 27 percent reduction in electricity consumption and a 30 percent reduction in peak electricity demand for Saudi Arabia.

It is well recognized, however, that given the low electricity prices in Saudi Arabia there is little incentive for households and businesses to invest in energy efficiency. On the other hand, when system-wide benefits of energy efficiency investments are included their value is much higher, especially from the government's perspective. These wider benefits include the reduced need for new electricity generation capacity investment, reduced carbon emissions and new employment opportunities. Among the key findings are:

- Investments in residential buildings are by far the most cost effective, with payback periods of less than a year for low cost energy efficiency programs. More ambitious plans with a wider scope have longer payback periods depending on the prevailing electricity price. This finding sits somewhat in contrast to the current focus of public policy on government buildings.

- The potential reduction in the need for new power generation capacity could drive up to around $28 billion in reduced capital expenditure over a 10-year period.

- Depending on the retail electricity price and scope of the efficiency program, the value of avoided energy consumption could be as much as $17 billion per year.

- We estimate that the measures explored in this report could generate up to 247,000 jobs per year by the end of a 10-year investment program.

Successful implementation will require the building of strong institutional and labor force capacities and strengthened policy frameworks. In particular, we recommend that the current KSA building energy efficiency code is enforced for all new buildings, that the code is gradually mandated for the entire existing building stock and that electricity prices are steadily increased to better reward efficiency investments.

Summary

This paper explores investment options for policymakers interested in improving the energy efficiency of the building stock in Saudi Arabia. To inform such efforts, we provide a comprehensive analysis of large-scale retrofit options for both new and existing buildings in terms of avoided energy consumption, power generation capacity, job creation and carbon dioxide mitigation. This study fills a gap in published literature on the topic as most other work has only considered a limited set of design and operating measures and generally focuses on residential buildings, rather than the entire building stock, as we do here.

Our optimization analysis assesses the impact of different types of investment at both the individual building and the national building stock levels. We focus on the application of well-established and proven measures and technologies. The study is based on detailed simulation analysis of prototypical buildings located in five cities with differing climates across Saudi Arabia.

From an economic perspective, given the low electricity prices in Saudi Arabia, it makes little sense for households and other private organizations to invest in energy efficiency. However, when the system wide benefits from avoided fuel consumption and reduced need for electricity generation capacity are incorporated, then energy efficiency investments become highly cost effective, especially for residential buildings.

As would be expected, the benefits from energy efficiency are amplified when retail electricity prices are higher. In this report, we calculate the benefits from energy efficiency investments using a range of prices from current average tariffs after the recent round of price reforms of approximately $0.05 per kWh, up to an electricity price of around $0.17 per kWh.

We summarize our results in Table 1 below. Three levels of energy efficiency investments are considered, from a basic through to deep retrofits. In Table 1, we also highlight the results for residential buildings and the entire building stock, which includes commercial and government buildings.

A basic energy retrofit program based on easy to implement energy efficiency measures for the existing building stock and implemented for residential buildings could reduce electricity consumption by about 10,000 GWh/year and peak demand by 2,290 MW and carbon emissions by 7.6 million tonnes/year. Such a program is highly cost effective with an investment payback period of less than a year, driven by a reduced need for power generation capacity ($2.7 billion over the lifetime of the program) and an avoided cost of electricity consumption of between $500 million and $1.7 billion per year depending on the assumed power tariff.

Deeper retrofits for residential buildings are still cost effective within a reasonable payback period, but their attractiveness is significantly influenced by electricity tariffs, highlighting the importance of further price reforms in the Kingdom.

Our analysis suggests the most cost effective investments are to be found within the residential building stock, rather than the commercial or government sectors. This contrasts with where the bulk of recent state investments have been made, focused mostly on public buildings. While it is perhaps easier to implement energy efficiency measures on government buildings, our analysis suggests the payoff is probably higher if investment is extended to other building types.

Another potential reason for this distribution of attention is that most of the benefits of energy efficiency investment accrue at the system level

Table 1. An evaluation of building energy efficiency retrofit investments for Saudi Arabia.

Retrofit Program	Investment level 1 (Basic retrofit: lighting and weatherization)		Investment level 2 (Standard retrofit: a/c and building code compliance)		Investment level 3 (Deep retrofit: a/c windows and insulation)	
	Residential building stock	Total building stock	Residential building stock	Total building stock	Residential building stock	Total building stock
Total Investments Required (USD Bn)	2.8	10	28.4	104	56.7	207
Avoided Electricity Consumption (GWh/year)	10,000	16,000	28,900	46,000	62,800	100,000
Value of Avoided Electricity Consumption $0.05–$0.17/kWh (USD Bn/year)	0.5 - 1.7	0.8 - 2.7	1.4 - 4.8	2.2 - 7.7	3.0 - 10.5	4.8 - 16.9
Avoided Electricity Generation Capacity (MW/ year)	2,290	3,700	6,600	10,500	14,300	22,900
Value of Avoided Electricity Capacity (USD Billion)	2.7	4.4	7.9	12.6	17.2	27.5
Net Present Value Investment Payback $0.05–$0.17/kWh (Years)	0.2 - 0.1	8.9 - 2.3	20 - 4.6	30+ - 14.7	17 - 4.0	30+ - 13.
Jobs Created (per year for a 10-year period)	3,400	12,000	33,700	123,000	67,500	247,000
Reduced Carbon Emissions (kton/ year)	7,600	12,000	21,900	35,000	47,600	76,000

Source: KAPSARC.

Notes: KAPSARC analysis (assumes a 10-year investment implementation period and 30-year project period, 3 percent discount rate and generation capacity valued at $1,700 for reduced CAPEX per KW).

and therefore to the mostly state-owned utilities. In this report, we have (conservatively) not included the value that selling avoided energy consumption may have in terms of increased oil exports, which we evaluate elsewhere (Dubey, et al. 2016). Even so, the analysis in this paper suggests that the system-wide benefits at the utility level are attractive enough for the public sector to play a strong role in encouraging greater private sector investments through incentive programs, which is also explored in detail by (Dubey, et al. 2016).

Implementation of retrofit programs will require both innovative financing mechanisms to incentivize the private sector and a significant program of institutional capacity building in energy auditing and management. If such support programs are successful, we estimate that implementing the measures outlined in this paper has the potential to deliver up to an extra 247,000 skilled jobs per year over a 10-year period.

In addition to these employment benefits, energy efficiency measures have a significant potential to reduce carbon dioxide emissions. This could range from 7.6 million to 76 million tonnes of CO2 depending on the level and scope of investment.

Overview of Energy Demand and the Buildings Sector

Even before the Saudi 2030 Vision outlined a future for the Kingdom beyond oil and gas, the government considered it "…a strategic imperative that energy efficiency become a major topic for all decisions related to the increase in demand for fuel and feedstock" (Oxford Institute for Energy Studies 2014).

The rapid increase in domestic energy consumption drives this imperative (Figure 1). With low energy prices a feature of the domestic incentive structure, policymakers have rightly focused on whether this demand growth is delivering full value for society in an effort to maximize the benefits shared by citizens from the Kingdom's (Saudi Arabia) abundance of low cost fuel. Also important is the perception that increased domestic energy consumption may be limiting the oil produced for more productive use or for export, and exacerbate fiscal pressures associated with low oil prices. Such risks are well documented, most notability by Glada Lahn and Paul Stevens in their 2011 report for Chatham House *Burning Oil to Keep Cool.*

Such work put particular attention on the energy demands of air conditioning and more generally the buildings sector, which makes up around 75 percent (residential, commercial and governmental) of total electricity demand in the Kingdom of Saudi Arabia (KSA) (Figure 2). Figure 3 shows how monthly total electricity consumption in the KSA follows closely average ambient temperatures, reflecting the importance of air conditioning in the summer months when electricity demand is double of that in the winter.

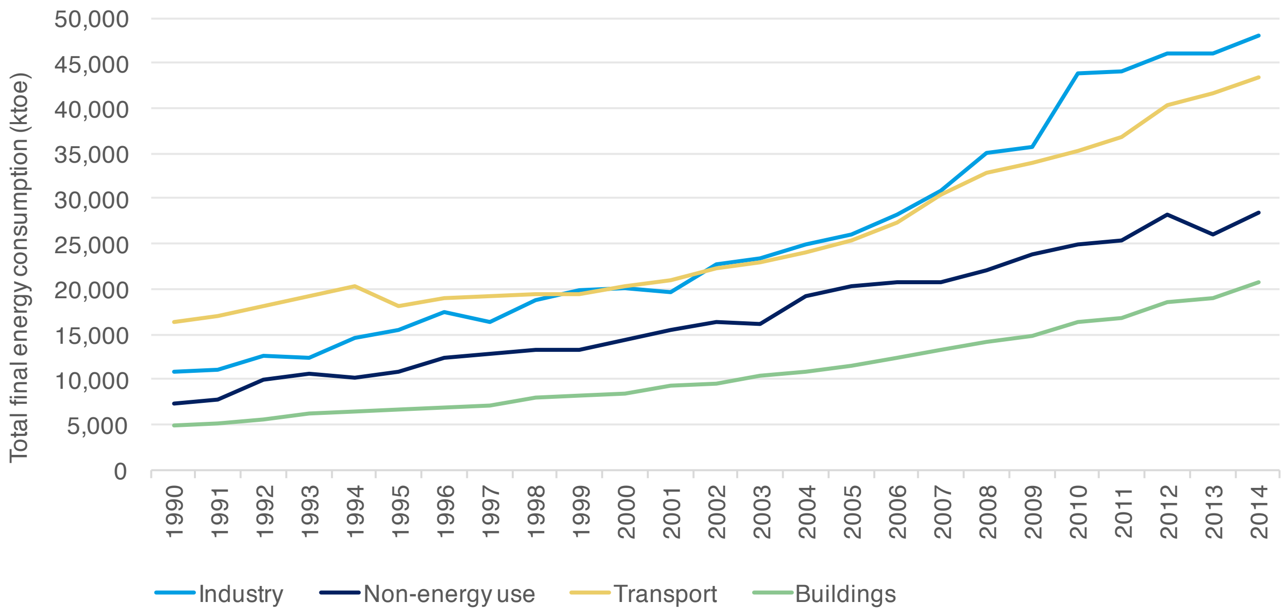


Figure 1. Total final energy consumption by sector in Saudi Arabia.

Source: IEA and Enerdata. This chart shows sectoral trends in Total Final Energy Consumption (TFC) for Saudi Arabia, which in 2013 was 133,066 ktoe, according to the IEA. The 2014 data assume a growth rate of 4.5% for TFC based on Enerdata. This compares with 2013 Total Primary Energy Consumption (TPEC) of 192,181 ktoe: IEA data. Using official local sources. Total Primary Energy Supply (TPES) in 2013 was 196,000 ktoe and its growth rate to 2014 was around 4%.

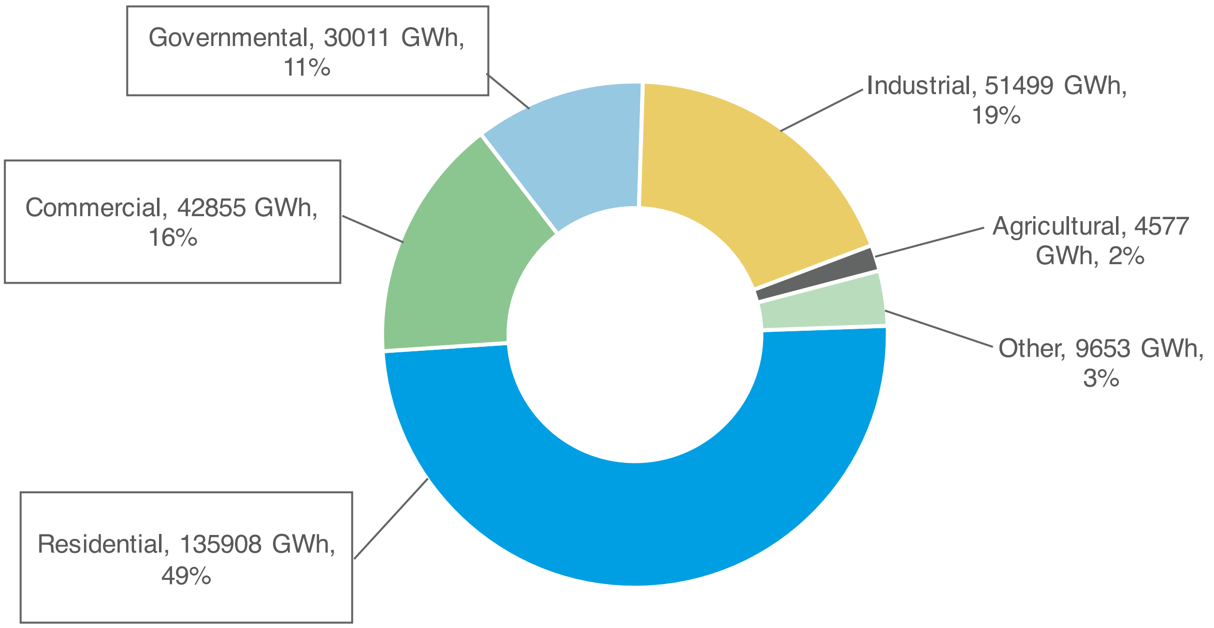


Figure 2. Electricity consumption in KSA during 2014.

Source: SEC, 2015.

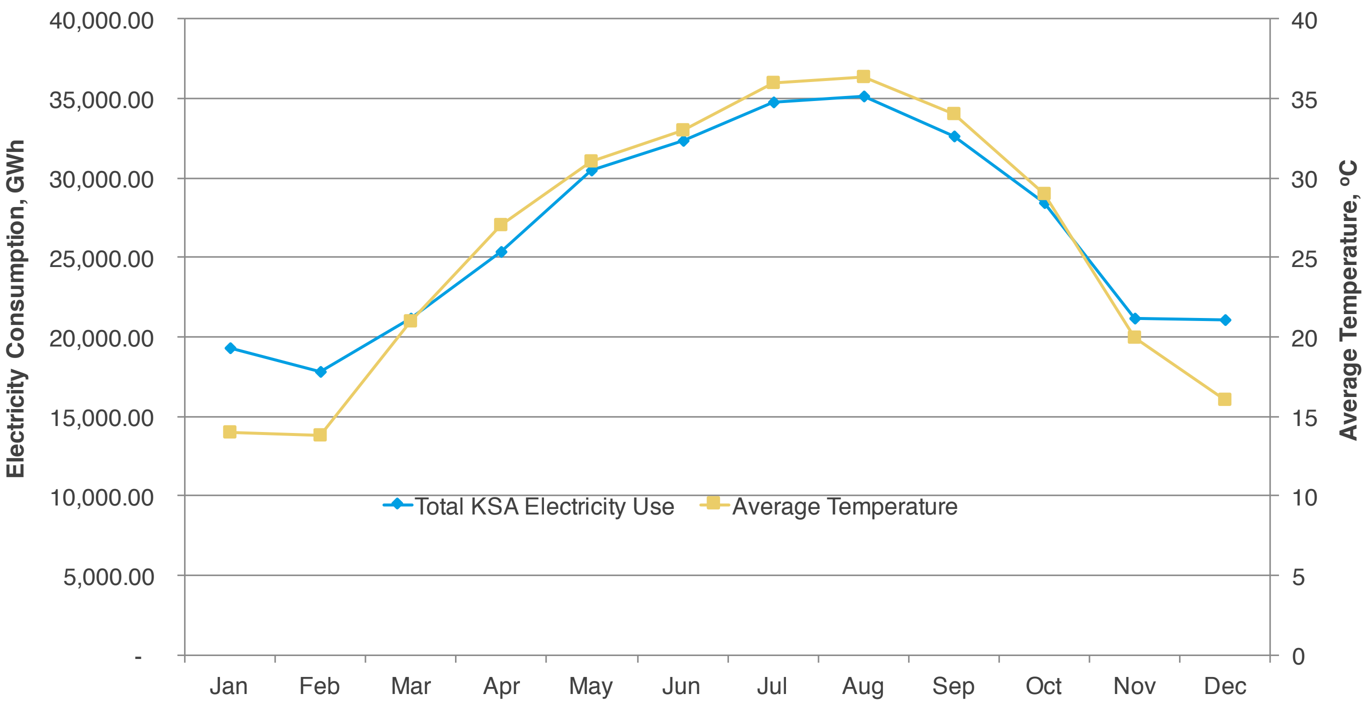


Figure 3. Monthly total KSA electricity consumption and average ambient temperature during 2014.

Source: SEC, 2015.

Figure 4 shows the annual electricity peak demand and power generation capacity and the annual growth in total electricity use consumed and generated from 2000 to 2014. KSA has a combined power generation capacity of 65,506 MW with peak demand at 56,547 MW as of 2014 (Saudi Electricity Company 2000-2013). The average annual growth rate of peak demand over 2000-2014 is 7.1 percent. The difference between generated and consumed electricity corresponds mostly to transmission and distribution losses. 2019 projections include 68,694 MW for generation capacity, 352 TWh for total generation and 324 TWh for net consumption (BMI Research 2015).

Ministry of Water and Electricity statistics show that the number of customers in KSA with electricity service was around 7.14 million in 2013 for all sectors (Figure 5) (Ministry of Municipal and Rural Affairs, Riyadh 2011). The vast majority of these are residential dwellings, representing 79 percent of total customers. The importance of residential units is also reflected in new construction permits approved during 2014 (Figure 6) (Ministry of Municipal and Rural Affairs, Riyadh 2014).

Electricity, like most energy resources in the region, is sold at a low price. Figure 7 shows current electricity prices for residential and non-residential customers in KSA, both before and after the recent energy price reforms. Electricity prices are around $0.0479/kWh based on current production costs, according to ECRA in its Annual Report. However, if international oil prices are used as a benchmark for utility fuel input costs, then the cost of production would be closer to $0.21/kWh (0.80 SAR) suggesting an opportunity cost of around $0.16/kWh when compared to the latest average retail electricity prices (ECRA 2014). For 2013, the International Monetary Fund (IMF) estimated that the total energy subsidies amount to $128.9 billion, or 13.6 percent of Saudi GDP, including electricity

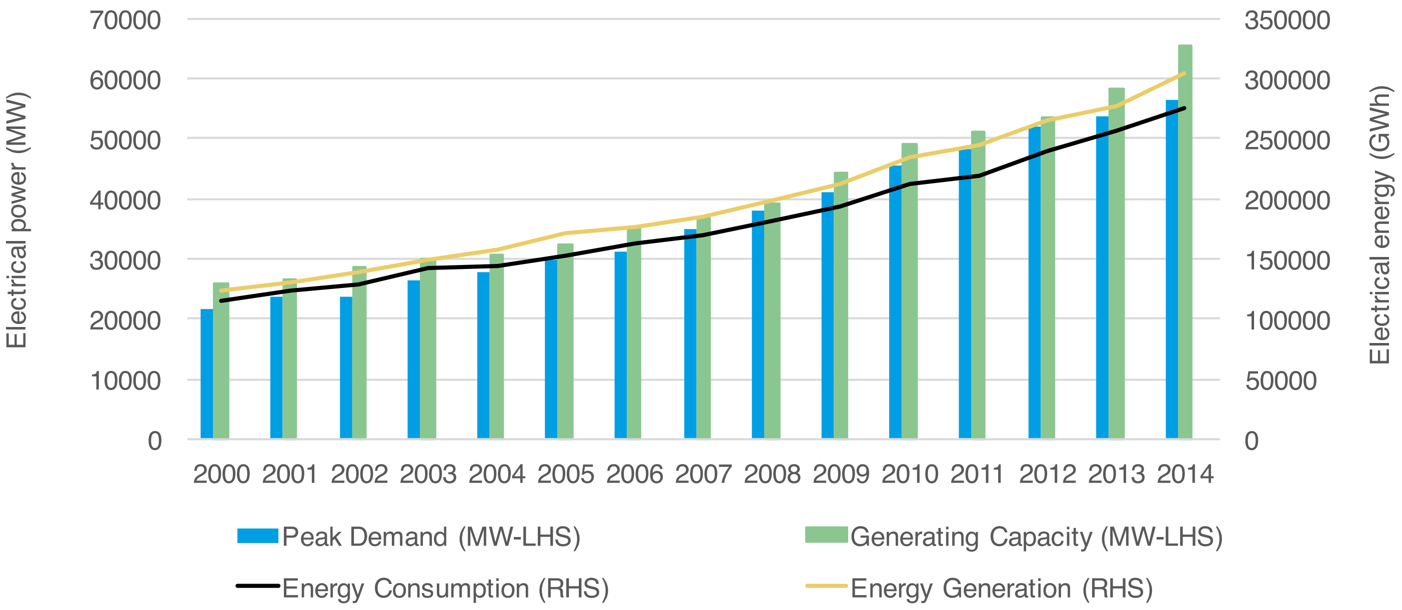


Figure 4. Peak demand, generating capacity, electricity generated and electricity consumed in Saudi Arabia.

Source: SEC, 2015.

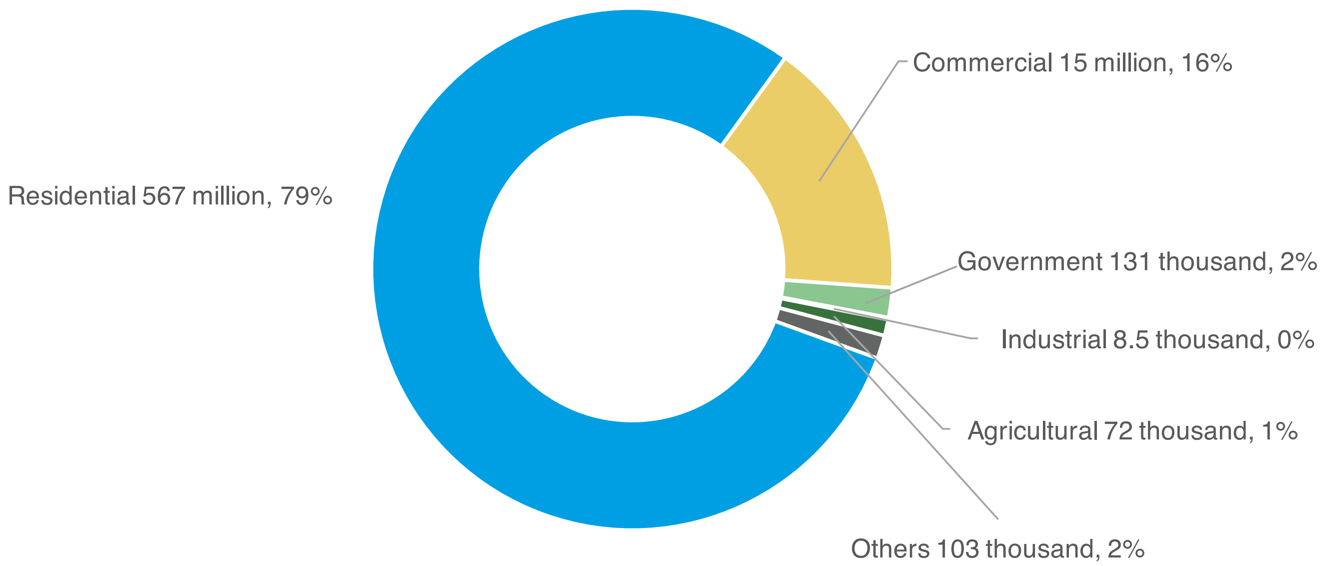


Figure 5. Type and number of customers of electricity in Saudi Arabia.

Source: Ministry for Water and Electricity (2014).

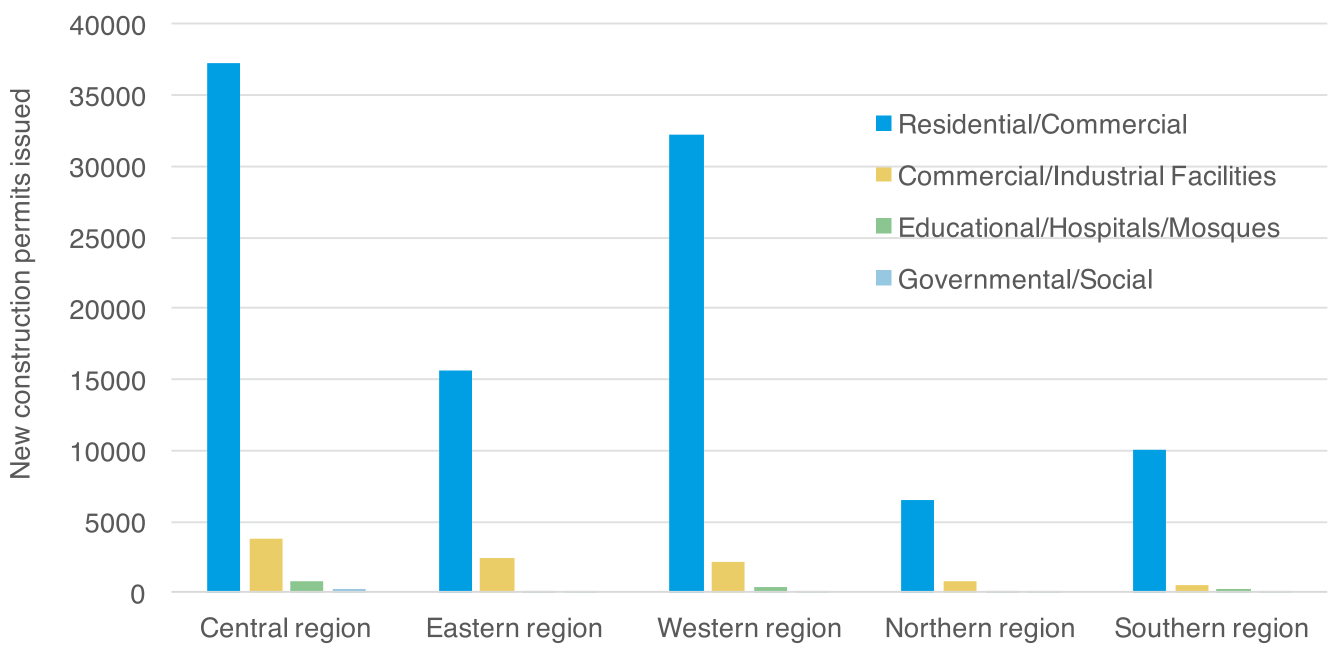


Figure 6. New construction permits in Saudi Arabia (2014).

Source: Ministry for Water and Electricity (2015).

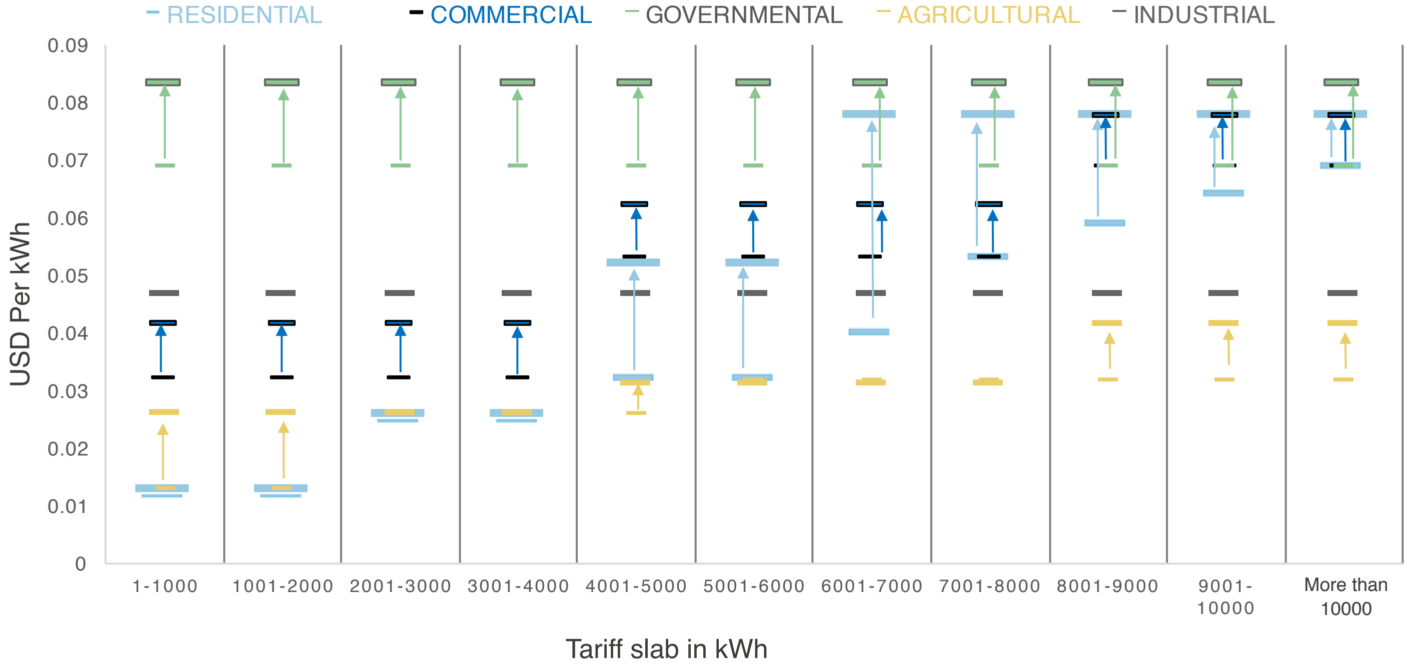


Figure 7. Electricity prices in Saudi Arabia (pre and post-January 2016 reforms).

Source: SEC (2015) and www.se.com.sa/en-us/customers/pages/tariffrates.aspx

subsidies of $19.1 billion (IMF, 2015). Based on 2013 electricity consumption in KSA of 256,688 GWh, this suggests that the IMF's estimate of energy subsidies amounted to about $0.07/kWh or $19.1 billion.

Based on the block schedule above, the average electricity price is estimated to be around $0.05 per kWh for a residential customer with a monthly energy consumption of 5,000 kWh.

While low energy prices combined with the extremely high ambient temperatures of the region are key forces behind the growth of domestic energy consumption, other important drivers are population gains, increasing wealth and energy efficiency. These can be assessed through a Kaya decomposition of building electricity consumption, as shown in Figure 8.

This suggests that both population growth and rising per capita incomes have played a leading role in driving the energy consumption of buildings in the Kingdom. In most years, the energy intensity of the economy has actually increased, suggesting that there is a slightly negative energy efficiency effect or at best only a very weak energy efficiency signal.

To address such issues, in 2003 the National Energy Efficiency Program (NEEP) was established at the King Abdulaziz City for Science and Technology (KACST). In 2008, NEEP articulated a number of objectives including providing capacity for energy audit services and industry support, promotion of the efficient use of oil and gas, minimum energy efficiency standards and labels for appliances and implementation of construction codes for new buildings through technical management and training. In particular, the program has sought to slow the growth in peak summer demand of electricity.

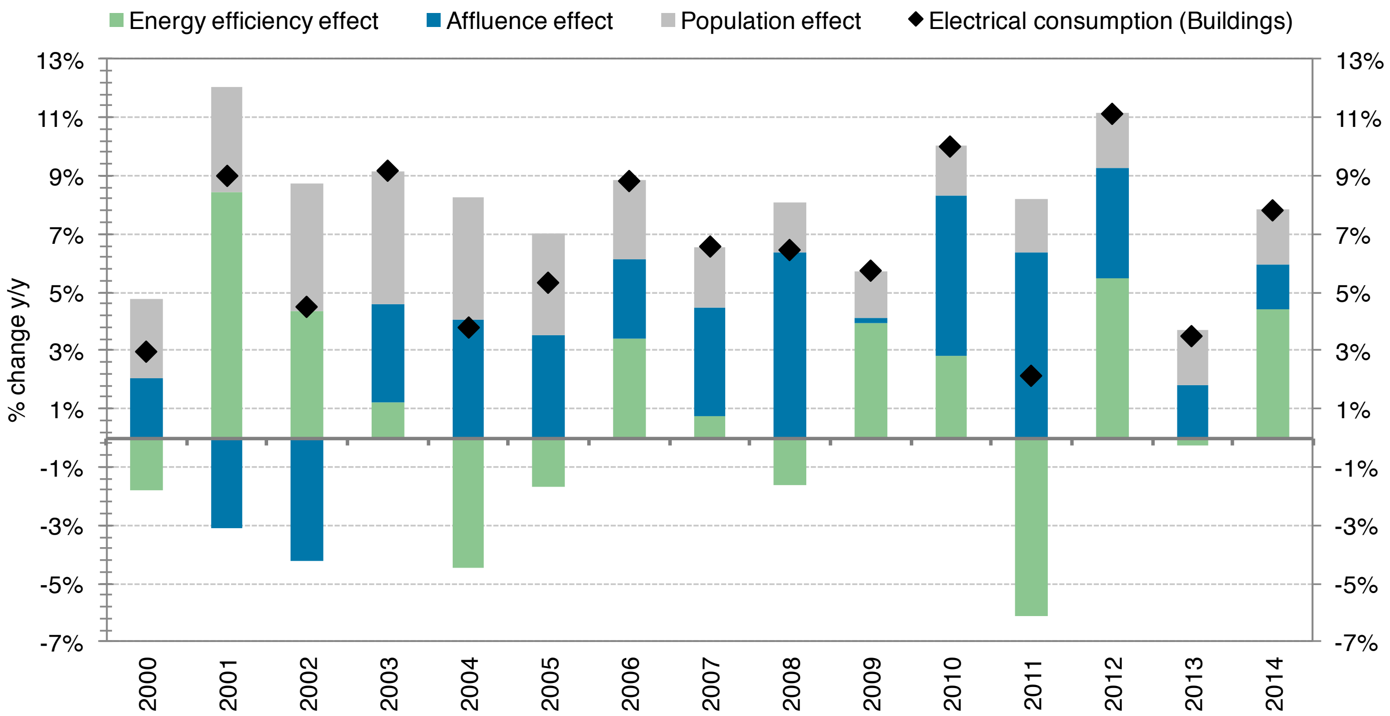


Figure 8. Drivers of change in energy consumption in buildings sector electricity demand (Kaya decomposition).

Source: KAPSARC based on Enerdata.

To strengthen these efforts, in 2010 the Saudi Energy Efficiency Center (SEEC) was established and the government is currently considering a number of reforms including a Mandatory Energy Efficiency Plan with specific conservation targets, as well as proposals for the development of an Energy Service Company (ESCO) market.

To inform such reform efforts, this paper provides a comprehensive analysis of large-scale retrofit options for both new and existing buildings in terms of avoided energy consumption, power generation capacity, jobs creation and carbon dioxide mitigation. This study fills a gap in published literature on the topic as most other works have only considered a limited set of design and operating measures and focus on residential buildings, rather than the entire building stock.

Several important studies on the effects of building envelope improvements on energy consumption have informed our analysis. For example, Abelrahman and Ahmad (1991) and Al-Sanea and Zedan (2011) investigated effects of thermal insulation to walls and roof on the reduction of energy consumption in residential and commercial buildings. Iqbal and Al-Homoud (2007) and Al-Homoud (1997) explored the installation of high performance windows and shading devices; and Alaidroos and Krarti (2015) explored the effects of various building envelope improvements. KAPSARC researchers have also studied this issue using a simplified building energy model to evaluate the impact of enhanced thermal insulation and efficient air conditioning systems on the electricity load curves and the effective operation of power generation in KSA (Matar 2016).

Current Building Energy Policies

Saudi Arabia has developed one of the most comprehensive building energy efficiency codes in the region. The codes, introduced on a voluntary basis in 2009, became mandatory in 2010 for new government buildings. The code covers all of a building's energy systems including the envelope, mechanical, electrical, lighting and domestic hot water systems (Saudi Code National Committee 2007). It has both prescriptive and performance compliance options (See Appendix A). The prescriptive approach defines minimum performance levels for specific building features, whereas the performance approach includes a provision for testing a proposed building design against a baseline with an energy simulation tool to assess whether it meets code requirements for overall energy consumption.

The building code was finalized in 2007 based on the International Energy Efficiency Code of 2003 and American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) standard 90.1 of 2001. It thus reflects an earlier standard than the most recent 2013 ASHRAE.

Given the impact of air conditioning on overall electricity demand, the enforcement of compliance with air conditioning energy efficiency standards was one of the first focus areas for SEEC. In 2012 new minimum energy performance standards (MEPS) were brought in for air conditioners to an Energy Efficiency Ratio (EER) of 8.5 (three stars in the label) for window type and an EER of 9 (four stars) for split type.

In September 2013, the Saudi Standards, Metrology and Quality Organization (SASO) stopped issuing licenses for non-compliant units. Since then the Ministry for Commerce and Industry has confiscated more than 40,000 units from stores and more than 850,000 were disclosed as non-compliant around the country.

While it is still below that of the European Union, the MEPS for small capacity air conditioners in KSA matches the energy efficiency rating of those in the United States. This represents a 35 percent improvement in energy efficiency compared with 2012, when standards were weak and enforcement was ineffective. The IEA estimates energy savings from the Kingdom's new standard at 25TWh by 2020 (International Energy Agency 2015).

Since 2014, the Saudi government has required the mandatory installation of thermal insulation in walls and roofs for all new buildings as a condition to obtain a connection to the electricity grid (Asif 2016). However, enforcing this regulation is a challenge with low energy prices acting as a disincentive for the private sector to invest in energy efficiency (Asif 2016, Aoun and Nachet 2014).In addition to air conditioning, KSA has introduced MEPS for refrigerators, freezers and washing machines. Table 2 illustrates the regulations for them as set by the Saudi Arabia Standard Organization (SASO, 2012, 2013). Regulations are also currently being prepared on the phasing out of inefficient lighting.

Table 2. Labels for energy performance for refrigerators, freezers and air conditioners.

Star Rating	**Air Conditioners** (EER=3.412 COP expressed in Btu/Wh)	**Refrigerators/Freezers** (Percent of energy consumption relative to a baseline)	**Washing Machines** (function of energy use per load capacity)
1	< 7.5	5%	< 2.0
2	7.5 - 8.5	10%	2.0 – 2.9
3	8.5 – 9.0	15%	3.0 – 3.9
4	9.0 – 9.5	20%	4.0 – 4.9
5	9.5 – 10.0	25%	5.0 – 5.9
6	10.0 – 11.5	30%	>6.0
7	11.5 – 12.4		
7.5	12.4 – 13.4		
8.0	13.4 – 14.5		
8.5	14.5 – 15.6		
9.0	15.6 – 16.8		
9.5	16.8 – 18.1		
10	< 18.1		

Source: SASO, 2012, 2013, 2014.

Notes: SASO has updated the energy performance standards for washing machines (conforming to star rating 4 and above only), refrigerators (conforming to star rating 1 and above only), and air conditioners (only those conforming to star rating 3 and above can be sold and manufactured).

Framework for the Analysis of Energy Efficiency Investment Options

In order to assess the impact of current and more stringent energy efficiency options for the buildings sector, we developed a simulation environment using a detailed whole-building energy building simulation tool, EnergyPlus. This includes a sequential search optimization technique for assessing the best combinations of energy efficiency actions at minimal cost (Figure 9). A parametric analysis is used to assess the most effective single energy efficiency measures that can significantly reduce annual energy consumption and peak demand, while the optimization analysis determines the best combination of energy efficiency measures to minimize life cycle costs.

Within this simulation environment, a series of energy efficiency options for both existing and new buildings are evaluated. This includes the potential impacts on energy consumption, peak electricity demand and carbon emissions. A life cycle cost analysis is performed to determine the optimal set of energy efficiency measures that can be implemented. The analysis considers prototypical residential buildings in five KSA sites to account for variation in climatic conditions (Alaidroos and Krarti 2014). The optimization analysis is based on a sequential search technique that was applied to a wide range of applications including designing net-zero energy buildings and retrofitting existing

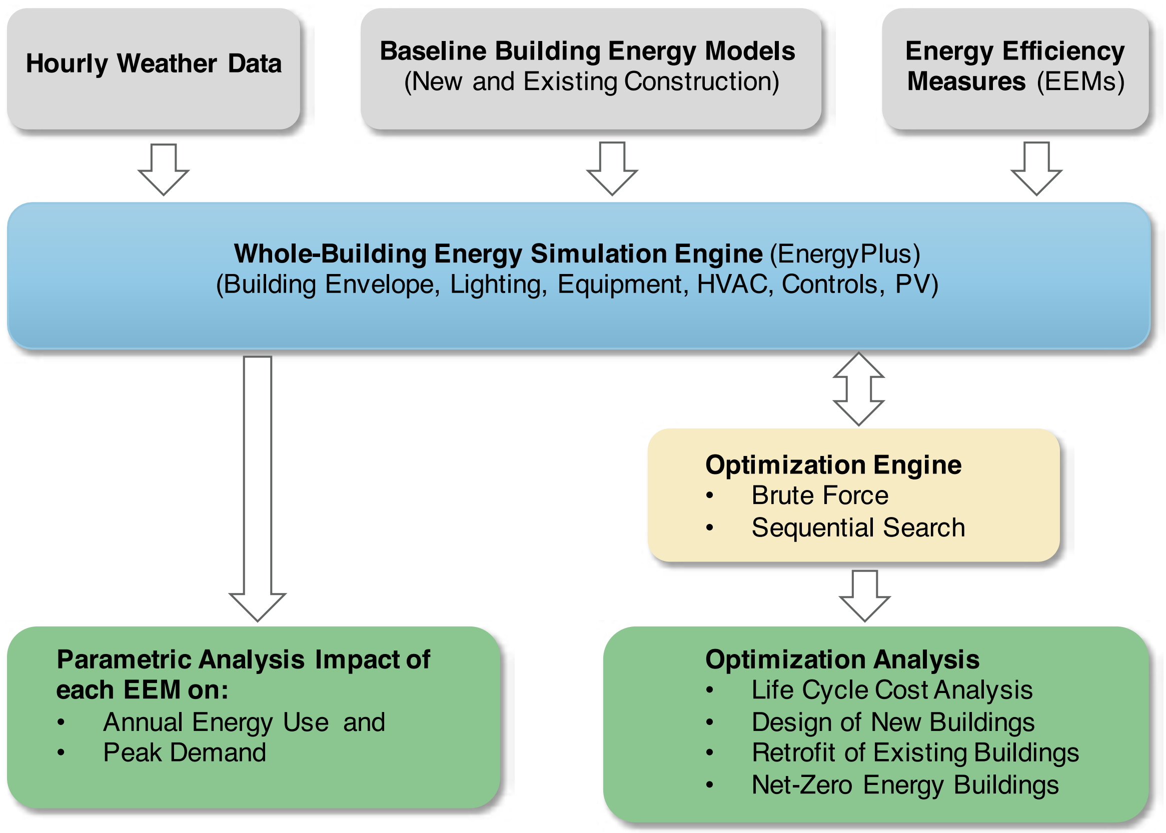


Figure 9. Flowchart for the simulation environment used for the optimization analysis.

Source: KAPSARC.

buildings (Ihm and Krarti, Design optimization of energy efficient residential buildings in Tunisia 2012, Ihm and Krarti, Design Optimization of Energy Efficient Residential buildings in MENA region 2014).

Table 3 illustrates for the selected five cities in Saudi Arabia their climatic variation in both cooling and heating degree-days (Krarti, Weatherization and energy efficiency improvement for existing homes: an engineering approach 2012). Riyadh is located in the center of the Kingdom and has a dry and hot climate. Jeddah on the west coast and Dhahran on the east coast are hot and humid. Tabuk in the north has some cold winter days and Abha in the southwest, with an elevation of about 10,000 feet above sea level, has rather mild winters and summers.

The simulation environment and analysis approach is applied to several building energy models (residential and commercial buildings) and climatic conditions. For this study, the analysis focuses on a residential buildings located in the five most heavily populated cities in the Kingdom.

Table 3. Cooling and heating degree-days for the five cities in KSA.

City	CDD [°C-days (°F-days)]	HDD [°C-days (°F-days)]
Jeddah	**3,659 (6,587)**	0
Dhahran	**3,307 (5,953)**	79 (142)
Riyadh	**3,160 (5,688)**	162 (291)
Tabuk	**2,422 (4,359)**	317 (571)
Abha	**1,740 (3,132)**	270 (486)

Source: Alaidroos and Krarti 2015.

Energy Use for Baseline Building Models

Based on the simulation analysis, the energy end-use for a prototypical home in KSA is estimated in Figure 10 (Alaidroos and Krarti 2014). As expected, space cooling is the main end-use of electricity consumption for a prototypical KSA villa, representing 66 percent and 71 percent of total villa power use in Riyadh and Jeddah, respectively. Figure 11 compares the total villa annual electricity consumption in the five KSA sites. The hot and humid climate of Jeddah results in the highest energy consumption for the prototypical residential building, while the relatively mild climate of Abha yields the lowest.

Figure 10 also shows that no space heating is needed for a villa in Jeddah, though heating may be required in other sites, especially in Tabuk, in the cooler months.

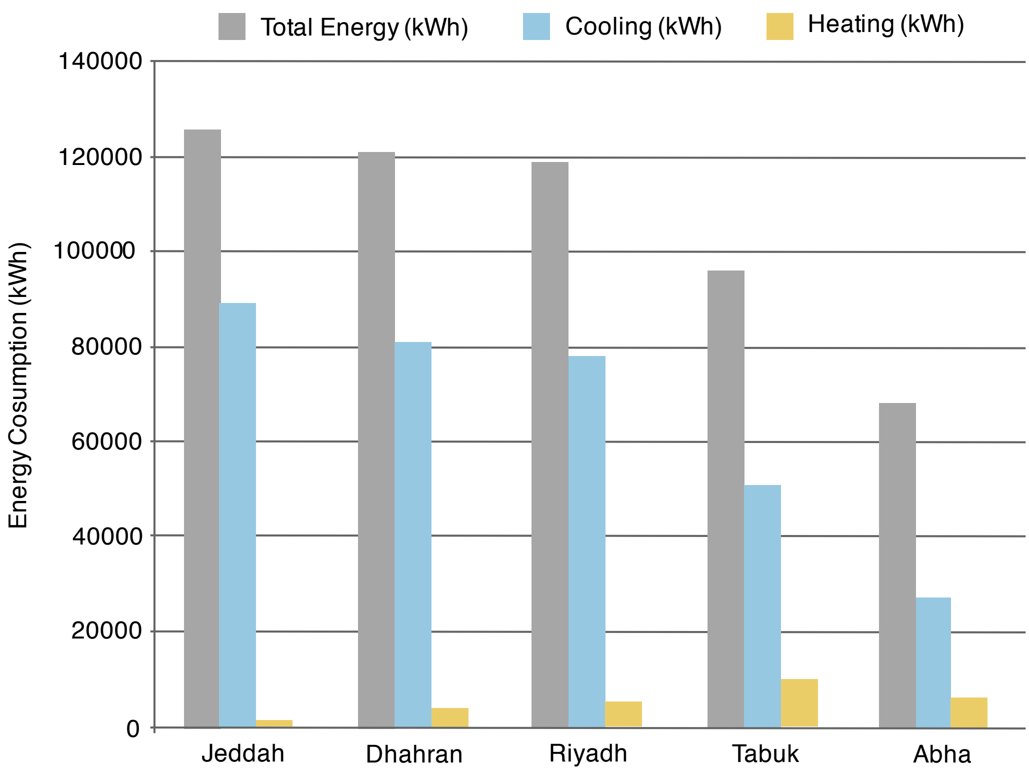


Figure 10. Annual electricity consumption for a prototypical villa in five KSA sites.

Source: Alaidroos and Krarti, 2015.

Energy Use for Baseline Building Models

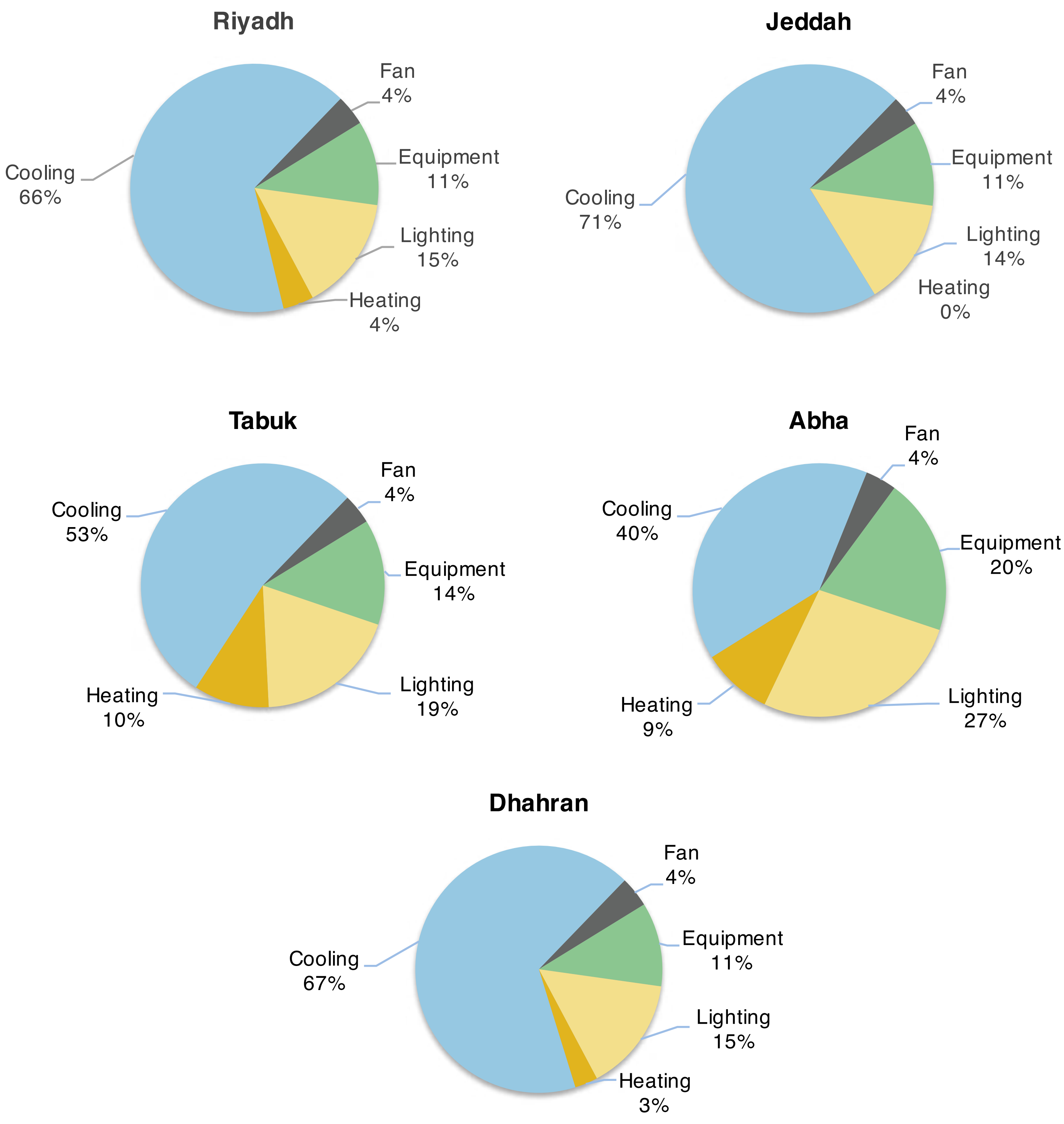


Figure 11. Annual energy end-use distribution for a prototypical villa in five KSA sites.

Source: Alaidroos and Krarti, 2015.

Energy Efficiency Investment Option Impact Analysis

Next, the impact of several design and operating measures on annual energy consumption as well as peak electricity demand can be evaluated using a comprehensive parametric analysis based on our prototypical residential building model (Alaidroos and Krarti, 2015).

Figure 12 shows the percent reduction in annual energy consumption and actual peak power demand associated with all options for a specific design and operating measures. For illustrative purposes, we have only shown the baseline villa model located in Riyadh. However, this analysis was also performed for all the other sites (See Appendix D).

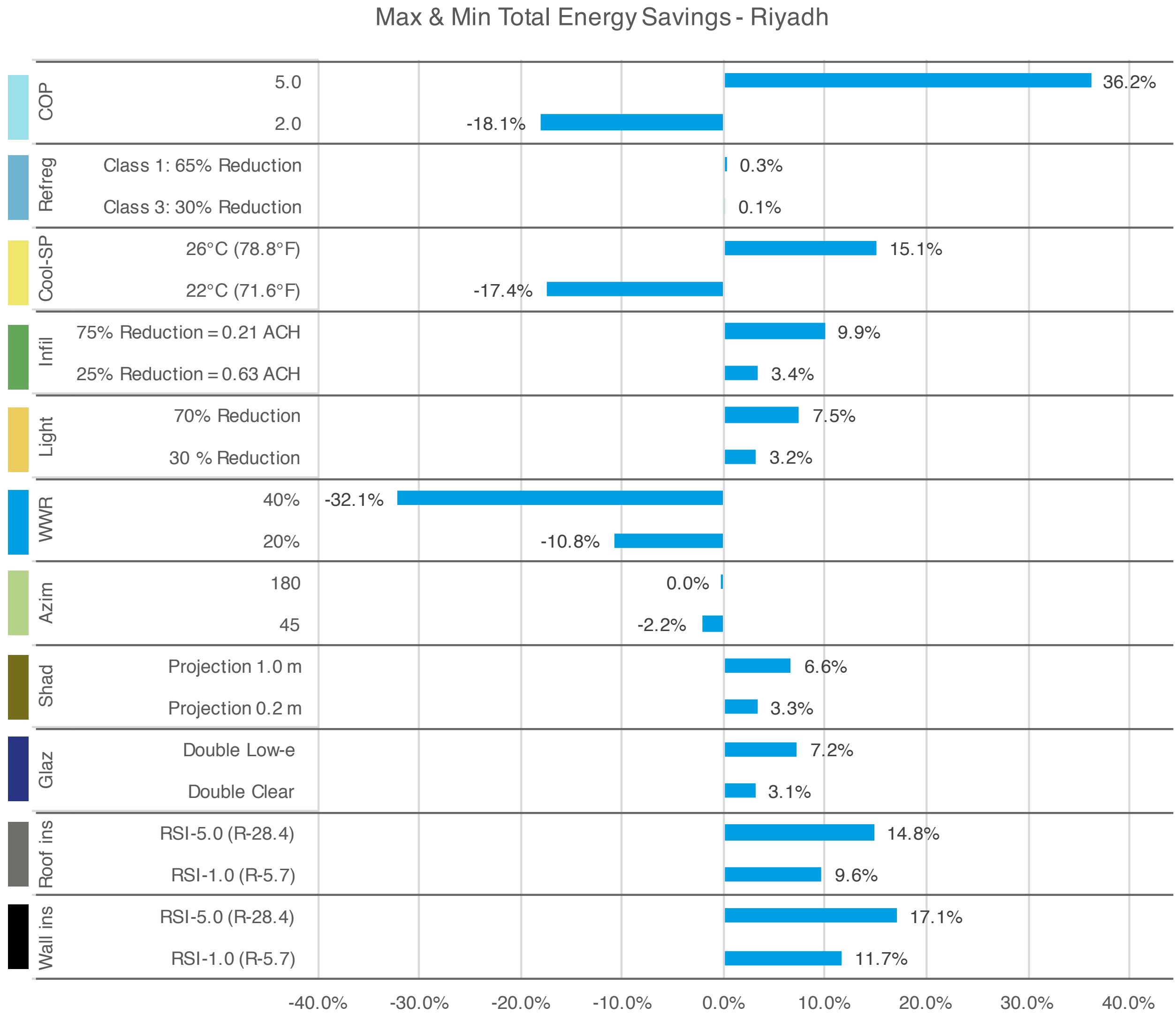


Figure 12a Annual Energy Consumption. The impact of each optimal energy efficiency measure on energy savings.

Source: KAPSARC.

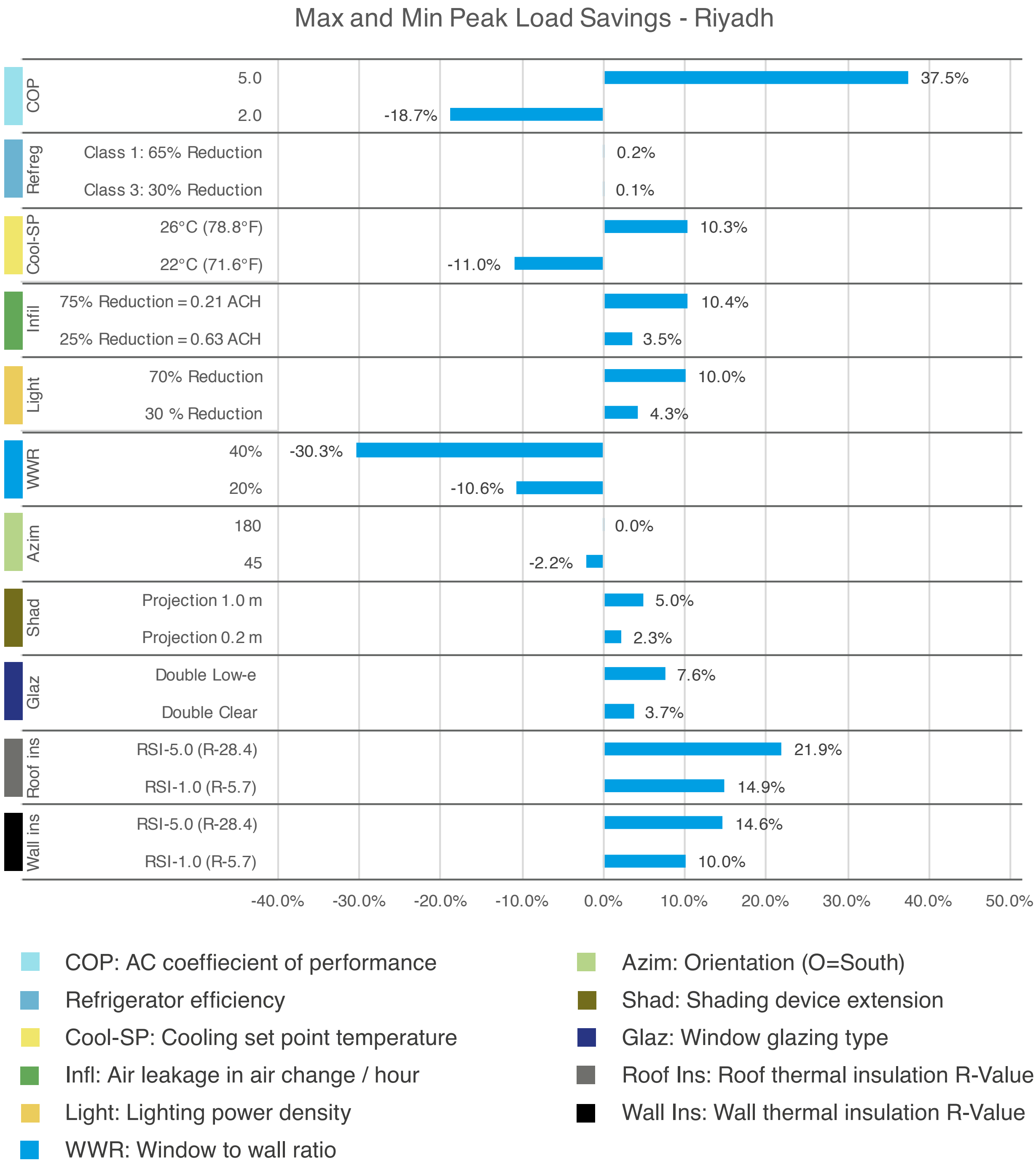


Figure 12b Peak Electricity Demand. The impact of each optimal energy efficiency measure on peak electricity demand.

Source: KAPSARC.

As expected, Figure 12a and 12b indicate that installing an energy efficient air conditioning system has the most significant impact, reducing annual energy consumption by 36 percent and peak electricity demand by 37 percent from the baseline values (See Table C-1 in Appendix C). The measure that has the second most impact is adding wall insulation to reduce energy consumption and adding roof insulation to lower peak demand. Generally, the measures that are the most effective in reducing annual energy consumption are also effective in lowering peak electricity demand.

The addition of thermal insulation in both the walls and roof can achieve around a 25 percent savings in total energy consumption and peak electricity demand. Thermal insulation requirements for exterior walls and roofs were made mandatory for all new KSA buildings in 2014. This is consistent with other studies, which suggested reductions of 15 percent to 35 percent (Al-Homoud 1997, Al-Sanea and Zedan 2011, S. A. Al-Sanea 2002, Alaidroos and Krarti 2014)

Based on this analysis, Table 4 provides three energy efficiency retrofit options along with their implementation cost estimates.

Level 1 – Implementing low cost energy efficiency measures, installation of thermostat, use of CFL or LED lighting and reduce air leakages.

Level 2 – Level 1 + use of energy efficient cooling systems and appliances.

Level 3 – Level 1 and 2 + deep retrofit programs, such as window replacement, cooling system replacement, installation of daylighting control systems

Table 4. Cooling and heating degree-days for the five cities in KSA.

Recommended Options	Retrofit Description (a)	Retrofit Level for Residential Buildings		
		Level-1	Level-2	Level-3
1	List of EEMs	EEM-1	EEM-1, EEM-2, and EEM-3	EEM-1, EEM-2, EEM-3 and EEM-4
	Energy Use Savings	10.0%	26%	52.5%
	Cost	$0 (b)	$1,489 (b)	$7,920 (b)
2	List of EEMs	EEM-2	EEM-4	EEM-2, EEM-3, and EEM-6
	Energy Use Savings	10.0%	28.1%	51.0%
	Cost	$462	$6,250	$8,670
3	List of EEMs	EEM-3	EEM-1 and EEM-5	EEM-1, EEM-5, and EEM-6
	Energy Use Savings	10.4%	28.5%	53.5%
	Cost	$1,208	$6,958	$12,550

Notes (a) Description of Energy Eff1iciency Measures (EEMs):

- EEM-1: Increase the cooling set from 21^{o}C to 23^{o}C, from 22^{o}C to 24^{o}C, or from 23^{o}C to 25^{o}C depending on the existing operating conditions.
- EEM-2: Replace existing lighting fixtures by LEDs
- EEM-3: Seal air leakage sources around building envelope (i.e., window and door frames so ACH =0.21)
- EEM-4: Replace the existing AC unit by high efficiency system (COP=4.0)
- EEM-5: Replace the existing AC unit by standard efficiency system (COP=3.5)
- EEM-6: Insulate the roof using RSI-3

(b) A programmable thermostat is assumed to be already installed in the residential building/apartment unit.

Source: KAPSARC.

Energy Efficiency Investment Portfolio Optimization

The basic setup for the results of an optimization analysis using the sequential search technique is shown in Figure 13. The life cycle cost of the energy efficiency investment is a function of the percentage source of energy use savings. In addition to the baseline for new or existing building conditions, four options for energy models to design or retrofit buildings are identified.

These options include:

The optimal energy efficient option, depicted in Figure 13 at the bottom of the optimal path. This has the lowest life cycle costs (LCC).

The switch-over energy option is associated with the package of energy efficiency measures that achieves the maximum energy savings obtained without using any PV system. With this option, using PV becomes more cost effective than implementing any additional EEMs.

The neutral energy option corresponds to the combined package switch-over EEMs and a roof-mounted PV array selected so the total LCC is the same as the baseline LCC.

The net zero energy buildings (NZEB) option combines both EEMs and PV panels. The annual building energy consumption is entirely compensated by the PV electricity production. (Figure 14)

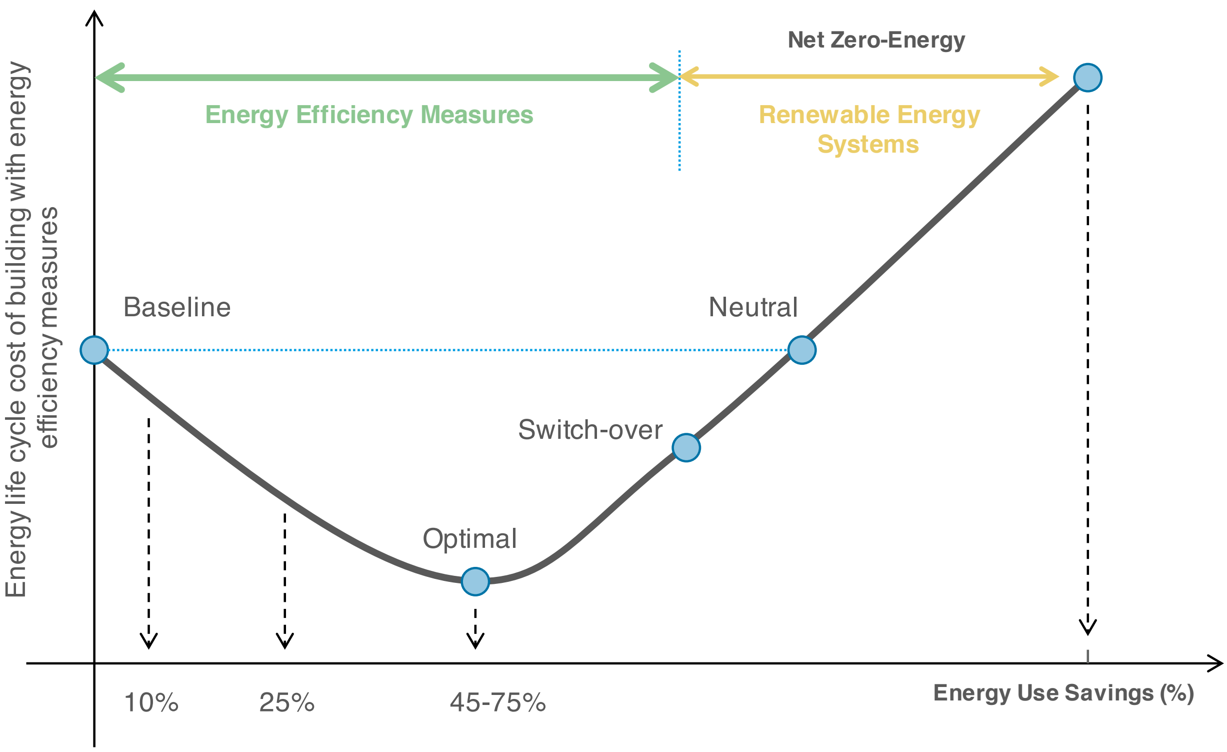


Figure 13. Sequential optimization path toward net-zero energy building.

Source: KAPSARC.

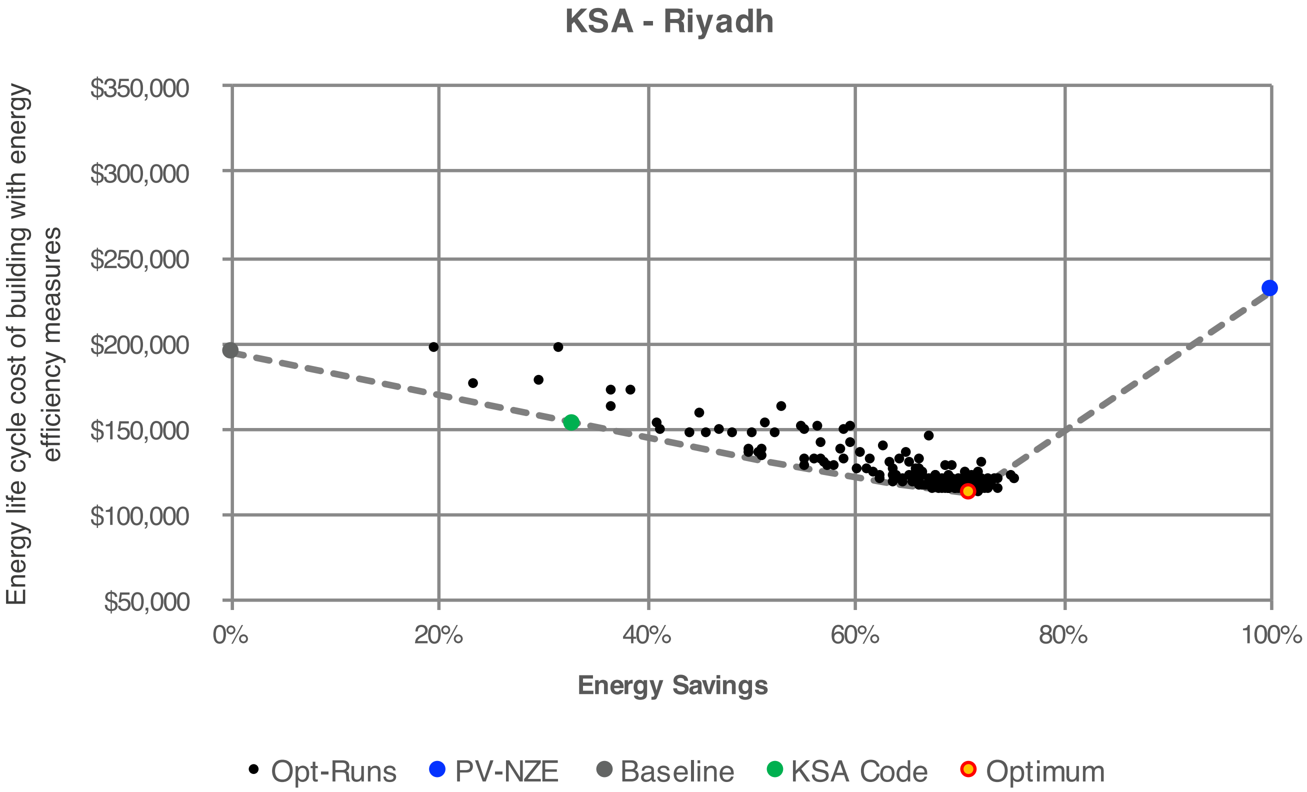


Figure 14. Optimization path toward next zero energy residential building for Riyadh.

Note: a) Optimization Runs, b) PV – Net Zero Energy.

Source: KAPSARC.

Table 5 (next page) illustrates the results of the sequential search optimization analysis when electricity prices of 38 SAR/kWh ($0.10/kWh) are used. A wide range of energy efficiency measures are included in the modeled optimal designs for all sites including wall and roof insulation, high efficiency air conditioning systems and lighting systems and higher cooling set-points.

Figure 13 illustrates the Pareto graph that provides the optimal path to achieve net-zero energy design for a prototypical residential building in Riyadh. The details of the optimization methodology and the assumptions for the costs of various energy efficiency measures are discussed in Alaidroos and Krarti (2014) (See Appendix B).

The results indicate that optimal cost-effective residential building designs can have a significant impact on energy consumption and peak electricity demand.

For instance, a potential reduction of 63 percent in total electricity consumption and 68 percent on peak electricity demand is obtainable for residential buildings located in Riyadh. In Abha, with milder climate, potential energy reductions of 52 percent in electricity consumption and 67 percent in peak electricity demand are achievable using optimal energy efficiency design for residential buildings.

Figure 5. List of optimal design and operating strategies, potential energy use and peak demand savings for residential buildings in five KSA sites.

EEM	Riyadh	Jeddah	Dhahran	Tabuk	Abha
Wall insulation	RSI-2.0	RSI-2.0	RSI-3.0	RSI-1.0	No insulation
Roof insulation	RSI-3.0	RSI-3.0	RSI-3.0	RSI-3.0	RSI-3.0
Glazing	Double Bronze	Double Bronze	Double Bronze	Single Clear	Single Clear
Shading	Projection 0.2 m	Projection 0.5 m	Projection 0.2 m	Projection 0.2 m	Projection 0.2 m
Azimuth	0	0	0	0	0
WWR	10%	10%	10%	10%	10%
Lighting	2.2 W/m^2	2.2 W/m^2	2.2 W/m^2	2.2 W/m^2	2.2 W/m^2
Infiltration	0.21 ACH	0.21 ACH	0.21 ACH	0.21 ACH	0.84 ACH
Cooling Set Point	26°C	26°C	26°C	26°C	26°C
Refrigerator	Typical (800 kWh/year)	Class 1 (280 kWh/year)	Class 2 (440 kWh/year)	Class 3 (560 kWh/year)	Typical (800 kWh/year)
HVAC COP	4.0	4.0	4.0	3.5	3.0
Total Energy Savings	71.1%	70.5%	71.2%	63.1%	54.2%
Life Cycle Cost	$111,640	$115,070	$113,860	$104,660	$92,116
Peak Demand (W)	9,461	8,573	9,409	10,954	10,101
Peak Savings	76.3%	74.2%	76.2%	69.6%	58.9%
Peak Time	07/28 6 p.m.	08/19 6 p.m.	07/29 6 p.m.	07/29 6 p.m.	06/12 6 p.m.

Source: KAPSARC.

Estimation of Avoided Energy Consumption: Reduction in Peak Demand

New buildings

In this section, we estimate the impact on electricity consumption and peak demand of three different investment options for new buildings. (Figure 14.)

- Thermal insulation requirements.
- Performance based requirements to achieve optimal life-cycle costs.
- Net-zero energy design.

An analysis was carried out for representative energy models of new buildings using an approach set out in Krarti (2015). The results are summarized in Table 6.

The addition of thermal insulation to exterior walls and roofs for all new buildings can achieve reductions of 755 GWh/year in electricity consumption and 172 MW reduction in peak demand. Moreover, optimal building energy efficiency designs for all new buildings could decrease electricity consumption by 1,751 GWh/year and peak demand by 468 MW. While it is not cost-effective (as illustrated in Figure 14), net-zero energy buildings may lead to 3,000 GWh/year savings in electricity consumption. However, it should be noted that technical and regulatory implementation challenges have to be considered, including net metering and grid system stability. Similar optimization runs were performed for other sites in KSA. (See Appendix E.)

Existing buildings

Three investment options for energy efficiency building retrofits were modelled in this analysis:

Level-1: In this scenario, the buildings undergo basic or low cost energy efficiency measures such as installation of programmable thermostat, use of CFL or LED lighting and weatherization of building shell to reduce air infiltration (Krarti, Weatherization and energy efficiency improvement for existing homes: an engineering approach 2012). The estimated savings from a Level-1 retrofit program are 8 percent for all building types based on documented studies and case studies reported for residential, commercial and government buildings.

Level-2: To improve the building envelope components to meet at least the current energy efficiency code as well as use of energy efficient cooling systems and appliances. Based on existing literature, average savings of 23 percent can be achieved for Level-2 retrofits for all building types (Krarti, Weatherization and energy efficiency improvement for existing homes: an engineering approach 2012).

Level-3: Deep retrofit of existing buildings is undertaken. A wide range of energy efficiency measures are considered in this program including window replacement, cooling system replacement, use of variable speed drives and installation of daylighting control systems. While deep retrofits are typically costly, they are linked with architectural refits to minimize costs, and can provide significant energy use savings exceeding 50 percent as noted in the study by Krarti and Ihm (2014).

It should be noted that the savings from the various energy audit levels are rather conservative, based on estimates shown in Table 6 to account for behavioral variations including any rebound effects (Majcen, Itard and Visscher 2013, Jacobsen and Kotchen 2010).

Table 6. Potential energy and demand reductions from energy efficiency programs for total and new buildings.

Building Type	Annual Energy Reduction (GWh/yr)			Electricity Peak Demand Savings (MW)		
	Prescriptive Insulation	Performance Based	Net Zero Energy	Prescriptive Insulation	Performance Based	Net Zero Energy
Residential	471	1,093	1,884	107	292	334
Commercial	148	344	592	34	92	106
Governmental	103	238	412	23	64	72
Others	33	76	132	7	20	22
Total	755	1,751	3,020	172	468	537

Note: Prescriptive Insulation compliance approach specifies minimum performance building features. Performance based compliance approach comprises of two types of designs, the standard design and the proposed design (refer to Appendix A).

Source: KAPSARC.

Table 7. Potential energy and demand reductions from energy efficiency retrofit programs for total building stock.

Building Type	Annual Energy Reduction (GWh/yr)			Electricity Peak Demand Savings (MW)		
	Level 1	Level 2	Level 3	Level 1	Level 2	Level 2
Residential	10,054	28,906	62,839	2,290	6,583	14,312
Commercial	3,160	9,085	19,750	720	2,069	4,498
Governmental	2,191	6,298	13,692	499	1,434	3,118
Others	700	2,014	4,378	160	459	997
Total	16,105	46,303	100,659	3,668	10,546	22,926

Source: KAPSARC.

The impacts of the behavioral changes in KSA absent any significant increases in energy prices are expected to be minimal (Borenstein 2014).

Table 7 summarizes the annual energy cost savings, which originate from two sources:

- Using less fuel to generate electricity
- The peak demand reductions associated with avoided demand for new transmission and distribution capacity of new power plants.

As might be expected, greater benefits can be achieved from Level-2 and Level-3 programs compared with Level-1. However, these programs require higher investments. The benefits are significantly larger for residential buildings than for commercial or government buildings for any retrofit level. Indeed, 50 percent of the benefits can be achieved solely by retrofitting KSA residential buildings.

Program Implementation

According to Asif (2016) implementation of energy efficiency programs, rather than further tightening of standards per se, is the main challenge in capturing the benefits from new energy efficiency investments. Asif points to regional building surveys and notes that, despite strong enforcement efforts by authorities, there are still non-compliant air conditioners on the market and a large number within the existing building stocks. Achieving full implementation of announced policies therefore requires dedicated and realistic institutional support policies in the areas of energy auditing and management.

Figures 15 through 18 illustrate the impacts of implementing various energy efficiency programs for both new and existing buildings on future electricity consumption and peak demand. Specifically, the following programs are compared to the baseline business as usual (BAU) scenario:

> Implementation and enforcement of existing building energy efficiency code (BEEC) for new construction. Both the current code and a performance based code (more stringent) are modelled (Figure 15).

> Implementation of energy retrofit programs including Levels 1, 2, and 3 for only existing residential buildings (Figure 16).

> Implementation of energy retrofit programs including Levels 1, 2, and 3 for the entire existing building stock (Figure 17).

> Implementation of a performance based or more stringent (See Appendix A) building energy efficiency code combined with energy retrofit programs for the entire new and existing building stocks (Figure 18).

In estimating future electricity load projections, it is assumed that:

> The construction of new buildings will continue at a steady annual rate of 4 percent.

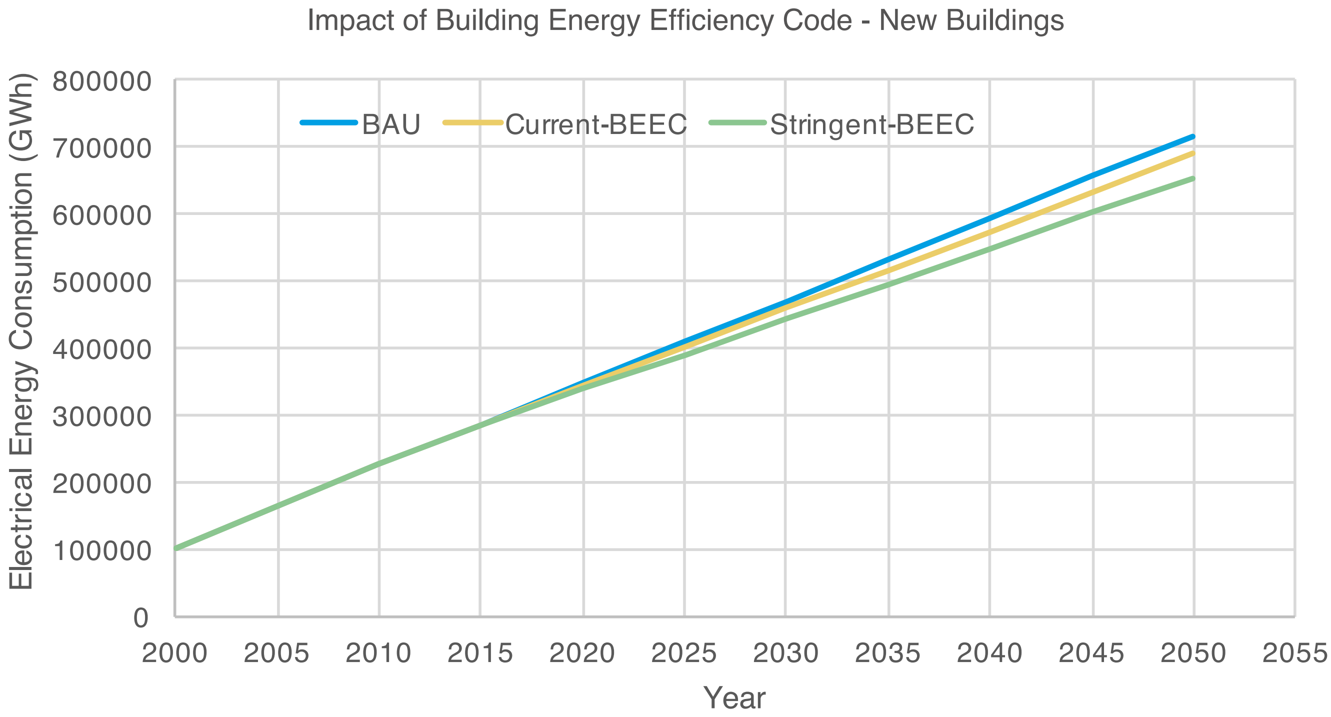
> The building energy efficiency code is fully enforced starting in 2015.

> The retrofit programs are implemented over a period of 10 years starting with industry capacity building in 2017, and a ramp up of retrofits over five years so that about 10 percent of the existing building stock is retrofitted annually.

A more aggressive retrofit program can be implemented over 10 years if sufficient financial support is allocated. Less aggressive retrofit programs can also be considered with a period extending over 20 or even 30 years. As indicated in the profiles of Figures 15 through 18, the implementation of 'only new' building energy efficiency interventions reduces energy consumption and peak demand slowly as the building stock is replaced by new construction over time. On the other hand, the energy retrofit program has significant impacts on both energy consumption and peak demand during the 10-year implementation period.

The highest impact scenario for reducing energy use and peak demand would be to implement a more stringent building energy efficiency code for new buildings and to retrofit over a 10-year span the entire existing building stock. Figure 15 shows the significant potential energy savings in existing building stock with both energy consumption and peak demand actually falling over the implementation period of 10 years, and even through new (due to the stringent code) buildings.

In this fourth scenario, by 2030 total KSA annual electricity energy consumption could be reduced by up to 27 percent from a projected 470,000 GWh per year under the baseline scenario to 341,000 GWh, and peak demand could decrease by up to 30 percent from a projected 108,000 MW under the baseline to 75,500 MW.



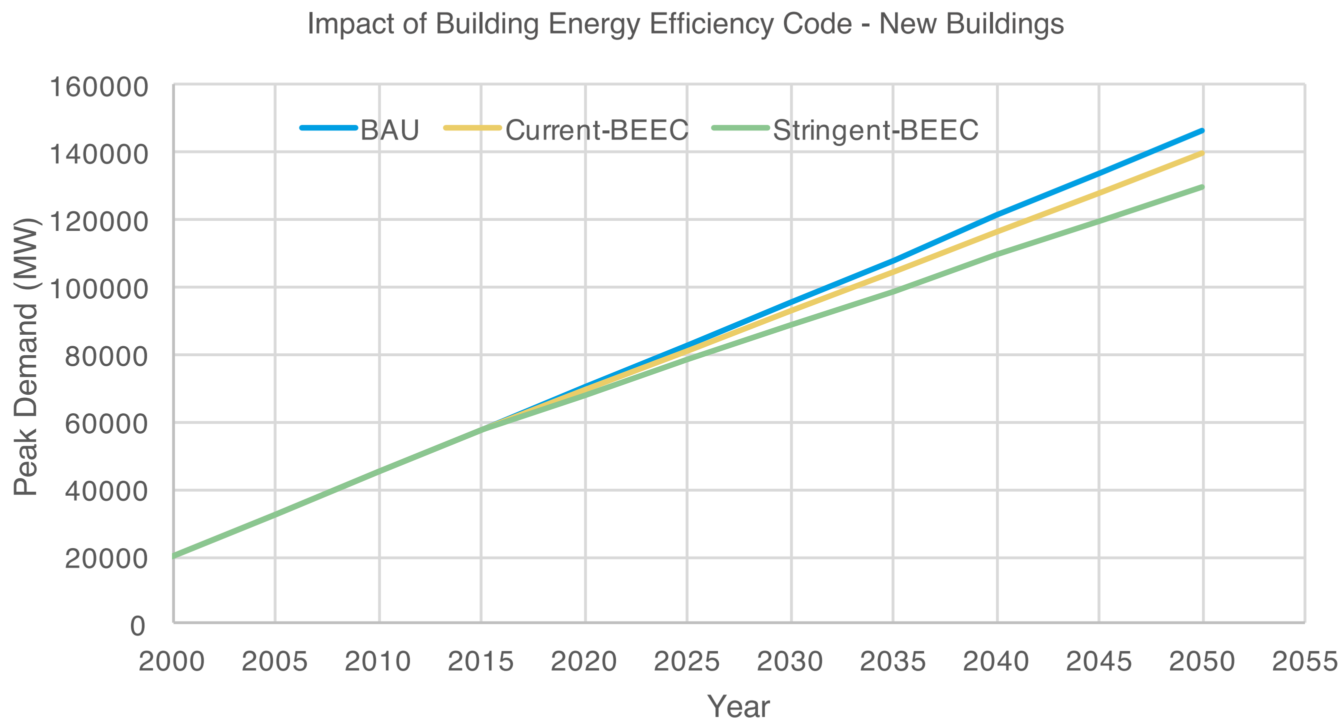
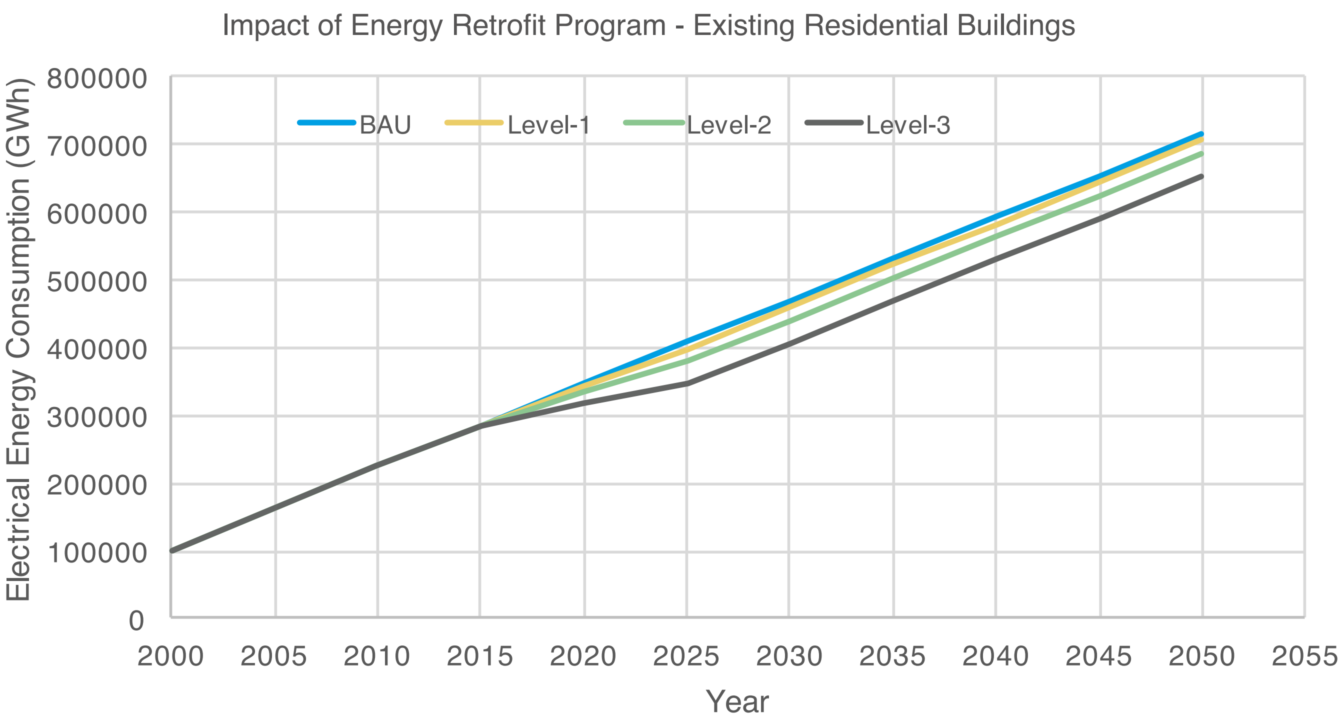


Figure 15. Scenario 1: Code compliance for new construction only.

Source: KAPSARC.



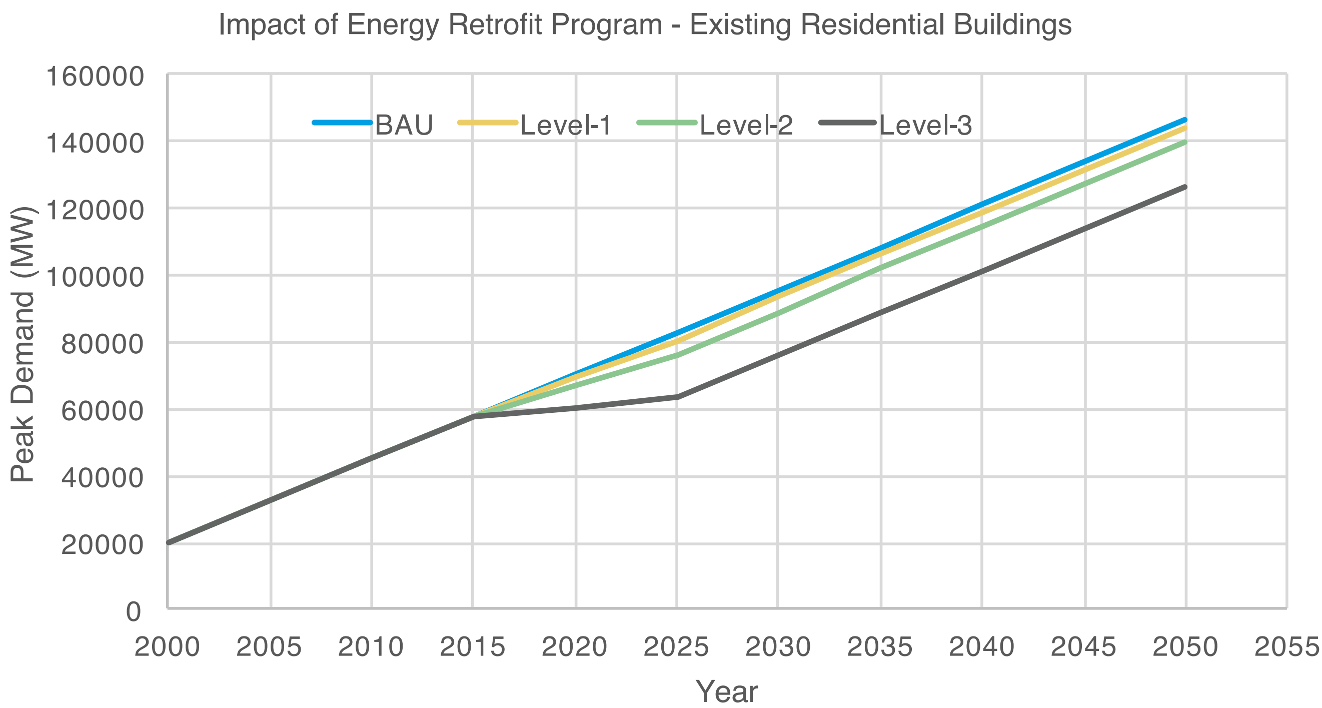
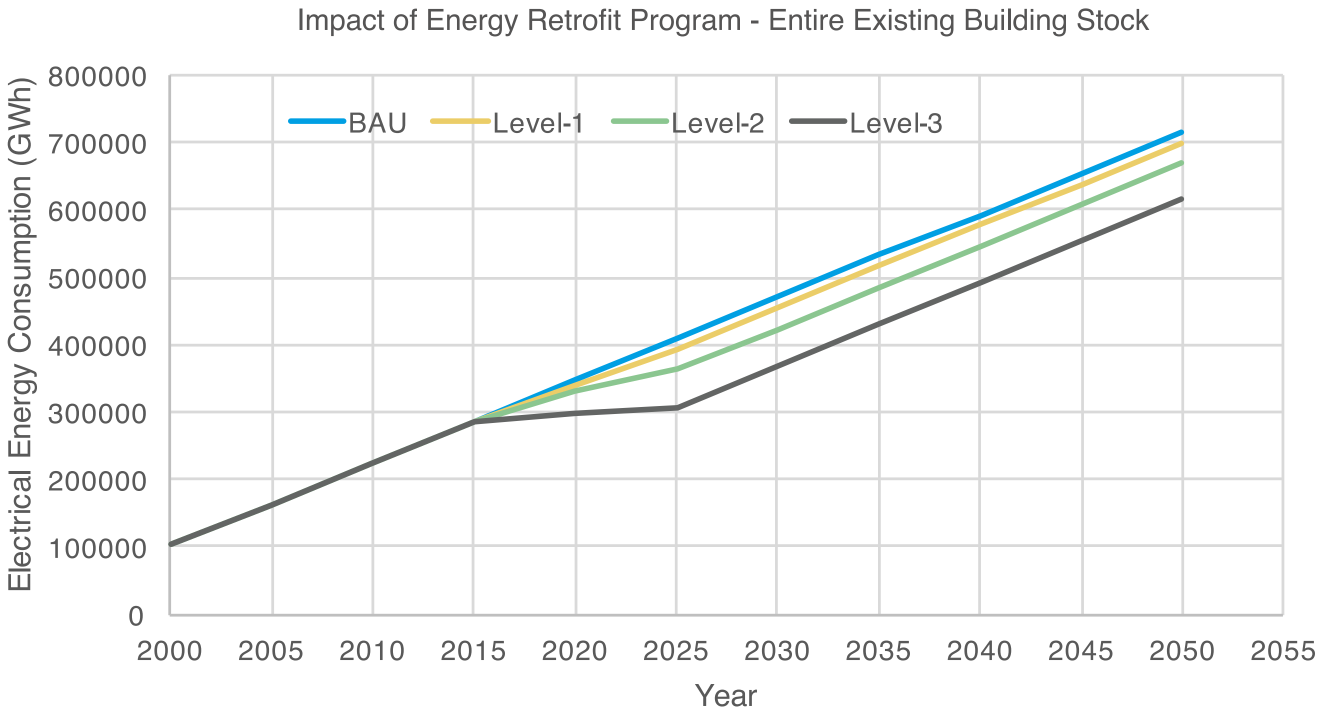


Figure 16. Scenario 2: Code compliance retrofit for existing residential buildings.

Source: KAPSARC.



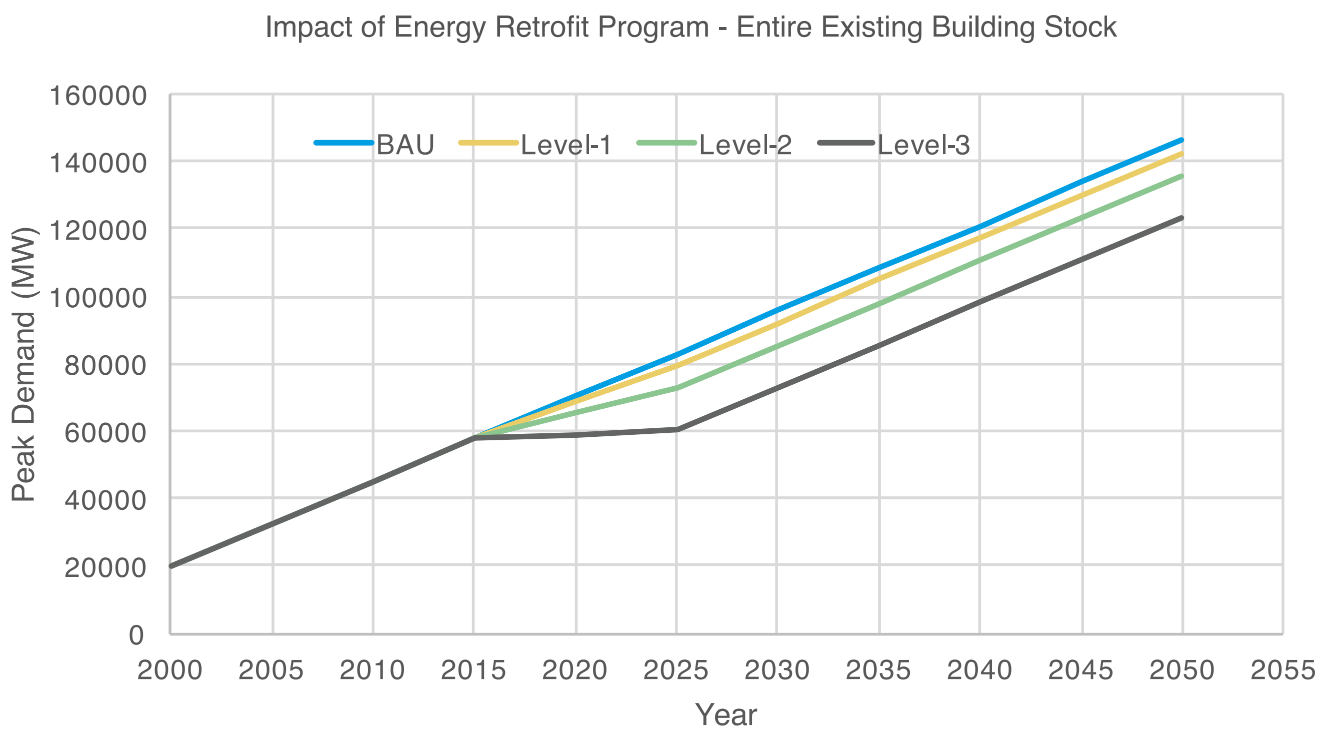
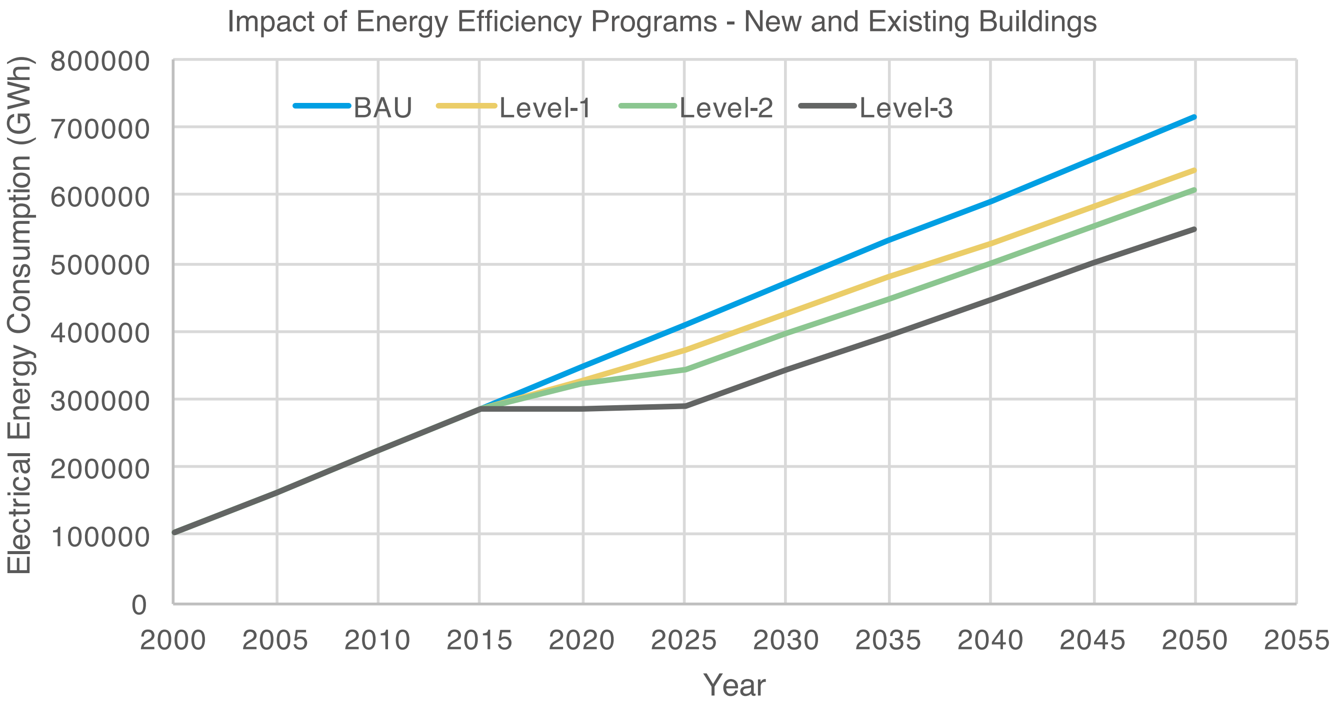


Figure 17. Scenario 3: Code compliance retrofit for the entire building stock.

Source: KAPSARC.



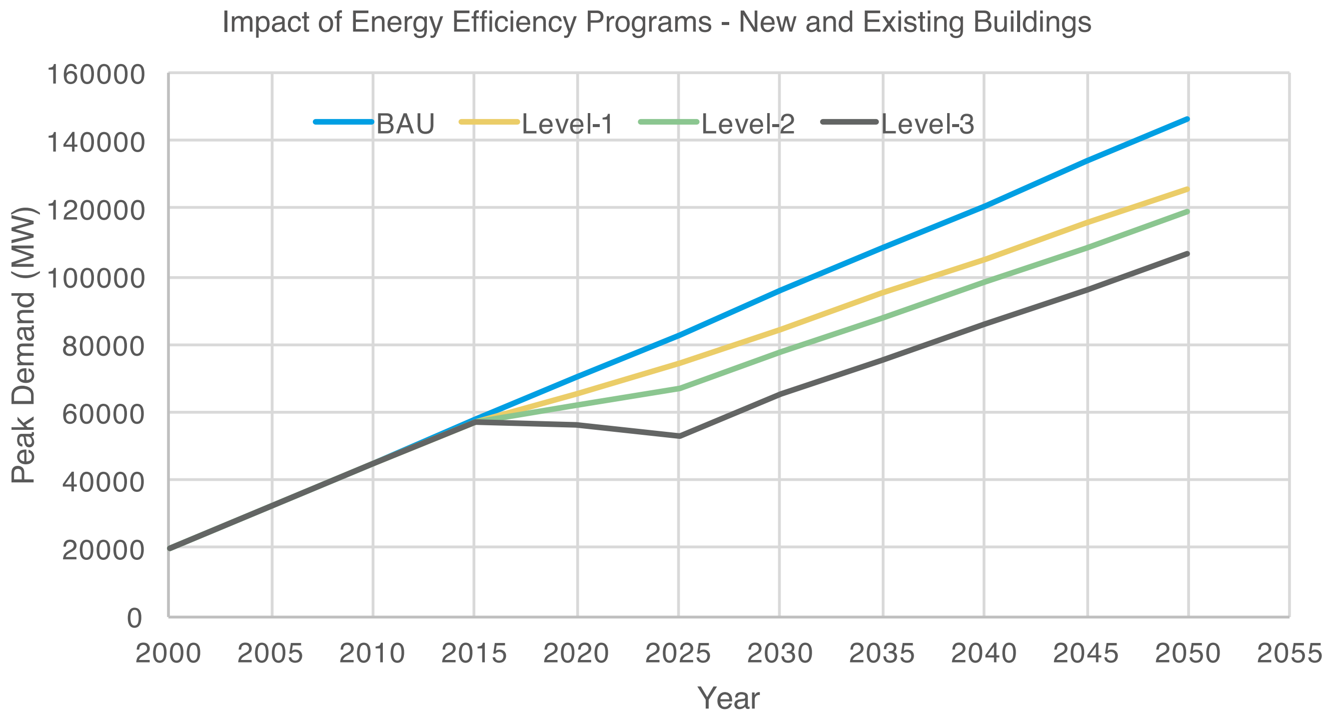


Figure 18. Scenario 4: Enhanced code retrofit for entire building stock including new construction.

Source: KAPSARC.

Cost Benefit Analysis

The implementation cost for each level of building energy retrofit depends on several factors including the building size and physical conditions of the building energy systems. Based on various sources for the cost of labor and materials in KSA, the average costs of completing energy retrofit for buildings is estimated. (Krarti, Weatherization and energy efficiency improvement for existing homes: an engineering approach 2012, AECOM 2013, Ihm and Krarti, Design optimization of energy efficient residential buildings in Tunisia 2012, Ihm and Krarti, Design Optimization of Energy Efficient Residential buildings in MENA region 2014.)

Table 8 summarizes the implementation costs for the three levels of energy retrofit specific to residential, commercial and government buildings including costs for performing energy audits. Buildings in the 'others' category are made up of hospitals and mosques, and it is assumed that the costs for energy retrofits of these facilities are the same as those considered for government buildings.

Based on 2013 building stock data, a retrofit of the entire building stock would require investments of $10 billion, $104 billion and $207 billion for Level-1, Level-2 and Level-3, respectively. While significant in the context of ongoing capital investment in the building stock, it is not an exceptional amount. For instance, the government allocated SAR 969 billion ($258 billion) to real estate in its targeted investment plan (2015-2019) as part of its comprehensive growth strategy tabled at the G-20 Summit in Brisbane in 2014. In other research, KAPSARC has discussed energy efficiency financing mechanisms in detail.

Tables 9 and 10 summarize the results from the cost benefit analysis. The cost-effectiveness of the programs depends largely on the estimated avoided costs for electricity consumption.

Using cost of production and international benchmark prices, taken from ECRA's 2014 Annual Report (ECRA 2014), to give a range of the potential effect, we explore two scenarios for estimating the

Table 8. Average costs for energy retrofits of total building stock (USD).

Building Type	Level 1	Level 2	Level 3
Residential Buildings	500	5,000	10,000
Commercial Buildings	5,000	50,000	100,000
Governmental Buildings	7,500	75,000	150,000
Others	7,500	75,000	150,000
Total	16,105	46,303	100,659

Source: KAPSARC.

cost-effectiveness of energy efficiency programs for existing buildings:

- A price of electricity at $0.0479/kWh (based on the current stated cost of power production in Saudi Arabia)
- A price of electricity at $0.1678/kWh (the opportunity cost of power production based on international prices).

The cost of constructing new power plants in KSA is taken to be $1,700/kW (ECRA 2014).

Based on the electricity costs considered, implementation of retrofit programs for all existing buildings is only cost-effective when the opportunity electricity prices (i.e., $0.1679/kWh) are considered.

The residential building stock offers the most cost effective investment option with Level-1 retrofit yielding a net benefit to even the private investor when electricity costs of $0.0479/kWh are considered. (Figure 19.)

From the government's perspective, a Level-1 retrofit program does not effectively require any net outlay since it provides sufficient savings from the reduction in peak electricity demand to avoid investing in additional power plants.

For residential buildings, Level-2 and Level-3 retrofit programs have a payback period of eight years and seven years, respectively, when opportunity costs of electricity are considered.

The implementation cost for a Level-3 retrofit program for the entire Saudi residential building stock is estimated at $56.73 billion.

As a reference, when oil prices were high the IMF estimated the implicit subsidy based on the opportunity cost of oil consumed domestically at $128.9 billion (International Monetary Fund 2015). Thus, investment in large-scale retrofit would represent a substantial benefit to Saudi society, if the international price of oil properly represented the opportunity cost, especially when oil prices are high.

Table 9. Cost benefit analysis of investments in entire existing building stock energy retrofit options for the government.

Retrofit Level	Total Retrofit Cost (Million $)	Peak Demand Savings (Million $)	Annual Energy Cost Savings (Million $/year)		NPV Payback Analysis* (Years)	
			(Million $)	$0.1678/kWh	$0.0479/kWh	$0.1678/kWh
Level-1	10,369	4,402	772	2,703	8.9	2.3
Level-2	103,695	12,655	2,218	7,769	-	14.7
Level-3	207,390	27,511	4,822	16,891	-	13.0

Source: KAPSARC.

Note (*): net present value analysis assumes a discount rate of 3%.

Table 10. Cost benefit analysis of investment in residential building stock energy retrofit options for the government.

Retrofit Level	Total Retrofit Cost (Million $)	Peak Demand Savings (Million $)	Annual Energy Cost Savings (Million $/year)		NPV Payback Analysis* (Years)	
			$0.0479/kWh	$0.1678/kWh	$0.0479/kWh	$0.1678/kWh
Level-1	2,836	2,748	480	1,686	0.2	0.1
Level-2	28,365	7,900	1,385	4,851	20	4.6
Level-3	56,730	17,174	3,010	10,545	17	4.0

Source: KAPSARC.

Note (*): net present value analysis assumes a discount rate of 3%.

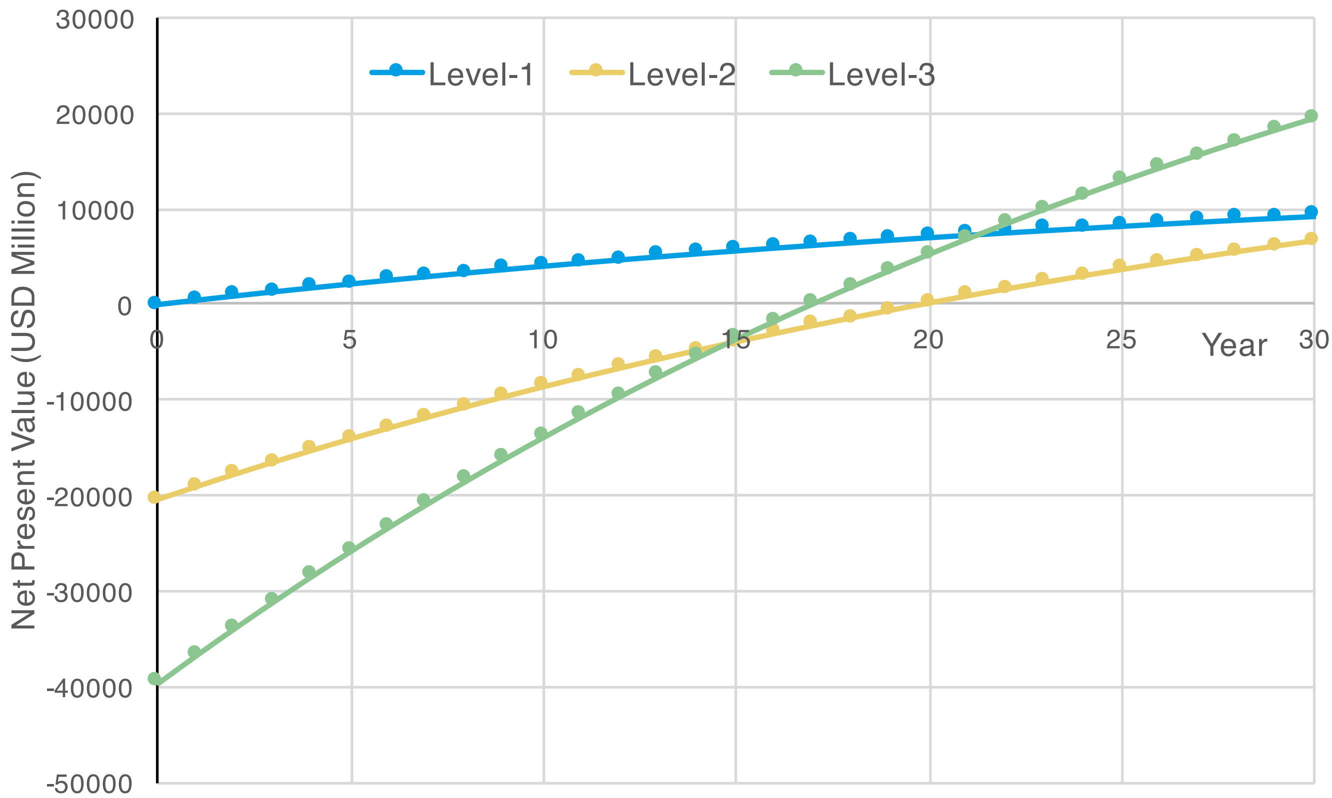


Figure 19. Payback period of investment options in residential building stock for the government at $0.0479/kWh.

Source: KAPSARC.

Carbon Reduction Benefits

Table 11 provides estimates for the annual CO_2 emissions reductions for various energy efficiency programs considered in this analysis for both new and existing buildings. The carbon emissions for generating electricity within KSA is taken to be 0.757 $kgCO_2/kWh$ (International Energy Agency 2015).

Table 11. Carbon emission reduction estimates for energy efficiency investment options expressed in kton per year.

Building Type	New Buildings			Existing Buildings		
	Insulation Only	Performance based	Net-Zero Energy	Level 1 Retrofit	Level 2 Retrofit	Level 3 Retrofit
Residential	357	828	1,426	7,611	21,882	47,569
Commercial	112	260	448	2,392	6,877	14,951
Governmental	78	180	312	1,658	4,768	10,365
Others	25	58	100	530	1,525	3,314
Total	571	1,326	2,286	12,192	35,051	76,199

Source: KAPSARC.

Job Creation Benefits

Another major benefit of a large-scale energy efficiency investment program is its potential to create new jobs. The direct effects for retrofitting buildings include jobs needed to implement the energy efficiency measures while the indirect effects are associated with the jobs needed to produce and supply energy efficiency equipment and materials. Most of the jobs created in building retrofits are in the construction and manufacturing industries with a wide range of pay level and technical specialization including electricians, HVAC technicians, insulation installers, energy auditors, building inspectors and construction managers.

Using the job creation model considered in the analysis of Krarti (Krarti, Evaluation of large scale building energy efficiency retrofit program in Kuwait 2015), up to 246,800 new jobs could be created when the existing building stock is retrofitted during a 10-year period using Level-3 program in KSA (Table 12). It should be noted that retrofitting commercial buildings can generate significantly more jobs than in the residential sector regardless of the retrofit level.

Table 12. Number of Jobs that can be created from 10-year Building Energy Retrofit Programs.

Building Type	Level 1	Level 2	Level 3
Residential Buildings	3,375	33,754	67,509
Commercial Buildings	6,872	68,715	137,430
Governmental Buildings	1,172	11,722	23,443
Others	921	9,207	18,413
Total	12,339	123,398	246,794

Source: KAPSARC.

Conclusion and Policy Implications

This paper has investigated options to improve the energy efficiency of the building stock in Saudi Arabia. Among the benefits investigated in this analysis are: reducing the pressure on utilities from rapidly rising electricity demand, lowering peak demand pressures and the need for new power plants, cutting carbon emissions and improving the environment, as well as the creation of a significant number of employment opportunities.

Our analysis highlights a pathway of domestic energy efficiency reforms from the most feasible and cost effective measures through to more ambitious programs, such as the implementation of Net Zero energy buildings. It is found that the implementation of energy efficiency programs for new and existing buildings has a significant potential to reduce both electricity consumption (27 percent) and peak electricity demand (30 percent), for instance, among the options for the next steps in the reform path we show how:

> The application of thermal insulation for new buildings can provide savings of 755 GWh/year in annual energy consumption, 172 MW in peak demand reduction and 571 10^3 tonnes/year in annual carbon emissions.

> If a more stringent building energy efficiency code is developed and enforced for newly constructed buildings, KSA could reduce its energy consumption by 1,751 GWh/year, peak demand by 486 MW and carbon emissions by 1,611 10^3 tonnes/year.

> A Level 1 energy retrofit of residential buildings (installation of programmable thermostat, use of CFL or LED lighting and weatherization of building shell) is highly cost-effective even if the government has to finance all the implementation costs for the entire existing stock. Indeed, a Level 1 energy retrofit program when applied to existing KSA residential building stock could achieve savings of 10,054 GWh/year in electricity consumption, 2,290 MW in peak demand and 7,326 10^3 tonnes/year in carbon emissions.

Key recommendation of our analysis include:

> Ensuring that the current KSA building energy efficiency code is implemented and enforced for all new buildings. The code should be reviewed and updated at least once every 5 years to include progress in proven energy efficiency technologies.

> Implement gradually a mandatory energy efficiency retrofit program for the residential building sector, then for the entire existing building stock. A Level 1 energy retrofit is highly recommended to replace inefficient lighting and air conditioning systems. This retrofit program is highly cost effective.

> Review energy prices to ensure that a developing market for energy efficiency can be cost-effective for all buildings.

This paper has shown that when wider system benefits are incorporated into the analysis of energy efficiency investment options, their attractiveness to government is significantly enhanced. While we have focused on Saudi Arabia, future research in this area can usefully explore in more detail this energy productivity potential for other GCC countries.

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Glossary

Acronyms:

CDD: Cooling Degree Days

CFL: Compact Fluorescent Lamp

COP: Coefficient of Performance

EEM: Energy Efficiency Measure

EER: Electrical Efficiency Ratio

GCC: Gulf Cooperation Council

GDP: Gross Domestic Product

HDD: Heating Degree Days

HVAC: Heating, Ventilating and Air Conditioning

KSA: Kingdom of Saudi Arabia

LCC: Life Cycle Cost

MENA: Middle East and North Africa

NZEB: Net Zero Energy Building

PV: Photovoltaic

SASO: Saudi Arabia Standard Organization

SBC: Saudi Building Code

SEC: Saudi Electricity Company

SEEC: Saudi Energy Efficiency Center

SEEP: Saudi Energy Efficiency Program

WWR: Window to Wall Ratio

Symbols

LCC: Life Cycle Cost [expressed in $]

N: Life Period [defined in years]

rd: Annual Discount Rate [provided in %]

RSI: Thermal resistance of building materials including insulation [expressed in m^2.K/W]

USPW: Uniform Series Present Worth factor [defined by Equation (2) and expressed in years]

Appendix A: Outline of Saudi Building Code Energy Conservation Requirements

The energy conservation requirements section 601 in the Saudi Building Code (SBC) was developed to provide the required standard of energy efficient building components such as the building envelope, mechanical systems, electrical systems, lighting fixtures, domestic water heating systems (Saudi Code National Committee 2007). The KSA energy conservation code is based on the International Energy Conservation Code (IECC) and ASHRAE standard 90.1. Specifically, the SBC energy conservation section covers both residential and commercial buildings, with chapters 3, 4 and 5 aimed specifically at residential buildings. Detached family dwellings with a window to wall ratio (WWR) of 15 percent and less have to meet the requirements outlined in Chapter 5. On the other hand, chapters 3 and 4 are used for detached family dwellings that have more than 15 percent glazing area. In addition, chapters 3 and 4 cover townhouses and residential buildings that have 25 percent glazing area or more. Townhouses and residential buildings with less than 25 percent glazing area have to meet the requirements provided in Chapter 5 of the code.

Two compliance approaches are considered: prescriptive and performance. For the prescriptive compliance approach, specific minimum performance levels are defined for building features such as wall/roof/window thermal resistances, thermal mass, air infiltration rate, lighting power density, efficiency of heating and cooling systems. These minimum levels are defined for various climates using the cooling degree-days (base 18 °C) of each location estimated from 1993-2003 data obtained from the Meteorology and Environmental Protection Administration in Saudi Arabia. For the performance based compliance approach, two types of designs are considered and referred to in the code: the standard design and the proposed design. The standard design is the baseline building that complies with the prescriptive requirements of the energy efficiency code. While the proposed design is the actual design that can be considered in compliance with the code if the energy consumption for this design is the same or less than the annual energy used by the standard design. Both the standard and proposed designs have to have similar conditioned floor area, geometry, mechanical systems, operational schedules and also climate and design conditions.

In Chapter 3, the U-factors requirements of the exterior wall assemblies are provided based on the building location cooling degree-days. The lowest U-factor is 0.483 defined for cooling degree-days less than 1,400 °C-days. While the highest U-factor is 0.216 and is required for locations with cooling degree-days that are higher or equal to 7,230 °C-days. The fenestration U-factors are also selected according to the location cooling degree-days. The window U-factors range from 4.2 to 1.42 depending on the cooling degree-days.

It should be noted that exterior shading is not required in the standard design, while it is recommended to add exterior window shading in the proposed design. The solar heat gain coefficient (SHGC) for the fenestration system in the standard design is required to be equal to 0.4 for cooling degree days (CDD) less than 1,950 and 0.68 for CDD more or equal to 1,950. It should be noted that the fenestration system consists of both glazing and frame of the windows.

Cooling and heating indoor temperature settings for residential buildings are specified to be 25.5°C for cooling mode and 20°C for heating mode. The allowable temperature setback is 2.8°C. There has to be at least one thermostat per zone, while the maximum number of zones per unit is two zones. Air infiltration is expressed using an annual average air change per hour (ACH), and is calculated using the following equation:

$$ACH = Normalized\ Leakage\ x\ Weather\ Factor \quad (A1)$$

In this case, the Normalized Leakage is equal to 0.57 and the Weather Factor is provided by ASHRAE 136. The internal heat gains are estimated using the equation provided:

$$Internal\ Heat\ Gains = 17{,}900 + (23.8 \bullet CFA) + (4140 \bullet BR) \quad (A2)$$

where CFA is the conditioned floor area and BR is the number of bedrooms. The code also requires that the thermal mass (heat storage) of the internal walls should be equal to 39 and for the exterior walls 17 when performing the annual energy simulation.

Chapter 4 in the SBC-601 defines the overall performance of the residential buildings using the performance compliance approach. For this approach, the U-factor of the exterior walls, roofs and floor slabs are selected based on degree-days. The fenestration solar heat gain coefficient (SHGC) should not exceed 0.4 for locations with CDD less than 1950°C-days. For a high thermal mass wall with a heat capacity of 1 or greater, U-factor is selected based on degree-days and the position of the thermal insulation layer. Other U-factor values are selected for walls with heat capacity less than 1. The minimum U-factors of the windows are based on the window to wall ratio (WWR) of the building. Specific requirements for both R-values and U-factors are provided in several tables listed in the SBC-601 for buildings with window area less or equal to 8 percent, 12 percent, 15 percent, 18 percent, 20 percent and 25 percent for the detached family dwellings.

Chapter 5 in the SBC-601 provides the simplified prescriptive energy efficiency requirements for detached family dwellings and townhouses.

The energy efficiency requirements provided in this chapter are specific for family dwellings with window area not exceeding 15 percent, in addition to townhouses with window area not exceeding 25 percent. In particular, the minimum required thermal performance for exterior walls, ceilings, floors, basement walls, slab perimeters, crawl space walls, and windows are specified in Tables listed in the SBC. The required R-values and U-factor values are based on degree-days associated with each location. A sample of the minimum required thermal performance values for various building envelope components is shown in The R-value selection of massive walls is provided in the code and is varied based on the thermal insulation layer position and climatic zone (using cooling degree days). As a reference, a solid concrete wall with 102 mm thickness has R-value equivalent to R=1.1 $m^2.^oC/W$. A sample of thermal mass wall requirements is shown in Table A-14.

Table A-13. The R-value selection of massive walls is provided in the code and is varied based on the thermal insulation layer position and climatic zone (using cooling degree days). As a reference, a solid concrete wall with 102 mm thickness has R-value equivalent to R=1.1 $m^2.^oC/W$. A sample of thermal mass wall requirements is shown in Table A-14.

Finally, it is required by the code to utilize an approved simulation tool for both the standard and proposed design for a detailed energy performance evaluation of each building through a full 8,760 hours operation period. ASHRAE Fundamentals Handbook should be used to obtain the required design data.

By forcing building owners and contractors to fulfill the minimum requirements, it is hoped that the developed energy efficiency code for buildings can have a great impact on reducing electricity consumption.

Table A-1. Simplified Prescriptive Building Envelope Thermal Component Criteria Minimum Required Thermal Performance.

Degree Days ⁰C	Maximum	Minimum					
	Glazing U-factor W/ m² . K	Ceiling R-value m² . K/W	Wall R-value m² . K/W	Floor R-value m² . K/W	Basement Wall R-value m² . K/W	Slab Perimeter R-value and Depth	Crawl Space Wall R-value
0 - 279	Any	R-2.3	R-1.9	R-1.9	R-0	R-0	R-0
280 - 559	5.11	R-3.3	R-1.9	R-1.9	R-0	R-0	R-0.7
560 - 829	4.26	R-3.3	R-1.9	R-1.9	R-0	R-0	R-0.9
830 - 1109	4.26	R-4.6	R-2.3	R-1.9	R-0.9	R-0	R-0.9
1110 - 1389	3.69	R-5.3	R-2.3	R-1.9	R-0.9	R-0	R-1
1390 - 1669	3.41	R-5.3	R-2.3	R-3.3	R-1	R-0.7, 610mm	R-1.2
1670 - 1949	3.12	R-5.3	R-2.3	R-3.3	R-1.2	R-0.7, 610mm	R-1.4
1950 - 2219	2.84	R-5.3	R-2.3	R-3.3	R-1.4	R-0.9, 610mm	R-1.8
2220 - 2499	2.56	R-6.7	R-2.3	R-3.3	R-1.4	R-0.9, 610mm	R-1.9
2500 - 27779	2.56	R-6.7	R-2.8	R-3.3	R-1.6	R-1, 610mm	R-3
2780 - 3059	2.56	R-6.7	R-3.2	R-3.3	R-1.6	R-1, 610mm	R-3
3060 - 3339	2.27	R-6.7	R-3.2	R-3.7	R-1.8	R-1.6, 1210mm	R-3.3
3340 - 3609	1.99	R-6.7	R-3.2	R-3.7	R-1.8	R-1.6, 1210mm	R-3.5
3610 - 3889	1.99	R-8.6	R-3.7	R-3.7	R-1.9	R-1.9, 1210mm	R-3.5
3890 - 4729	1.99	R-8.6	R-3.7	R-3.7	R-1.9	R-2.3, 1210mm	R-3.5
4730 - 4999	1.99	R-8.6	R-3.7	R-3.7	R-3.2	R-2.5, 1210mm	R-3.5
5000 -7229	1.99	R-8.6	R-3.7	R-3.7	R-3.2	R-3.2, 1210mm	R-3.5

Table A-2. Mass Wall Prescriptive Building Envelope Requirements.

Degree Days ⁰C	Mass Wall Assembly R-Value[a], m² . K/W	
	Exterior or Integral Insulation	Other Mass Walls
	Residential Buildings	Residential Buildings
0 - 279	R-0.7	R-1.7
280 - 559	R-0.8	R-1.7
560 - 829	R-0.8	R-1.7
830 - 1109	R-1.4	R-1.9
1110 - 1389	R-1.6	R-1.9
1390 - 1669	R-1.6	R-1.9
1670 - 1949	R-1.6	R-1.9
1950 - 2219	R-1.6	R-1.9
2220 - 2549	R-1.6	R-1.9
2500 - 2779	R-1.6	R-2.2
2780 - 3059	R-1.8	R-2.7
3060 - 3339	R-2.1	R-2.7
3340 - 3609	R-2.1	R-2.7
3610 - 3889	R-2.7	R-3.2
3890 - 4729	R-2.7	R-3.2
4730 - 4999	R-3.2	R-3.2
5000 - 7229	R-3.2	R-3.2

Source: SBC, 2007.

Appendix B: Overview of Sequential Search Optimization

Overview of the Optimization Technique

The optimization method used in the simulation environment identifies the optimal building design options from multiple possible alternatives using a sequential search methodology. This optimization approach is first applied to design zero-net energy (ZNE) buildings. A Sequential Search Technique for Identifying Optimal Building Designs on the Path to Zero Net Energy, 2004, (Horowitz, Enhanced sequential search strategies for identifying cost-optimal building designs on the path to net Zero energy 2003). It was also utilized for other applications including optimized selection of building shape, wall and roof constructions, and HVAC systems (Bichiou and Krarti 2011, Tuhus-Dubrow and Krarti 2010). Figure 4 illustrates the sequence search optimization approach to find a path that reaches the optimal package of EEMs that provides the lowest life cycle cost as defined by Eq. (B-1).

$$LCC = IC + USPW(N,rd) * EC \qquad \text{(B-1)}$$

where,

- *IC: is the initial cost for implementing all the design and operating features for both building envelope and HVAC system.*
- *EC: is the annual energy cost to maintain indoor comfort within the residential building for the selected design and operating features.*
- *USPW: is the uniform series present worth factor, which depends on the discount rate, rd and lifetime N.*

$$\mathrm{USPW}(\mathrm{N}, r_d) = \frac{1-(1+r_d)^{-N}}{r_d} \qquad \text{(B-2)}$$

The optimization method also finds the suboptimal path to design ZNE building. First, all the EEMs are considered individually for an initial building design with a specific life cycle cost. Then, the most cost-effective EEM option is chosen based on the steepest slope consisting of the LCC to energy savings ratio. The selected EEM optimal option is then removed from the parameter search space for future evaluation, and then the remaining EEMs are simulated to find the next optimal point. This process is repeated until the optimal solution is reached.

The advantage of the sequential search optimization methodology is to find multiple solutions, which include the optimal and near-optimal points as shown in Figure B-1 below to select a best combination of building design features. That is, the approach finds the intermediate optimal points for the minimum cost designs at various levels of energy savings. Indeed, the approach can provide in addition to the optimal solution, a set of options that achieve any set of desired energy use savings that reduces the life cycle cost before the optimal solution is reached. Thus, an optimal path to achieve various levels of energy use savings at the lowest life cycle costs can be obtained using the sequential search technique (Anderson, Christensen and Horowitz 2006) (Christensen, Barker and Horowitz, A Sequential Search Technique for Identifying Optimal Building Designs on the Path to Zero Net Energy, 2004) (Horowitz, Christensen, et al. 2008).

The developed simulation environment used in the optimization analysis is designed to easily accept and identify optimal packages of EEMs to reduce the life cycle costing of any residential or commercial building. It should be noted that the simulation environment can be extended and applied to any other type of buildings.

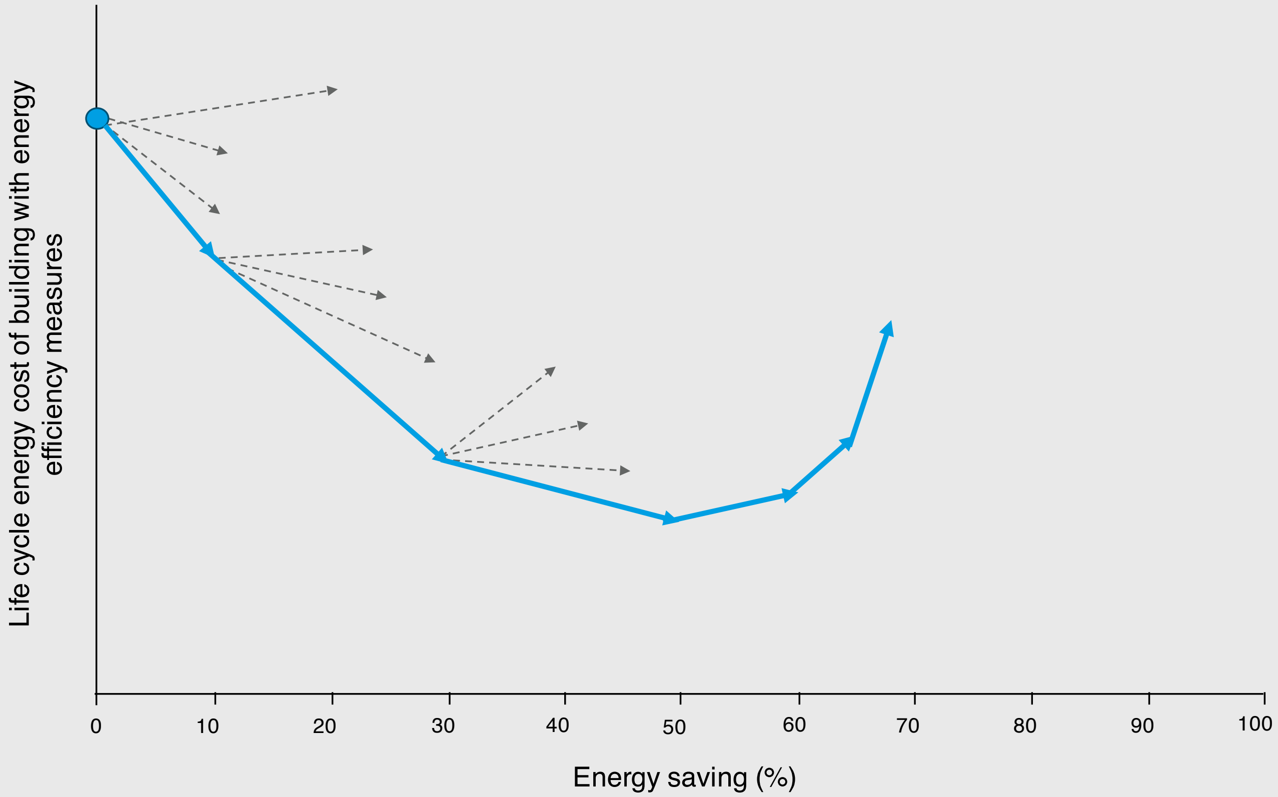

Figure B-1. Basic sequential search optimization approach to find optimal solution.

Source: KAPSARC.

Validation of Optimization Results

The results obtained from the sequential search optimization were compared with a 'brute force' search approach using the full combination options of energy efficiency measures to find the optimum design package for a prototypical single-family home by Ihm and Krarti (2015). The computational efforts required using the brute force search to find optimal design values for 11 EEMs (i.e., about 11.1 million possible combination of building design options) are significant and may take several months to complete using the current state-of-the art computing processors. Instead, three analysis cases were considered by Ihm and Krarti (2014) to validate the results of the sequential search optimization approach. The three cases considered by Ihm and Krarti (2014) consisted of different combinations of design options:

i. 4-EEM package: WWR, glazing type, lighting level, infiltration rate.

ii. 6-EEM package: Exterior wall insulation, roof insulation, WWR, glazing type, lighting level, Infiltration rate.

iii. 8 EEM package: Indoor and exterior wall insulation, roof insulation, WWR, glazing type, lighting level, infiltration rate, cooling set point.

Figures B-2 to B-4 validate the sequential search optimization results obtained for the three EEM-packages for a villa against those obtained with the full brute force approach (i.e., all combinations of options are considered) against those found by the sequential search optimization approach. The results in Figures B-2 through B-4 are presented in terms of life-cycle cost as a function of percent savings of total source building energy use. Table B-15 summarizes the comparative results for the brute force analysis and the sequential search optimization approach. As indicated in Figures B-2 through B-4 and Table B-1, the sequential search optimization technique finds the same optimum solutions found through the brute force technique for the three analysis cases. The computational time of the sequential search technique (4.6 minute) is significantly lower – up to 99.7 percent – when compared to the brute force analysis approach (28.9 hours) for the 8-EEM package analysis case using a 2.8-HGZ processor.

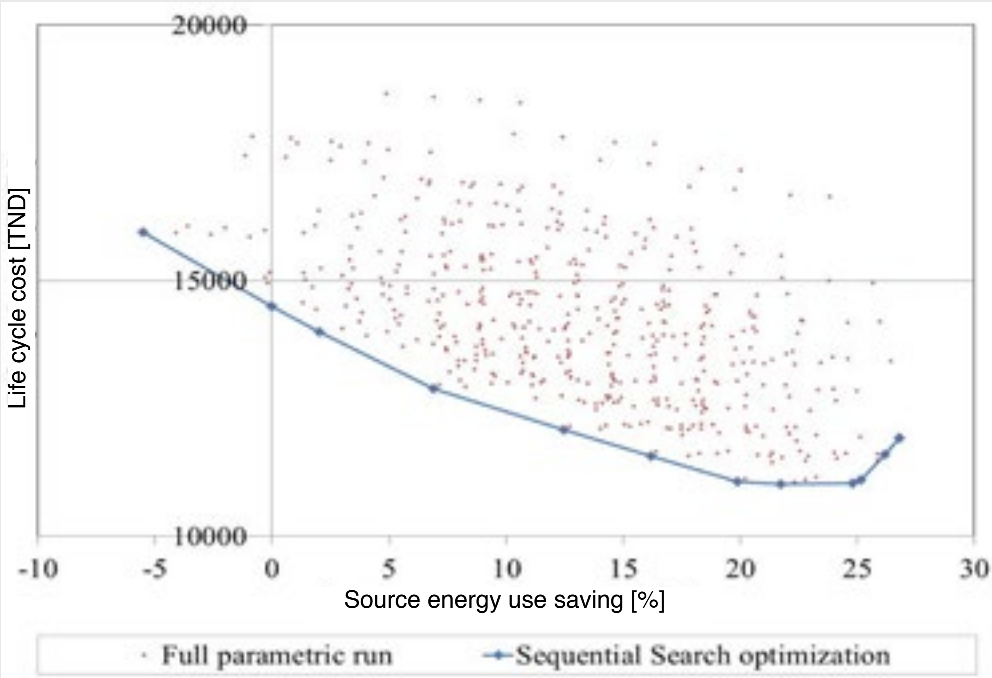

Figure B-2. Comparison of optimal results obtained by the brute-force analysis and the sequential search optimization for 4-EEM package for a villa.

Source: Ihm and Krarti, 2015.

Table 12. Number of Jobs that can be created from 10-year Building Energy Retrofit Programs.

Number of EEMs	Number of Possible building design options	Computing Time for Brute-Force Analysis [min]	Computing Time for Sequential Search [min]	Reduced CPU time [%]
4	480	7.0	2.1	69.9
6	7,680	123.5 (2.1 hour)	3.1	97.5
8	92,160	1,732.8 (28.9 hour)	4.6	99.7

Source: KAPSARC.

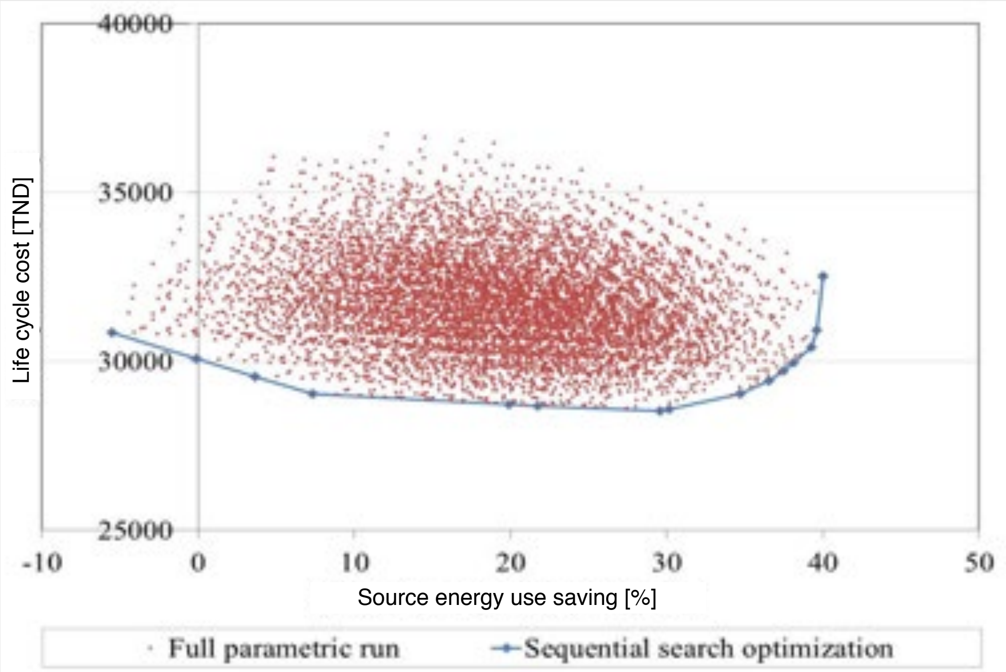

Figure B-3. Comparison of optimal results obtained by the brute force analysis approach and the sequential search optimization for the 6-EEM package for a villa.

Source: Ihm and Krarti, 2015.

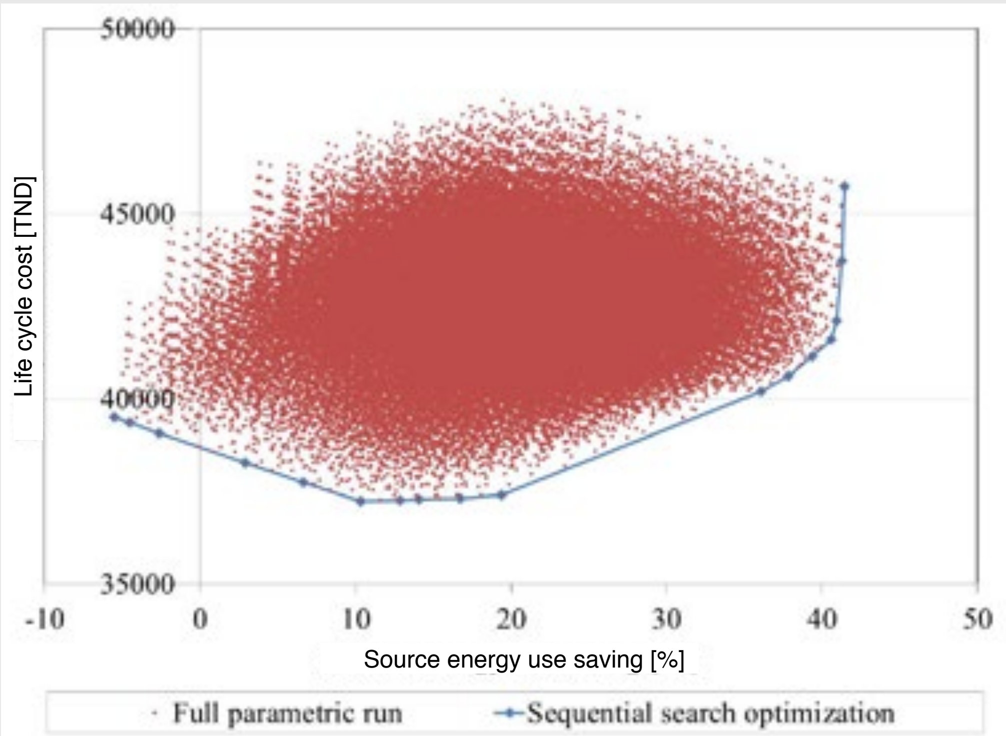

Figure B-4. Comparison of optimal results obtained by the brute force analysis approach and the sequential search optimization for the 8-EEM package for a villa.

Source: Ihm and Krarti, 2015.

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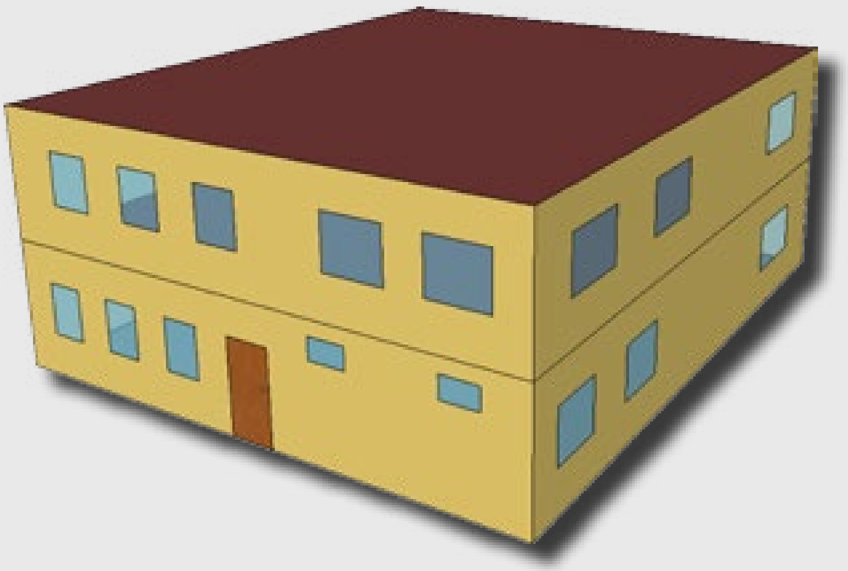
Appendix C: Description of the Residential Building Energy Model

The building construction details and HVAC specifications for the base-case energy model for the villa are summarized in Table C-1. Figure C-1 provides the floor plans and the 3-D rendering of the energy model of a villa considered for the parametric and optimization analyses of residential buildings in KSA and the GCC countries.

Table C-1. Building construction specifications for the prototypical villa.

Number of stories	2
Total height	7.0 m
Floor dimensions	15.0 m × 17.5 m
Gross floor area	525
Gross wall area	455
Window area	13.29% of Gross wall area
Type of glass	Single pane window
External walls	20 mm plaster outside + 200 mm concrete hollow block + 20 mm plaster inside
Roof	10 mm built-up roofing + 150 mm concrete roof slab + 12.7 mm plaster inside
Floor	150 mm slab on grade
Number of occupants	6
Lighting	3.0 kW (lower level), 2.0 kW (upper level)
Appliances	2.0 kW (lower level), 1.0 kW (upper level)
HVAC system type	Constant Volume DX Air-Cooled A/C System with Electric Heating
Temperature settings	22.2°C (72°F) for heating and 24.4°C (76°F) for cooling
COP	2.17

Source: Alaidroos and Krarti, 2015.



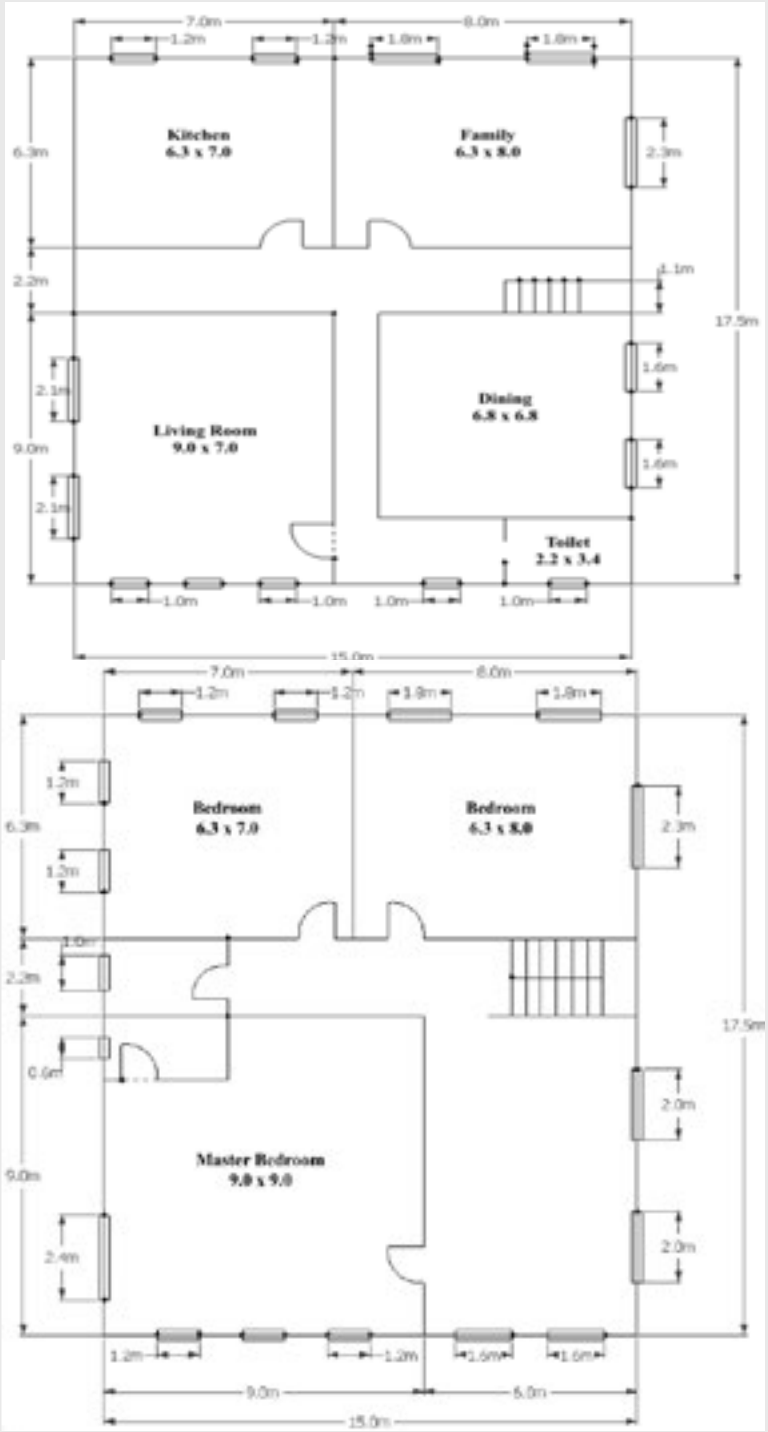


Figure C-1. Model for the prototypical villa (a) 3-D rendering, (b) ground floor layout plan, and (b) first floor layout plan.

Source: Alaidroos and Krarti, 2015.

In the optimization analysis, common and easy to implement design and operating energy efficiency measures (EEMs) are considered to improve the energy efficiency of the prototypical residential building. Table C-3 lists 11 EEMs considered for the optimization analysis including building envelope, lighting, appliances, temperature settings and HVAC systems. All possible options are listed in Table C-3 for each EEM with the baseline design option highlighted in bold. In addition to the EEMs, PV systems with various kW ratings are considered in order to reach net zero energy design.

Table C-3. Design measures, their associated options for a residential building.

EEM	Specification	Options
Azimuth	Orientation of the building relatively to the north	**0**, 45, 90, 135, 180, 225, 270
Exterior wall Construction	Wall insulation (Outdoor installation)	**No insulation** RSI-1.0 (R-5.7) Polystyrene (2cm thickness) RSI-2.0 (R-11.4) Polystyrene (4cm thickness) RSI-3.0 (R-17.0) Polystyrene (6cm thickness
Roof Construction	Roof insulation	**No insulation** RSI-1.0 (R-5.7) Polystyrene (2cm thickness) RSI-2.0 (R-11.4) Polystyrene (4cm thickness) RSI-3 .0 (R-17.0) Polystyrene (6cm thickness)
WWR	Window to Wall Ratio	**10%**, 20%, 25%, 30%, 40%
Window Type	Glazing type for window	**Single Clear (6mm, U: 6.172 W/m².°C)** Single Bronze (6mm, U: 6.172 W/m².°C) Single Low-e (6mm, U: 4.270 W/m².°C) Double Clear (6/6/6mm, U: 3.163 W/m².°C) Double Bronze (6/6/6mm, U: 3.160 W/m².°C) Double Low-e (6/12/6mm, U: 1.658 W/m².°C)
Lighting Density	Building Lighting Level	**Typical (7.3 W/m²)** 30% Reduction 50% Reduction 70% Reduction
Infiltration	Air Infiltration Level	**Typical (0.7 L/s/m²)** 25% Reduction (i.e., 0.63 ACH) 50% Reduction (i.e., 0.42 ACH) 75% Reduction (i.e., 0.21 ACH)
Cooling Set point	Temperature Set-Point for cooling	24°C (75.2°F), 25°C (77°F), 26°C (78.8°F)
Refrigerator	Electricity Consumption Level	**Typical (180W: 800 kWh/year)** Class 3: 30% Reduction Class 2: 45% Reduction Class 1: 65% Reduction
Air conditioner	Coefficient of Performance (COP)	**2.2** 2.6 3.0 3.3 3.5

Source: KAPSARC.

Note: Insulation R-value is expressed in RSI (m².ºC/W) and R (hr.ft².ºF/Btu).

Appendix D: Sensitivity Analysis for KSA Residential Buildings

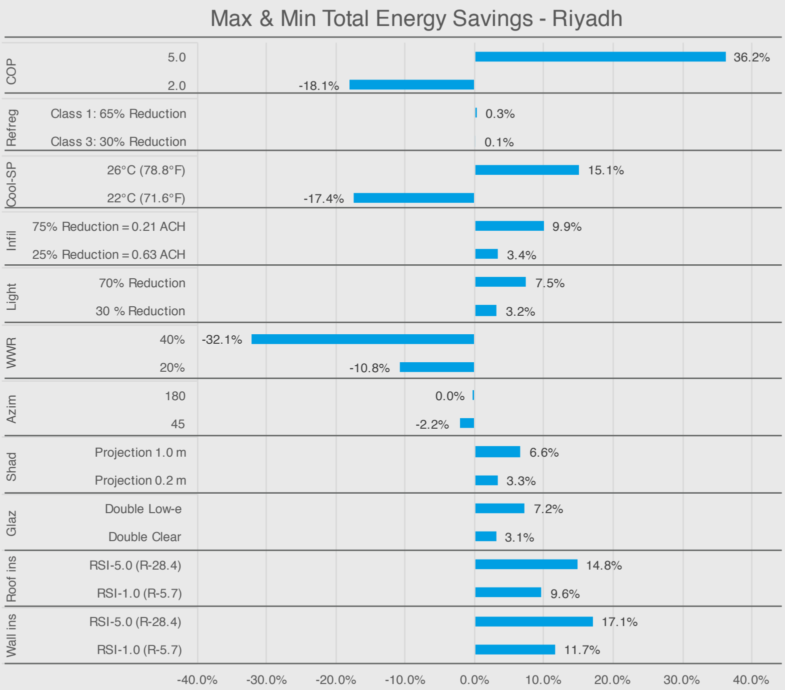


Figure D-1. Impact of design and operation parameter values on annual energy consumption for a villa in Riyadh.

Source: KAPSARC.

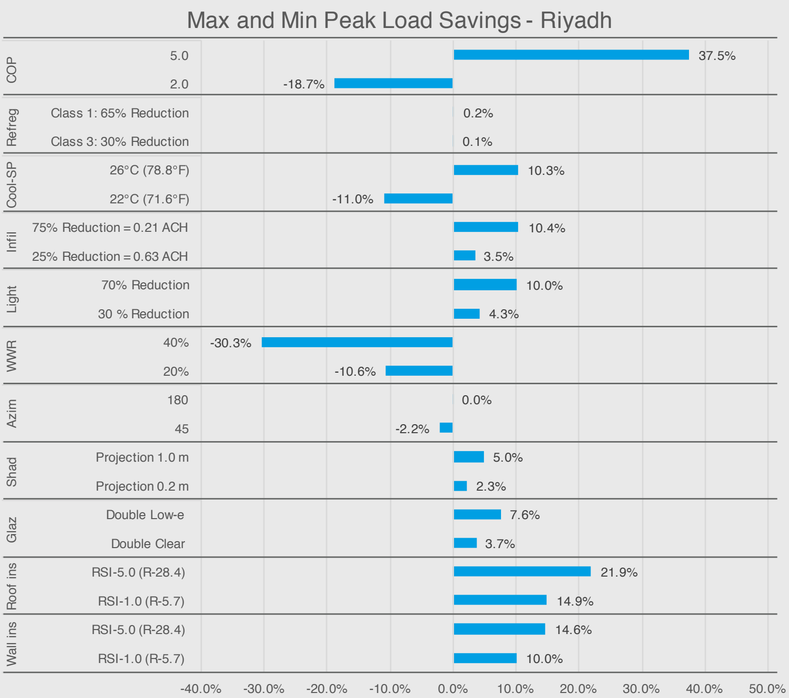


Figure D-2. Impact of design and operation parameter values on peak electricity demand for a villa in Riyadh.

Source: KAPSARC.

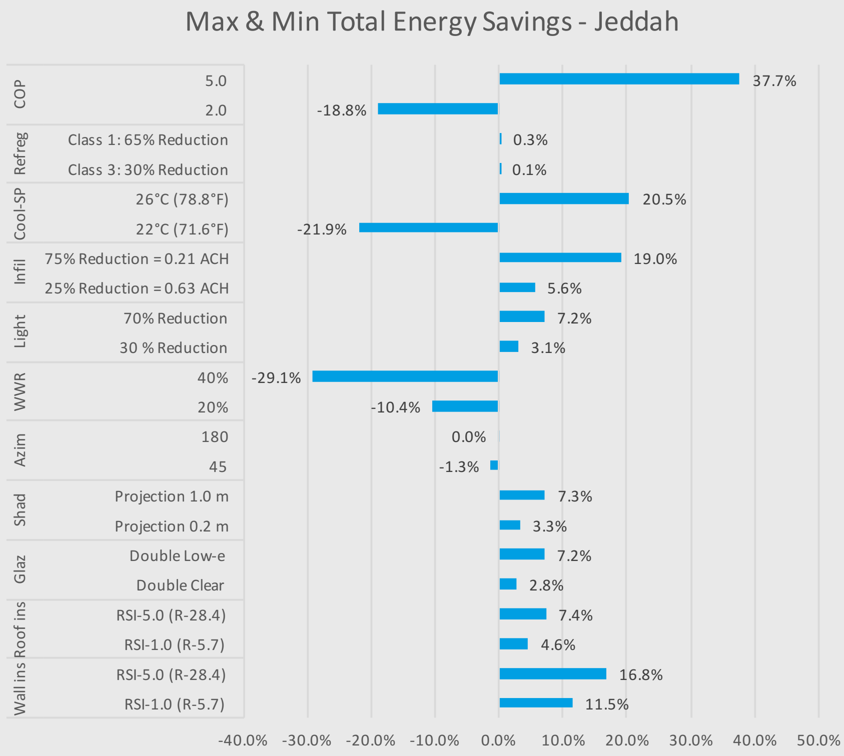


Figure D-3. Impact of design and operation parameter values on annual energy consumption for a villa in Jeddah.

Source: KAPSARC.

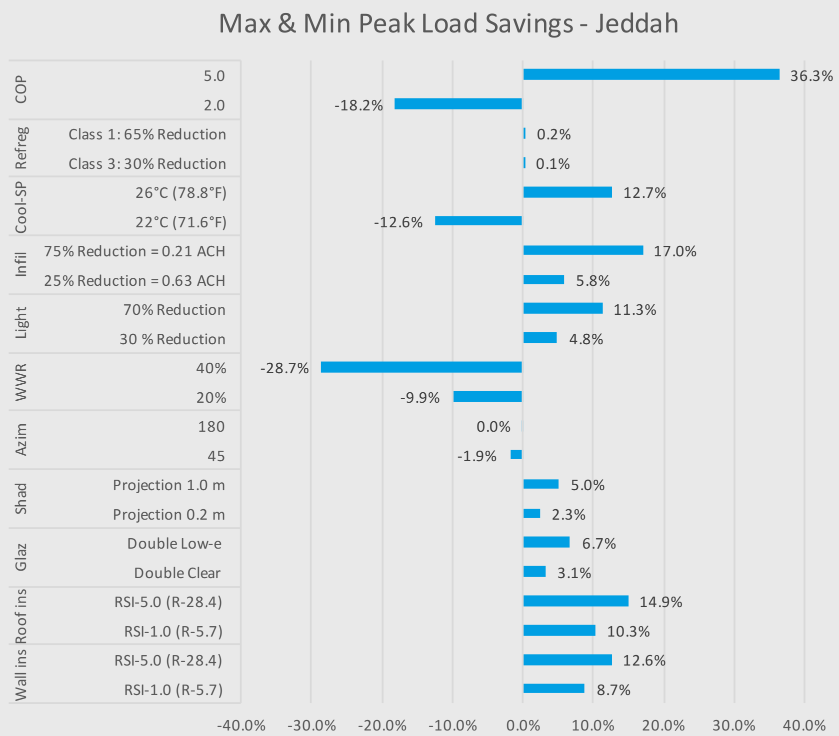


Figure D-4. Impact of design and operation parameter values on peak electricity demand for a villa in Jeddah.

Source: KAPSARC.

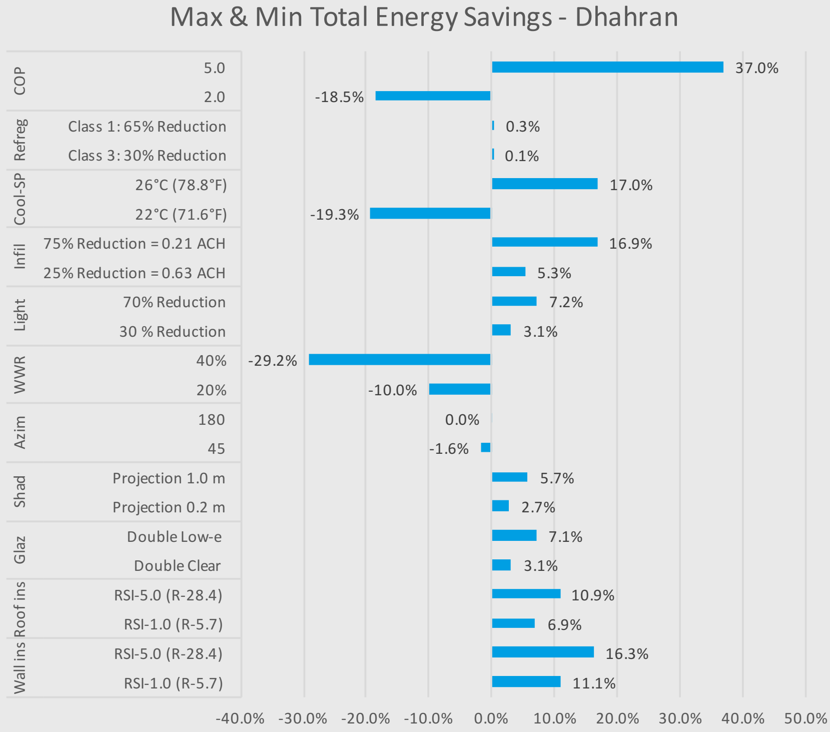


Figure D-5. Impact of design and operation parameter values on annual energy consumption for a villa in Dhahran.

Source: KAPSARC.

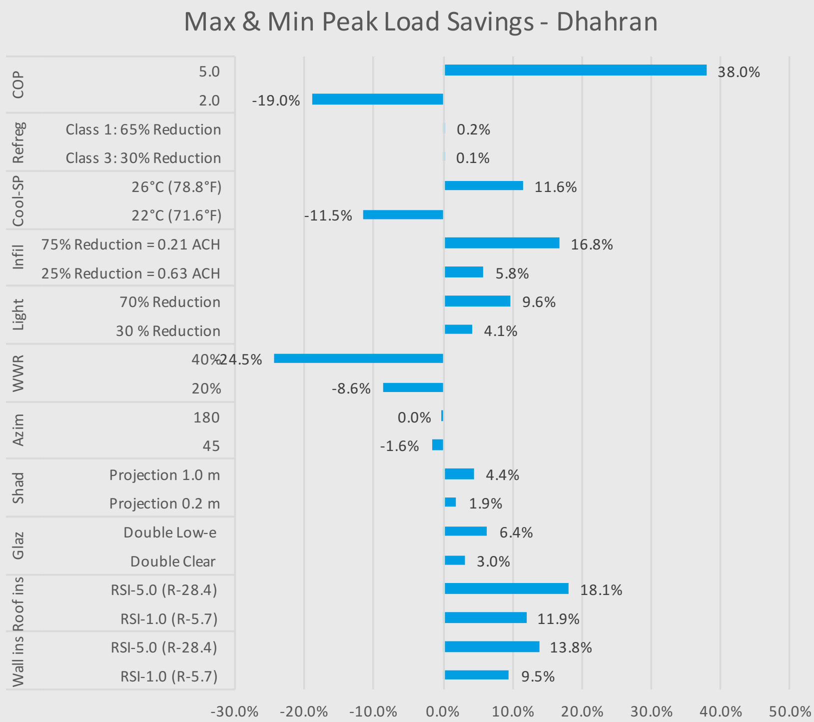


Figure D-6. Impact of design and operation parameter values on peak electricity demand for a villa in Dhahran.

Source: KAPSARC.

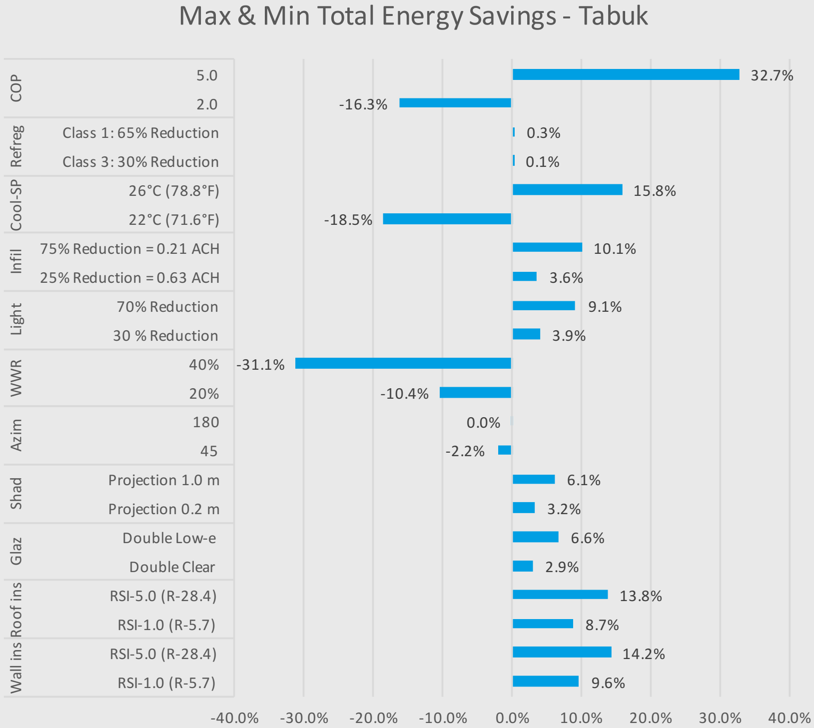


Figure D-7. Impact of design and operation parameter values on annual energy consumption for a villa in Tabuk.

Source: KAPSARC.

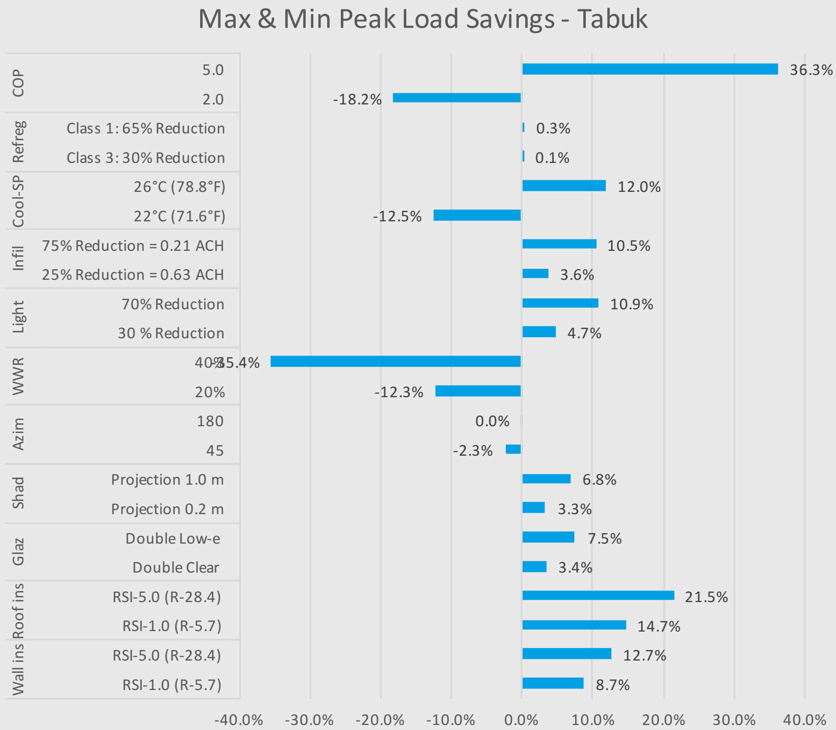


Figure D-8. Impact of design and operation parameter values on peak electricity demand for a villa in Tabuk.

Source: KAPSARC.

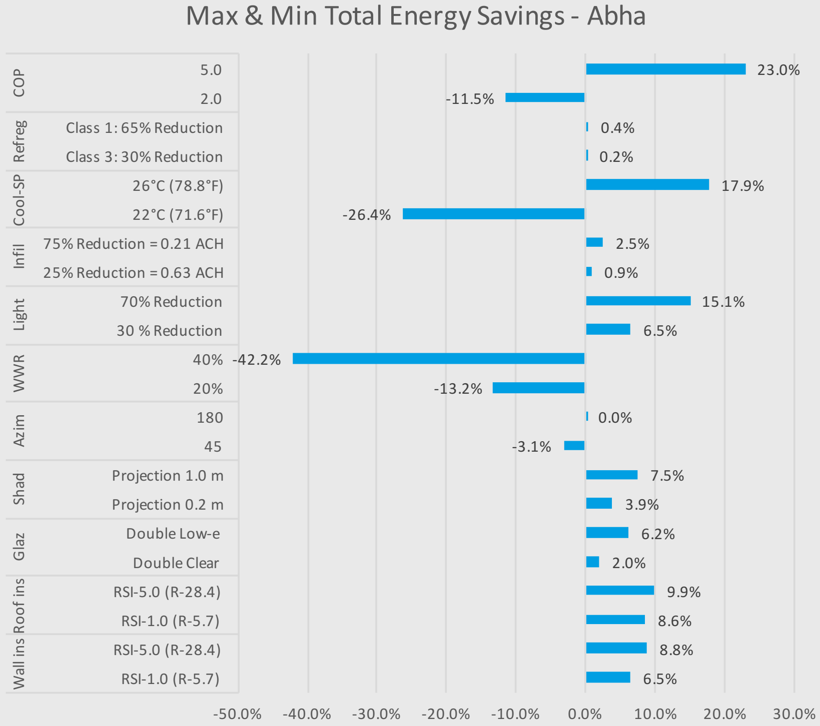


Figure D-9. Impact of design and operation parameter values on annual energy consumption for a villa in Abha.

Source: KAPSARC.

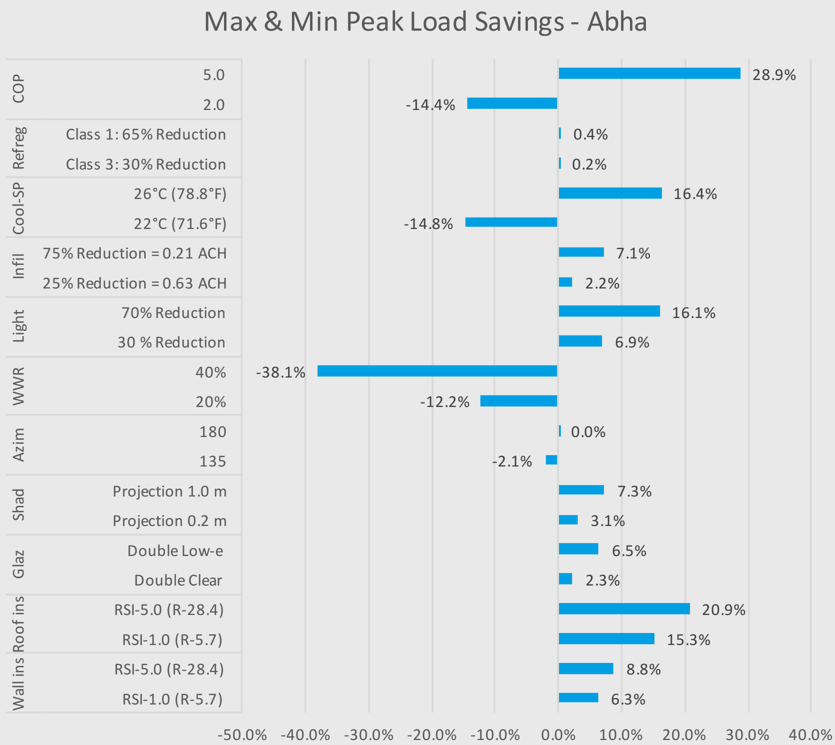


Figure D-10. Impact of design and operation parameter values on peak electricity demand for a villa in Abha.

Source: KAPSARC.

Appendix E: Optimization Results for KSA Residential Buildings

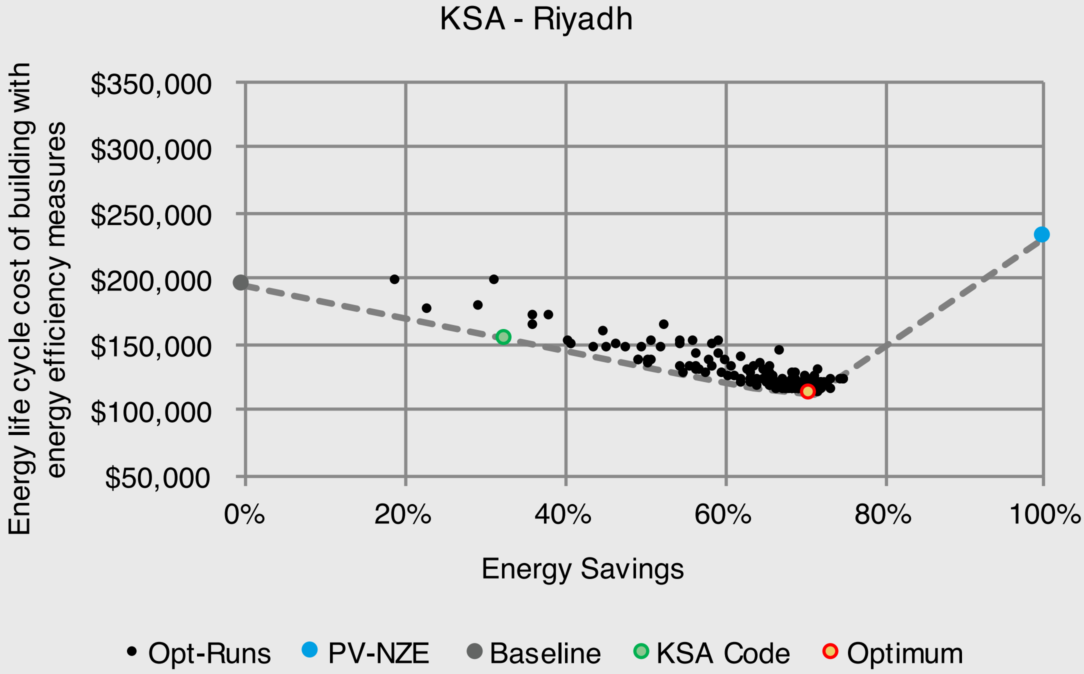


Figure E-1. Optimal path toward NZEB residential building in Riyadh.

Source: KAPSARC.

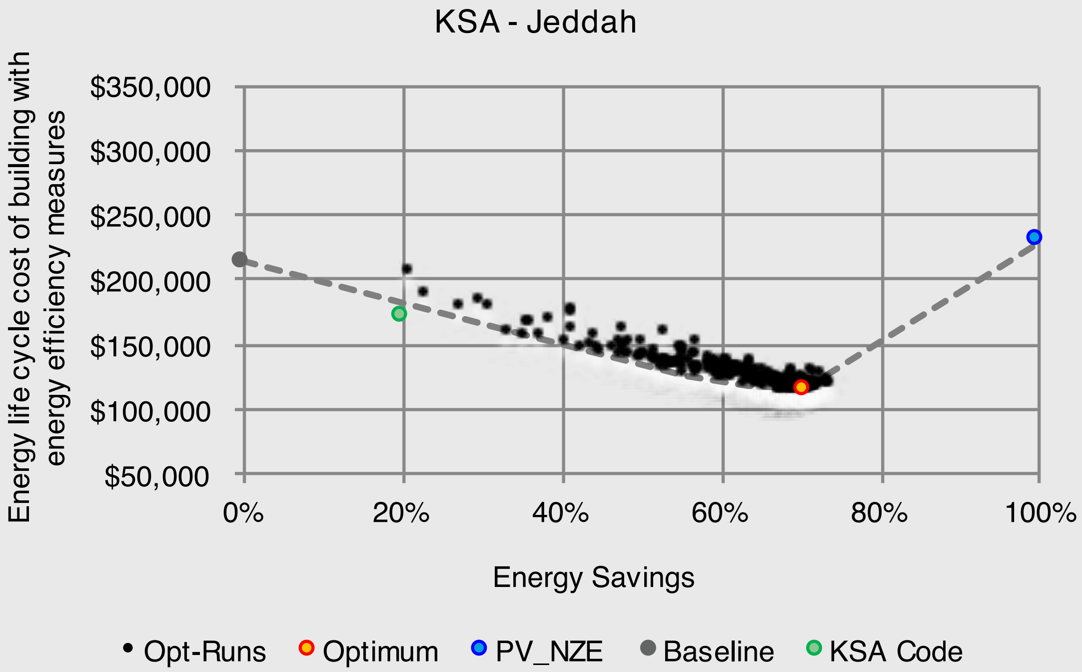


Figure E-2. Optimal path toward NZEB residential building in Jeddah.

Source: KAPSARC.

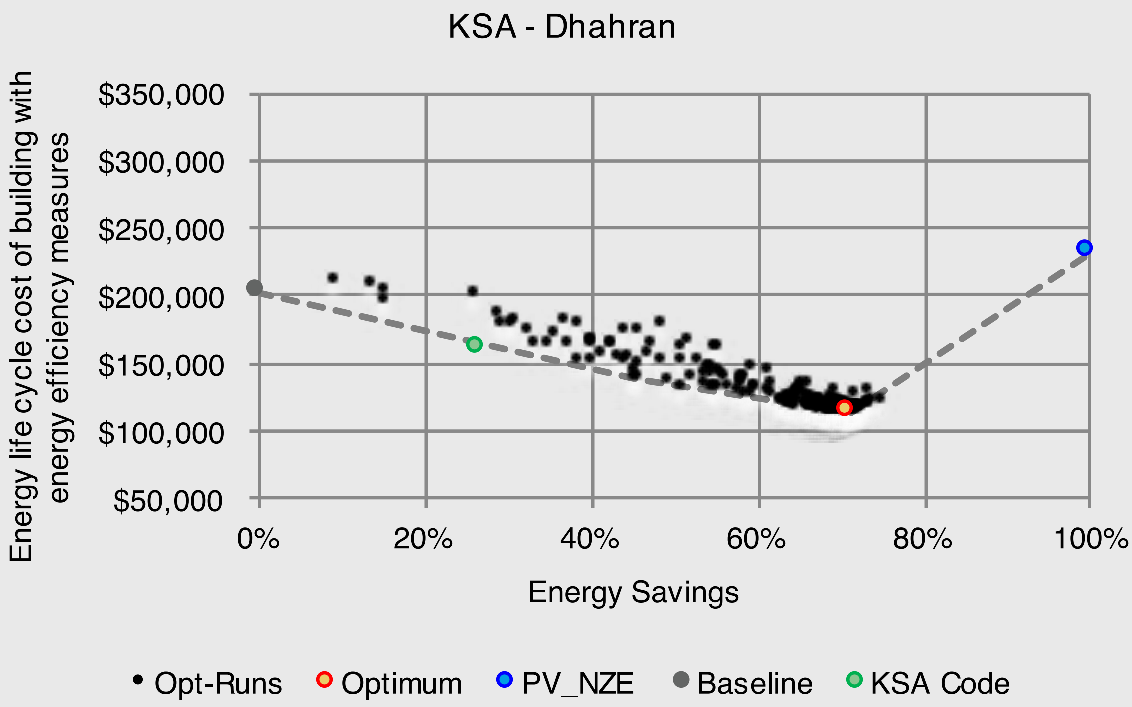


Figure E-3. Optimal path toward NZEB residential building in Dhahran.

Source: KAPSARC.

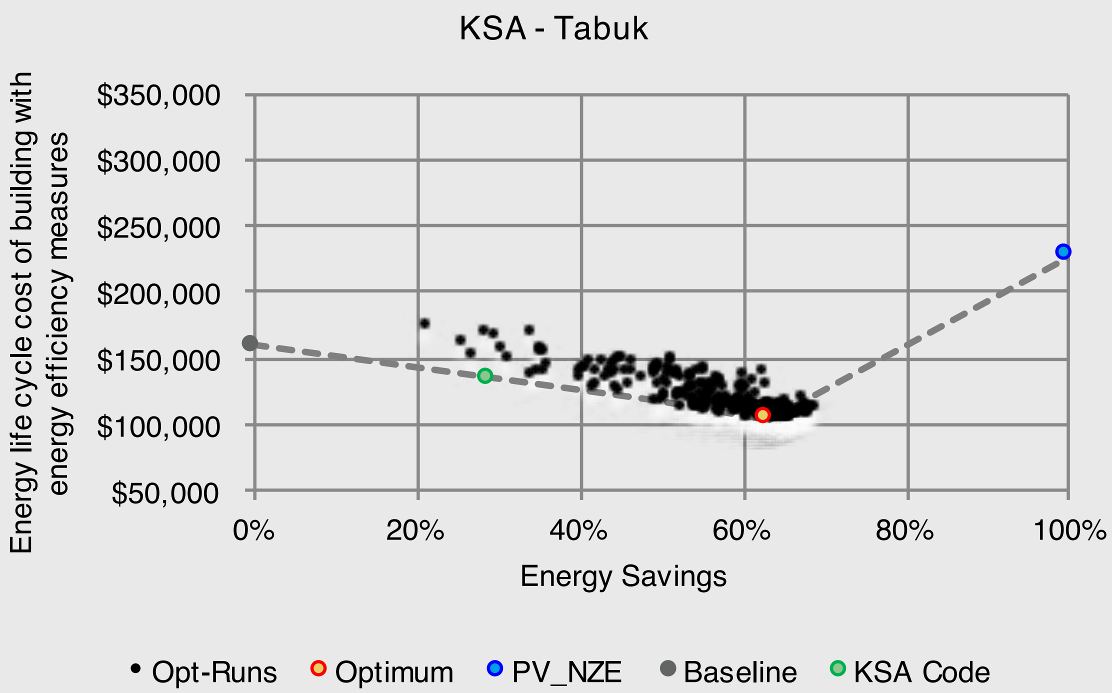


Figure E-4. Optimal path toward NZEB residential building in Tabuk.

Source: KAPSARC.

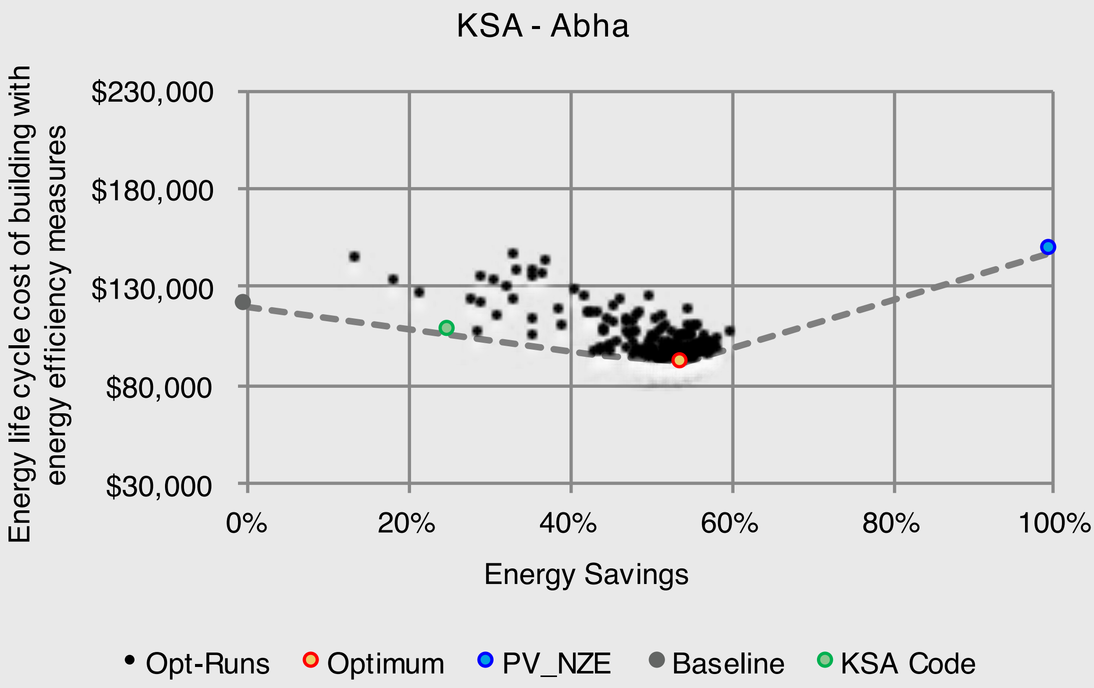


Figure E-5. Optimal path toward NZEB residential building in Abha.

Source: KAPSARC.

Appendix F: Optimal Wall and Roof Insulation R-value: Residential Buildings

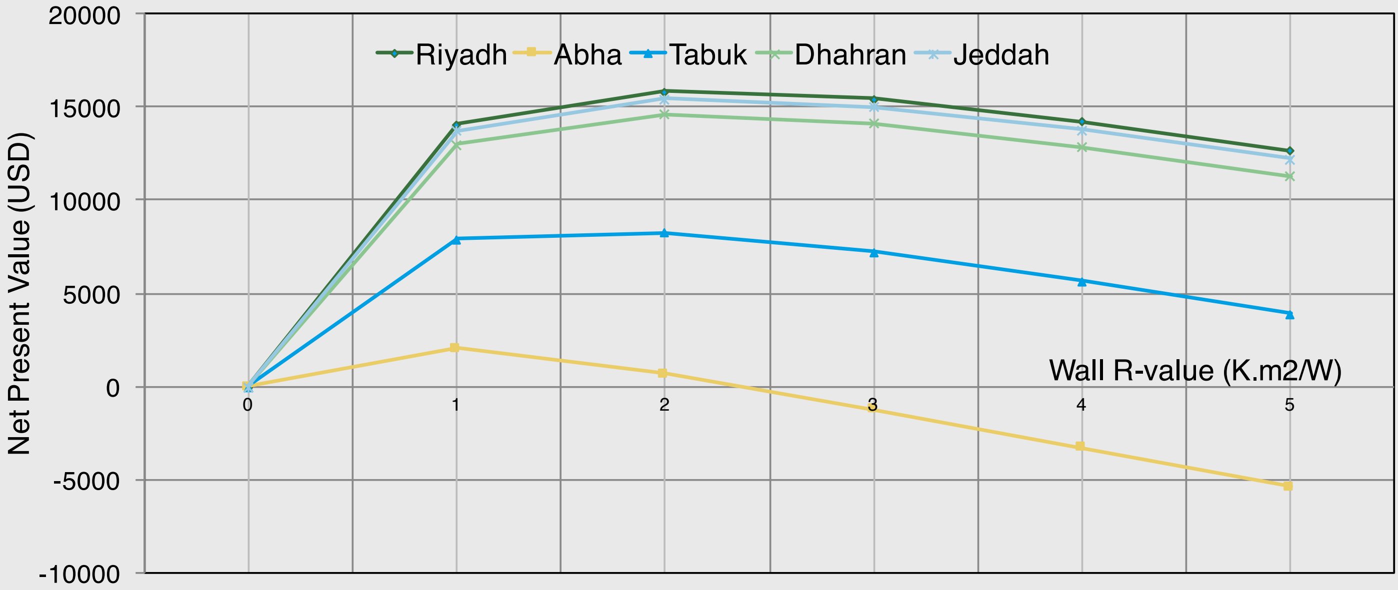


Figure F-1. Optimal wall insulation R-value for villas in five KSA sites using life cycle cost analysis.

Source: KAPSARC.

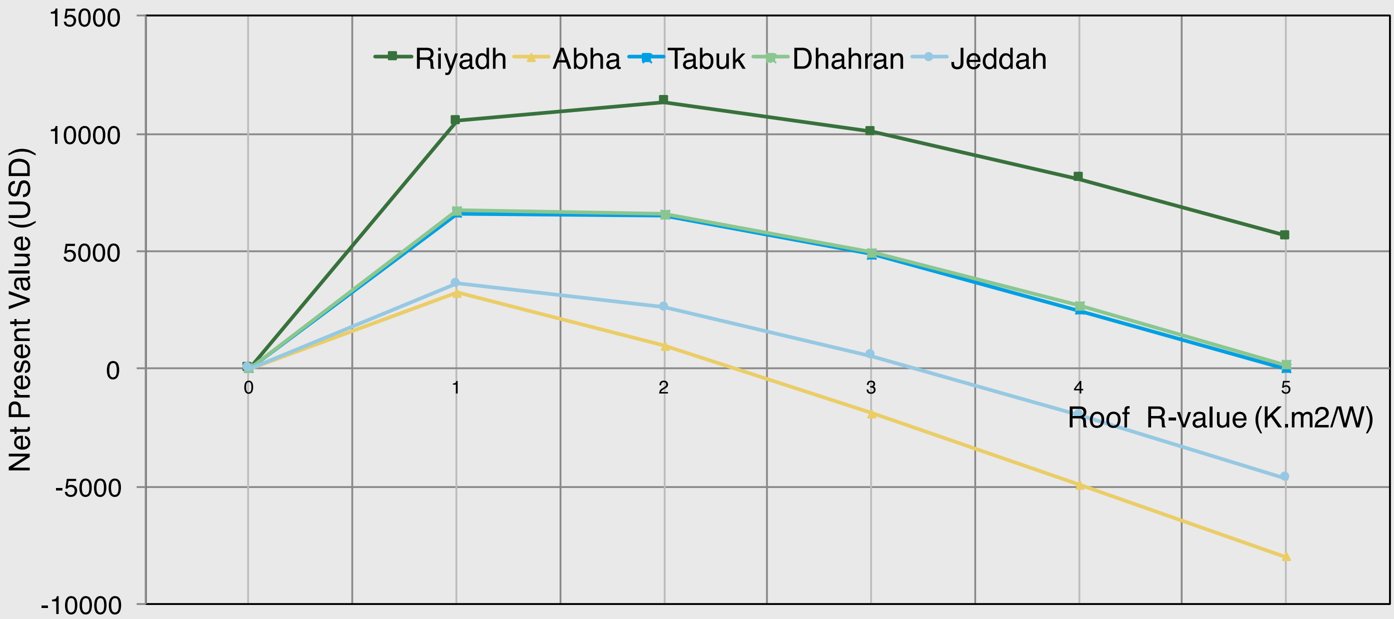


Figure F-2. Optimal roof insulation R-value for villas in five KSA sites using life cycle cost analysis.

Source: KAPSARC.

Notes

Notes

About the Authors

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About the Project

Increasing energy productivity holds some of the greatest possibilities for enhancing the welfare countries get out of their energy systems. It also recasts energy efficiency in terms of boosting competitiveness and wealth, more powerfully conveying its profound benefits to society.

KAPSARC and UNESCWA have initiated this project to explore the energy productivity potential of the Arab region, starting with the six GCC countries and later extending to other countries.

Aimed at policymakers, this project highlights the social gains from energy productivity investments, where countries are currently at, and pathways to achieving improved performance in this area.