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On the Incremental Investment in Residential Energy Efficiency:
A Saudi Perspective

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Key Points

This paper examines the marginal net benefit of adopting higher residential energy efficiency after an efficiency measure has already been installed. For example, how does installing more stringent thermal insulation influence energy efficiency investment decisions thereafter? To provide quantitative backing, a mathematical model that merges microeconomic and physical fundamentals is employed. Four typical households across Saudi Arabia and two electricity pricing schemes are chosen for this illustration. The households exhibit diverse socioeconomic attributes, face various climatic conditions, and live in dwellings with different physical characteristics. A few key findings from this analysis for Saudi households include:

- Investing in more stringent thermal insulation after already attaining more efficient air conditioners can reduce household welfare, but not necessarily vice versa.

- Under both electricity pricing schemes, household welfare is lowered when it invests in ‘reduced infiltration’ after installing more stringent insulation. Comparatively, welfare gains are made for all other pre-existing efficiency cases.

- In western Saudi Arabia, variability in households’ welfare between marginal investment decisions is low relative to that of other regions.

Summary

It has been shown in the literature that, in aggregate, actual household energy efficiency adoption is less than would be expected economically. Energy economists and policy analysts have described this phenomenon as the ‘energy efficiency gap.’ There could be myriad reasons for this gap, such as a lack of information about energy efficiency measures, or household decisions to invest in one energy efficiency measure rendering subsequent measures less attractive. The latter is especially the case when faced with discrete efficiency measures.

This paper examines households’ marginal energy efficiency investment beyond their adoption of initial measures. The analysis is carried out for typical households in four regions of Saudi Arabia. As an example, the marginal net benefit (or more formally, the marginal welfare gain) attained by installing higher-efficiency air conditioners would be greatly reduced if households installed better thermal insulation first, compared with a situation where no initial investment is made. Also, even though there may be room for attaining maximum welfare if energy efficiency were a continuous measure, the discrete nature of energy efficiency adoption may cause sub-optimal welfare.

Two contrasting electricity pricing cases are also analyzed: the electricity pricing scheme in place in Saudi Arabia in 2017, and a hypothetical time-of-use (ToU) electricity pricing scheme in which electricity tariffs are higher during the peak summer hours.

In all regions, investment in higher air conditioner efficiency, following an initial investment in improved thermal insulation, produces a higher welfare gain than all other initial efficiency measures in the base electricity case. This is not true for the ToU pricing case, where the lowest welfare gain is observed. In the summer, households would pay less for electricity on average under the ToU pricing scheme than the base price. However, they would pay more on average during the rest of the year.

Moreover, reducing infiltration after improving the thermal insulation of a dwelling lowers households’ welfare compared with no further efficiency measures. Welfare gains for reduced infiltration are made for all other pre-existing efficiency cases.

Introduction

The International Energy Agency (IEA 2018) shows how energy efficiency can play an important role in reducing greenhouse gas emissions beyond 2020. However, the IEA (2019) states that efficiency investment has stagnated since 2014. On the demand side, it attributes the slowdown to structural shifts that favor energy-intensive industries, rising consumer activity (e.g., increasing building floor areas), capital purchasing habits (e.g., larger vehicles and more appliances), and extreme global weather in 2018.

An improved understanding of energy efficiency investment is sought. In particular, looking at the combined socioeconomic and engineering case for further energy efficiency adoption as a result of having already invested in one energy efficiency measure. This paper explores how households' decision-making processes for incremental energy efficiency are altered once various efficiency measures are already installed. Complex physical interactions take place when energy efficiency measures are compounded. As such, those measures deemed economically sensible at the outset may be rendered uneconomic after another measure is installed first.

Gillingham et al. (2009) identify potential market failures that may cause over- or under-investment in energy efficiency. Major reasons for failure include the improper accounting of environmental externalities, energy pricing that deviates from its marginal cost of supply, a lack of information for consumers about energy savings, and capital constraints that consumers may face. Capital constraints may result in underinvestment in energy efficiency.

Hausman (1979), Allcott and Greenstone (2012), and more recently Gerarden et al. (2017), discuss longstanding questions in the literature. These include: Is there an energy efficiency gap? If so, what could be done to overcome it? An energy efficiency gap signifies the difference between economically sensible energy efficiency potential and what is actually realized. Key takeaways from those studies are that the actual magnitude of the energy efficiency gap is exaggerated, and that the substantial heterogeneity of the household population requires targeted energy efficiency policies.

A modified version of a mathematical model put forth by Matar (2018, 2019, 2020) is used to provide quantitative backing to any statements made. The analysis makes use of socioeconomic, dwelling, and climatic attributes, consistent with empirical studies such as those by Nair et al. (2010) and Trotta (2018). The model combines the physical attributes and the resulting benefits of specific energy efficiency measures with a household whose decision-making is guided by microeconomic principles. A household's satisfaction, which in economics is measured by utility and is maximized in that framework, is defined by analyst-calibrated preferences for each electricity-consuming service. Hence, the perceived benefits of energy efficiency are determined by consumer preferences and electricity reduction, which varies by efficiency measure.

A quantitative illustration is performed for four regions of Saudi Arabia. Five pertinent energy efficiency measures are examined: more stringent thermal insulation, higher air-conditioning efficiency, improved lighting technology, a more tightly fit building and more energy-efficient windows. These measures address the high cooling load placed on the electricity grid in Saudi Arabia and aim to improve the efficiency of lighting. Due to the historically low electricity prices administered by the government, residential energy efficiency has taken a back seat in Saudi Arabia. This was shown in Matar (2016), which was consistent with Faruqui et al. (2011), and is implied by the fact that Saudi Arabia had the third-highest per-household electricity consumption in the world in 2014 (World Energy Council 2020).

Investment in Residential Energy Efficiency

Analyzing marginal thinking when studying decision-making has been well documented in the economics literature. In the 1950s, Edwards (1954) combined economics and psychology to study the decision-making of individuals. He reinforces the notion that individuals make decisions to maximize their utility. Backed by experimental studies, Heath and Fennema (1996) later proposed the idea that people spread fixed costs over time, thus producing a perceived marginal cost that is different from the 'true' marginal cost. It is difficult to incorporate this perspective in long-run static (i.e., steady state) analyses, and it is primarily used in transient studies.

Consistent with Edwards (1954), the individual's urge to avoid negative marginal utility was used in Hausman's (1979) and Matar's (2020) analyses of investment in specific energy efficiency measures. Hausman (1979) studies the tradeoff between air conditioner performance and discomfort by embedding these tradeoffs in the utility function. Matar (2020) analyzes the potential purchase of several energy efficiency options and behavioral responses to electricity prices, such as thermostat adjustments, to maximize household satisfaction. Allcott et al. (2011) and Allcott and Greenstone (2012) present an energy efficiency investment model that adopts a utility-maximizing framework. It is based on user-specified energy-intensity parameters.

Nevertheless, most of the literature takes a pure monetary cost-based approach to studying specific energy efficiency investments (e.g., Guler et al. [2001]; Jakob [2006]; Malatji et al. [2013]; Krarti et al. [2017]), comparing the impact of energy efficiency measures with no energy efficiency measures. For example, Jakob (2006) empirically studies energy efficiency investment decision-making based on the marginal costs and benefits of its adoption. He considers the energy-saving benefits of compounding energy efficiency measures. Malatji et al. (2013) adopt an optimization framework that concurrently minimizes the payback period (i.e., discounts the initial investment and electricity costs) and maximizes the energy savings.

To the author's knowledge, no papers have yet discussed the particular issue of incremental investment in energy efficiency after an efficiency measure has been installed. It may not be economically feasible to further reduce one's energy consumption once an energy efficiency measure is installed. In other words, energy efficiency investment potential may be a discrete rather than a continuous process. For example, from 2014, the Saudi Electricity Company has required new residential buildings in Saudi Arabia to be fitted with thermal insulation (Asif 2016). Buildings that fail to meet this requirement are not connected to the power grid. Analyzing a dwelling with and without such insulation may yield some insight into the viability of adopting additional energy efficiency measures.

Model and Data Input

This paper provides views backed by quantitative evidence. A residential electricity use model is adapted for this study. Its rationale and data inputs are described in detail in the appendix. The modeling framework merges microeconomics and physics. The microeconomic component governs the households' decisions based on their optimal satisfaction. The physical component governs how much electricity is used and is able to explicitly represent energy efficiency. The model is calibrated to a 2017 setting in four regions of Saudi Arabia to capture different socioeconomic and climatic characteristics.

In summary, the physical component characterizes the conductive, radiative, and convective forms of heat that are transferred into and out of the air inside a thermal envelope. It resembles commercial building energy models in that respect, except it was designed from the bottom up to be linked[1] with the KAPSARC Energy Model (KAPSARC 2016), and to facilitate further development for the purposes of energy economics research. It incorporates the sensible and latent heat gains or losses as a result of air exchange between indoor and outdoor air, windows, lighting, and internal elements like occupancy and appliances. The total hourly power load is the sum of the direct uses of light bulbs and appliances, the power required to run the supply and return fans of the air-handling units, and the power draw from the refrigeration cycle of the air conditioners. The power used by the refrigeration cycle is directly related to the amount of heat transferred into and out of the interior to achieve the desired indoor temperature and relative humidity settings. It is this physical component that allows for the analysis of specific energy efficiency measures.

The microeconomic component finds the satisfaction state for each energy efficiency setting. The terms “welfare,” “satisfaction” and “utility” are used interchangeably in this paper (Johansson 1991). A constant elasticity of substitution (CES) utility function is used (Figure A1 and Equation A1). The utility function is formulated in a way where a household chooses among a basket of goods: electricity for cooling, lighting, or other goods and services. Contrary to the Cobb-Douglas functional form used by Matar (2018, 2019), the CES function allows the own-price elasticity of the goods' demand to vary based on the expenditure shares. It affects the performance of the approximate nature of the microeconomic component. The utility function contains an adjustment factor that approximates the satisfaction attained from installing each efficiency measure. A monetary budget constraint is also included, where incremental energy efficiency investment beyond the initial efficiency setting imposes an annualized investment cost. Energy efficiency investment will therefore induce a reduction in electricity consumption in the utility function and budget constraint, a higher investment cost in the budget constraint, and an adjustment factor that will raise the utility value. The effects of the costs and benefits of the specific energy efficiency measures will dictate household expenditure on other goods and services.

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[1] Matar (2016, 2017) assessed the short-run effects of residential electricity pricing policy and energy efficiency adoption on the wider Saudi energy system. Particularly, how the power generation costs and thermal efficiencies would be affected, and how the different fuel requirements of the electric power sector would affect oil refining and upstream operations.

Energy efficiency adoption

The appendix describes the modeling procedure undertaken to incorporate incremental additions of energy efficiency on top of a broad range of pre-existing energy efficiency measures. The physical model is needed to properly quantify the effects of compounding energy efficiency. For example, the effect of double-glazed low-e windows on their own differs from the effect of the windows added after the installation of better thermal insulation.

As shown in Table 1, the model considers an agent with a finite set of possible efficiency choices. This approach breaks down the investment options into discrete elements, rather than a continuous domain of infinitely possible choices. The options are upgrading the air conditioner from an average energy efficiency ratio (EER) to 15 British thermal units per watthour (BTU/Wh), sealing any cracks between doors, windows and walls in the thermal envelope, investing in low-e window glazing, retrofitting more stringent thermal insulation, or replacing all lightbulbs with LED lightbulbs. These options pertain to the high cooling demand exhibited in the region. Even changing the lighting technology will impact the cooling load, in addition to the impact it will have on direct electricity use.

Table 2 lists the materials of the walls and roofs for the villa archetypes in each region in the calibrated case. It also lists the materials used in the more stringent thermal insulation case, which exhibit lower overall heat conductivity. The material and thermal properties associated with low-e windows and LED adoption are acquired from McQuiston et al. (2005).

Table 1. Energy efficiency measures analyzed (author's assumptions).

	Without higher energy efficiency
Energy efficiency cases	Air-conditioning with an average EER of 15 BTU/Wh
	Reduced infiltration to 0.30 air changes per hour (ACH)
	Low-e double-glazed windows
	More stringent thermal insulation
	100% LED adoption

Table 2. Construction of the walls in the calibration and stricter thermal insulation cases (author's assumptions).

	Materials of walls and roofs, from exterior surfaces (top) to interior surfaces (bottom) [thickness, depending on region]
Standard villas	Cement plaster [2.0 cm] Concrete [15.0 cm to 20.0 cm] Cement plaster [2.0 cm]
More stringent thermal insulation	Cement plaster [2.0 cm] Concrete [13.0 cm] Polystyrene insulation [2.5 cm] Concrete [13.0 cm] Cement plaster [2.0 cm]

Following the average discount rate values reported by Harrison et al. (2002) and Enzler et al. (2004), each efficiency option installed after the initial state has a purchase cost that is annualized over its designed life using a discount rate of 30%. Hausman (1979) reported an average value for an individual of up to 26%. The up-front costs used in this analysis are summarized in Table 3.

The levels of thermal insulation, reduced infiltration, and/or how much heat is gained through the windows will affect the maximum cooling load [max($\dot{Q}_{cooling}$)] that a household experiences throughout the year. This will, in turn, influence the number of air conditioners the household needs and their capacity, which is reflected in their cost. Therefore, the cost of new air conditioners is formulated as a function of the maximum cooling load in each energy efficiency and demand response case. Since the cooling load is expressed in units of power, and air-conditioning capacity is given in units of energy, dt is included to indicate the time increment used. The air-conditioning unit cost includes installation.

ε stands for LED bulb efficacy in lumens per watt (W); r is the power rating of the bulb; TFA is the total indoor floor area of the residence; I is the lighting illumination required; ESA is the total area of the walls and roof; TGA is the total glazed area; $L(\cdot)$ are the labor costs for installing windows or thermal insulation; and $c(.)$ are the costs per unit for each efficiency measure. $c(.)$ are in US$ per Btu of capacity for air conditioners, US$ per lightbulb for LEDs, and US$ per square meter for windows, thermal insulation, and a stronger seal. ESA, TFA, and TGA differ by region and residence type, based on the calibration described in the appendix. L_{window} and $L_{thinsul}$ are estimated as US$100 and US$500, respectively.

Table 3. Full purchase costs of energy efficiency measures (US$).

Energy efficiency measure	Full purchase cost (US$ per household)
Air conditioners with an average EER of 15 Btu/Wh	$c_{AC} \cdot \max(\dot{Q}_{cooling}) \cdot dt$
Sealing cracks around windows, doors, power outlets, and lighting fixtures	$c_{seal} \cdot TFA$
Low-e double-glazed windows	$c_{window} \cdot TGA + L_{window}$
More stringent thermal insulation	$c_{thinsul} \cdot ESA + L_{thinsul}$
100% LED adoption	$\frac{c_{LED} \cdot I \cdot TFA}{\varepsilon \cdot r}$

Source: Author's estimates based on Austrotherm Insulation (2017) for thermal insulation and online retailers for the rest.

Note: c_{AC} = 4.6 U.S. cents per Btu of capacity; c_{seal} = 2.15 US$ per m2; c_{window} = 211 US$ per m2; $c_{thinsul}$ = 10 US$ per m2; c_{LED} = 4.4 US$ per bulb).

Electricity pricing scenarios

In the context of this study, electricity prices could have unexpected effects on the adoption of energy efficiency measures. Two electricity pricing schemes are examined, as summarized in Tables 4 and 5:

- The first is a progressive pricing structure applied in Saudi Arabia in 2017. Pricing for residential customers consisted of the progressive prices shown in Table 4. The pricing structure is ‘progressive’ because even if a household used more than 2 megawatthours (MWh), it paid 1.33 cents per kilowatthour (kWh) for the first 2 MWh. This scenario is referred to as the base pricing case.
- A time-of-use (ToU) price that stipulates a flat tariff of 5 U.S. cents per kWh is charged throughout the year except during the summer system peak hours in Saudi Arabia when a 15 cents per kWh charge is imposed. This scenario is referred to as the ToU pricing case.

Table 4. Household electricity pricing in 2017.

Monthly use (MWh)	Pricing in 2016 and 2017 (U.S. cents per kWh)
≤ 2	1.33
2 < and ≤ 4	2.67
4 < and ≤ 6	5.33
6 <	8.00

Source: ECRA (2016).

Table 5. ToU electricity price scheme used in our analysis (author’s supposition).

Time of year	ToU electricity pricing scheme (U.S. cents per kWh)
In the summer months during the peak hours (from 12 pm to 5 pm)	15.00
Outside of summer peak hours, including all other seasons	5.00

Results and Discussion

Figures 1 to 8 display the households' utility for each initial energy efficiency condition. Incremental energy efficiency purchases are made for the two electricity pricing cases in the four regions of Saudi Arabia. The graphs plot the utility value for the incremental energy efficiency investment option (vertical axis) for each electricity price and region combination, given an initial energy efficiency setting (horizontal axis). The utility values are relative to one another for a particular initial energy efficiency setting and are not necessarily comparable across initial efficiency settings.

As an example of how initial energy efficiency investments alter the full investment costs of combined energy efficiency measures, let us examine the costs of air conditioners before and after the installation of improved thermal insulation. In the status quo, the full costs of air conditioners are calculated to be US$1,875, US$3,254, US$3,446, and US$3,901 per household in the southern, western, central, and eastern regions of Saudi Arabia, respectively. After the installation of improved thermal insulation, the marginal investment costs for air conditioners become US$1,480, US$2,493, US$2,226, and US$2,439 per household in the southern, western, central, and eastern regions of Saudi Arabia, respectively. This is one example of the changing inputs into the utility-maximizing household's decision-making.

Because the installation of LED bulbs on top of pre-existing energy efficiency measures always results in one of the highest utility values, this paper does not show LED installation for the sake of a clearer presentation. The marginal investment in LED lightbulbs consistently increases household welfare, regardless of the initial efficiency condition or the electricity pricing scheme. However, they produce the lowest utility gains when shifting from the base pricing case to the ToU pricing scheme.

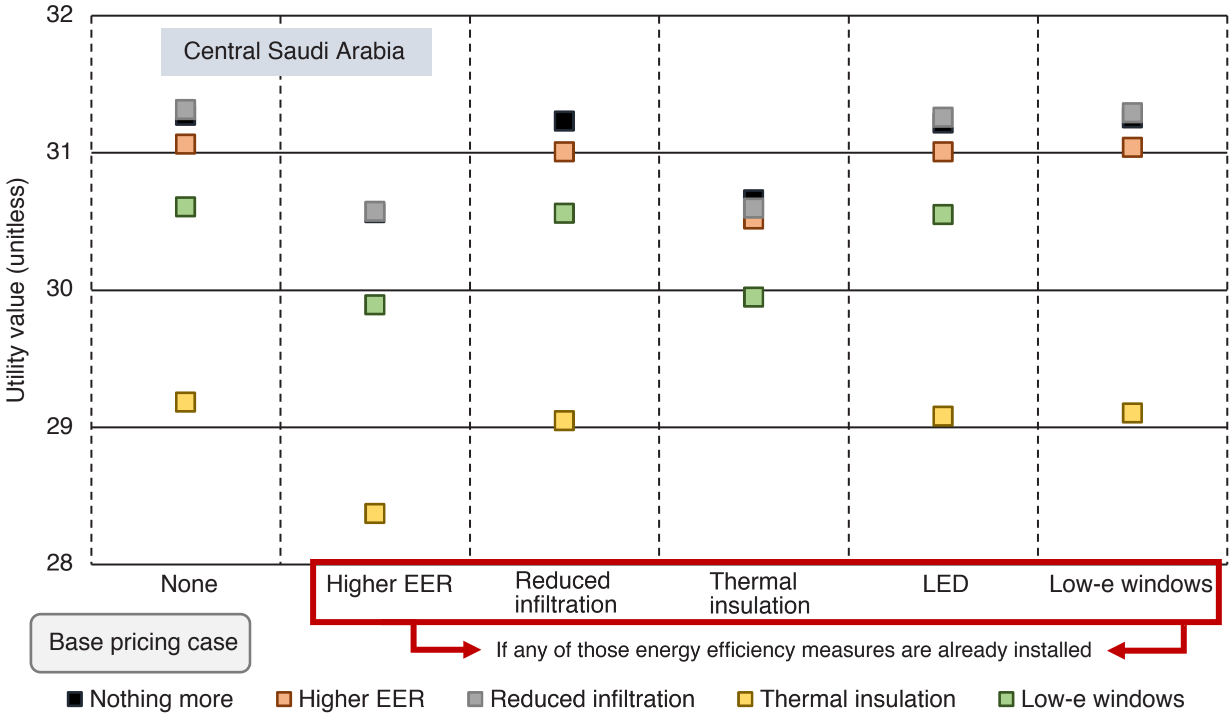
The higher average electricity prices of the ToU pricing case result in lower welfare across the board. As would be expected, higher electricity prices also make energy efficiency more attractive than not having it at all. In all regions with base electricity pricing, the higher EER for air conditioners, improved thermal insulation, and low-e windows yield lower household welfare than doing nothing. Under ToU pricing, higher EER generally produces higher welfare than doing nothing, while the other energy efficiency cases produce a lower welfare loss than with base pricing.

The results also show that the investment in low-e double-glazed windows is difficult to justify. More efficient windows cause welfare loss in both electricity price schemes when no previous energy efficiency measures are installed, but the satisfaction gained through their installation is improved by the household having no initial energy efficiency measures.

The interactions between improved thermal insulation and more efficient air conditioners are of particular interest. Matar (2016) shows that the compounded energy savings of both measures combined is greater than that of the individual measures but lower than the sum of both measures' energy savings. Furthermore, the results show that the pre-existence of air conditioners with the high EER rating can reduce the welfare gains of installing more stringent thermal insulation for certain climates, but not necessarily vice versa. As shown above, the purchase costs of air conditioners are lower when thermal insulation is installed. That is not true the other way around.

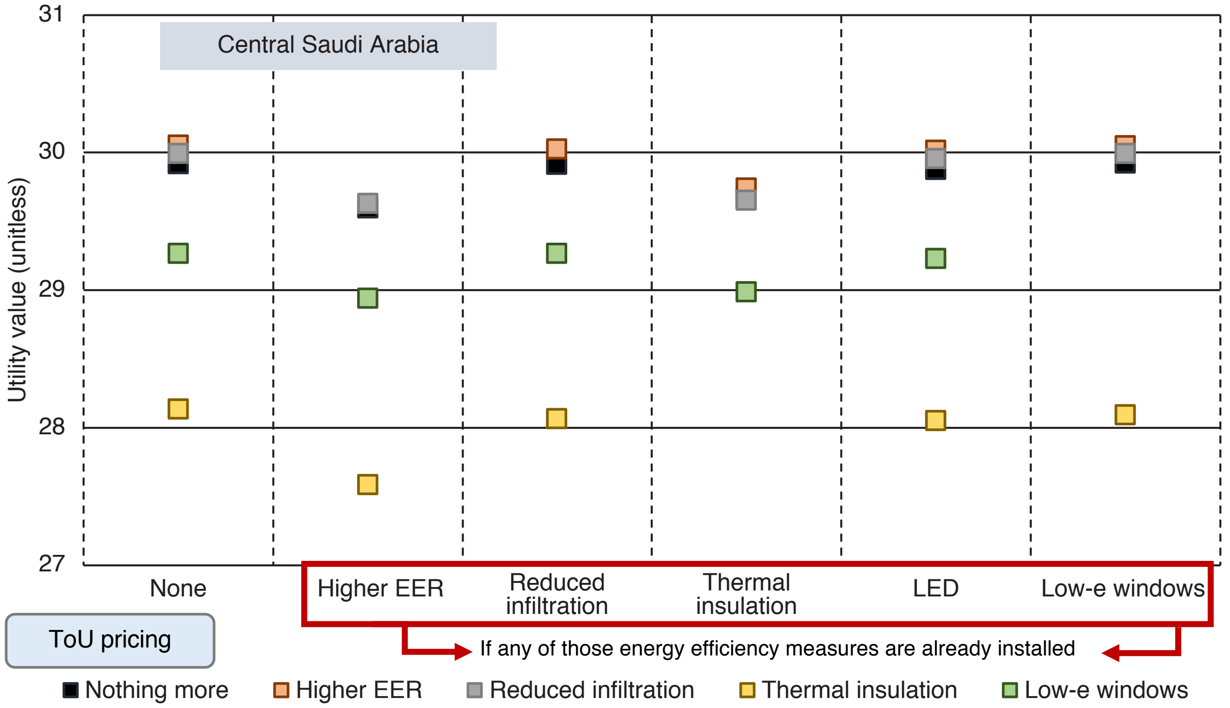
This claim is exemplified by looking at the resulting households' utility values when 'higher EER' air conditioning or 'thermal insulation' are adopted first. In the central and eastern regions, which

Figure 1. Energy efficiency investment for a typical villa in central Saudi Arabia with base pricing.



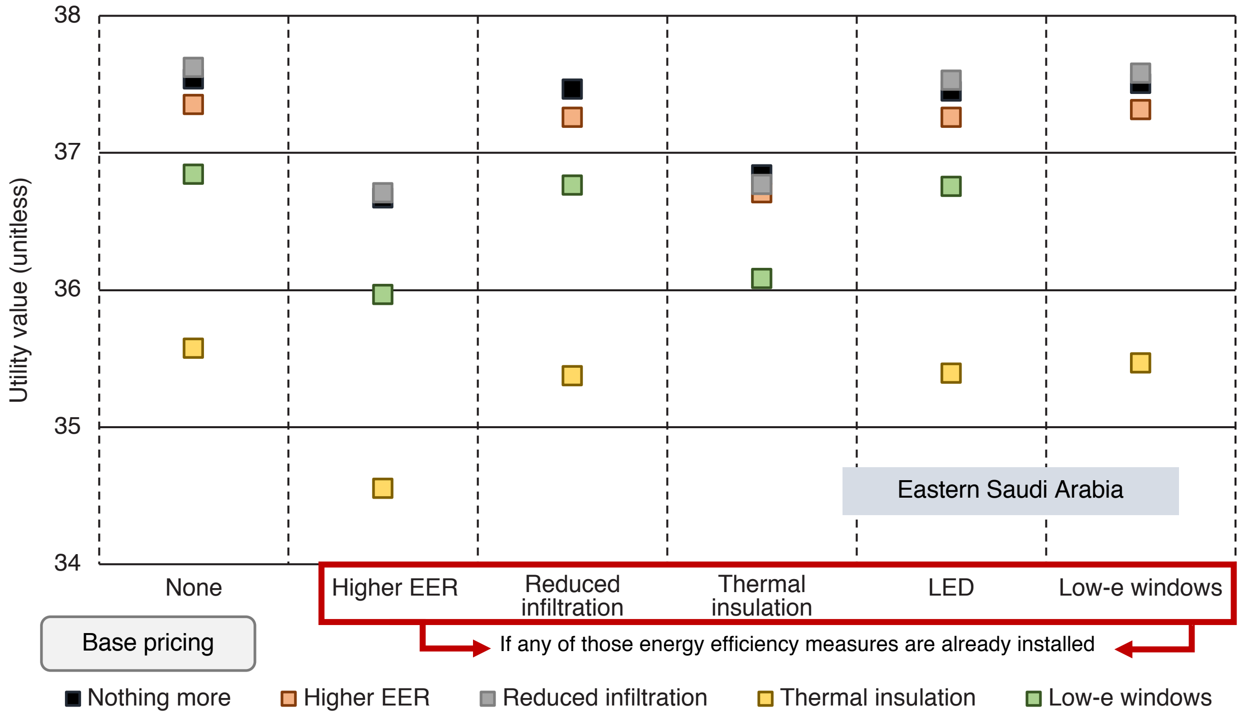
Source: Author's calculations.

Figure 2. Energy efficiency investment for a typical villa in central Saudi Arabia with ToU pricing.



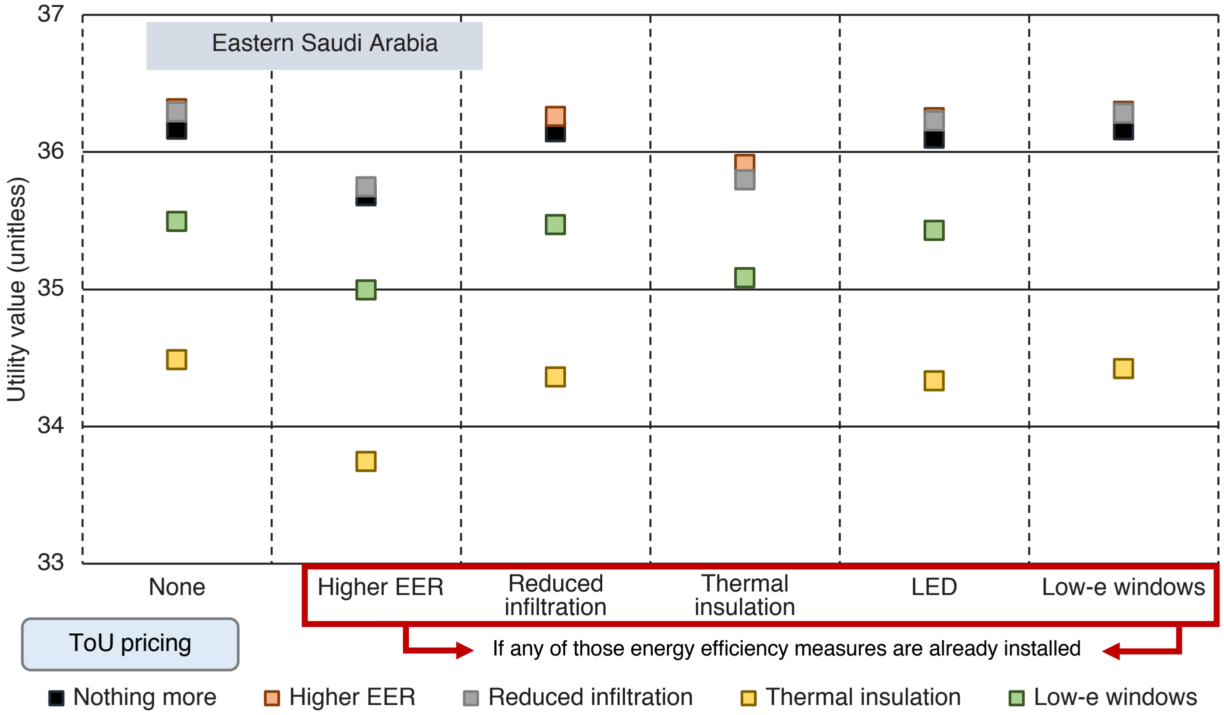
Source: Author's calculations.

Figure 3. Energy efficiency investment for a typical villa in eastern Saudi Arabia with base pricing.



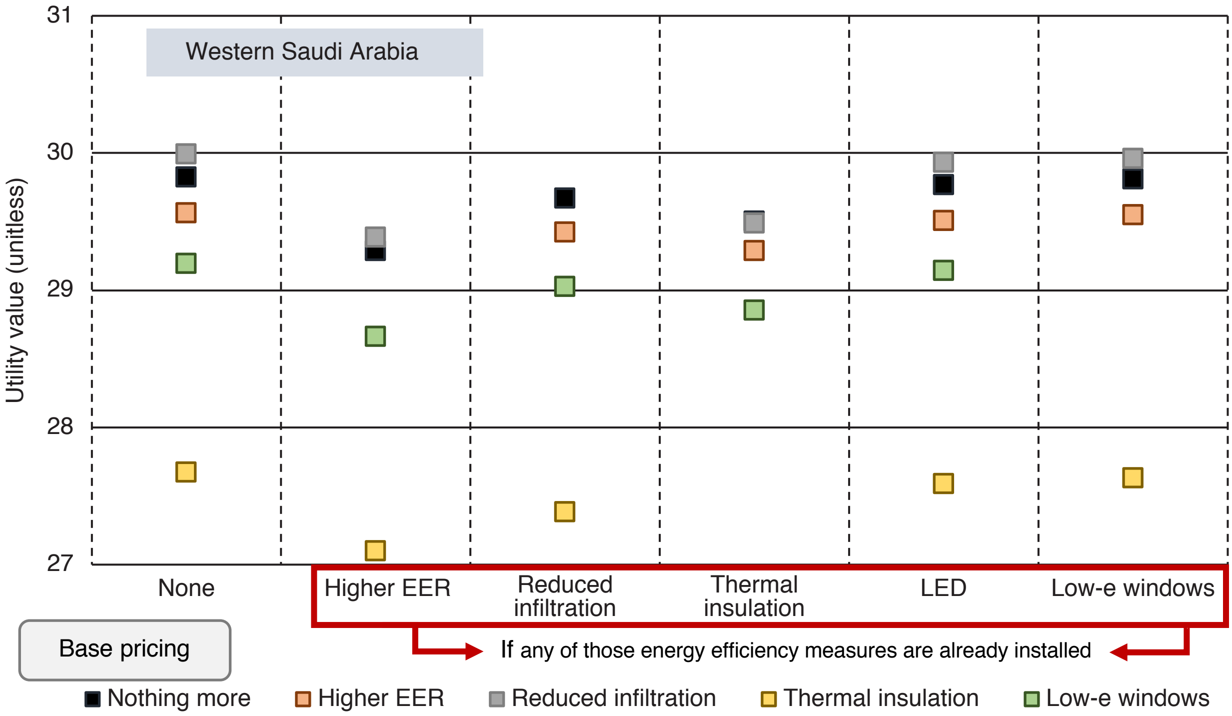
Source: Author's calculations.

Figure 4. Energy efficiency investment for a typical villa in eastern Saudi Arabia with ToU pricing.



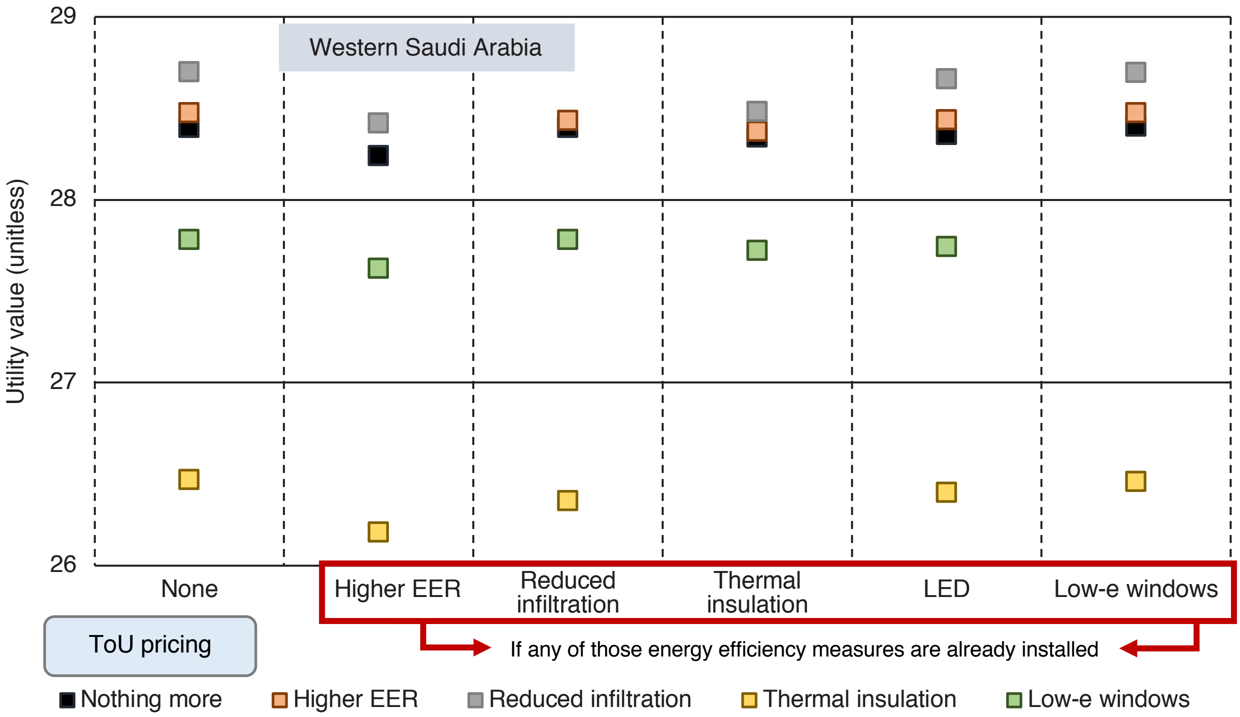
Source: Author's calculations.

Figure 5. Energy efficiency investment for a typical villa in western Saudi Arabia with base pricing.



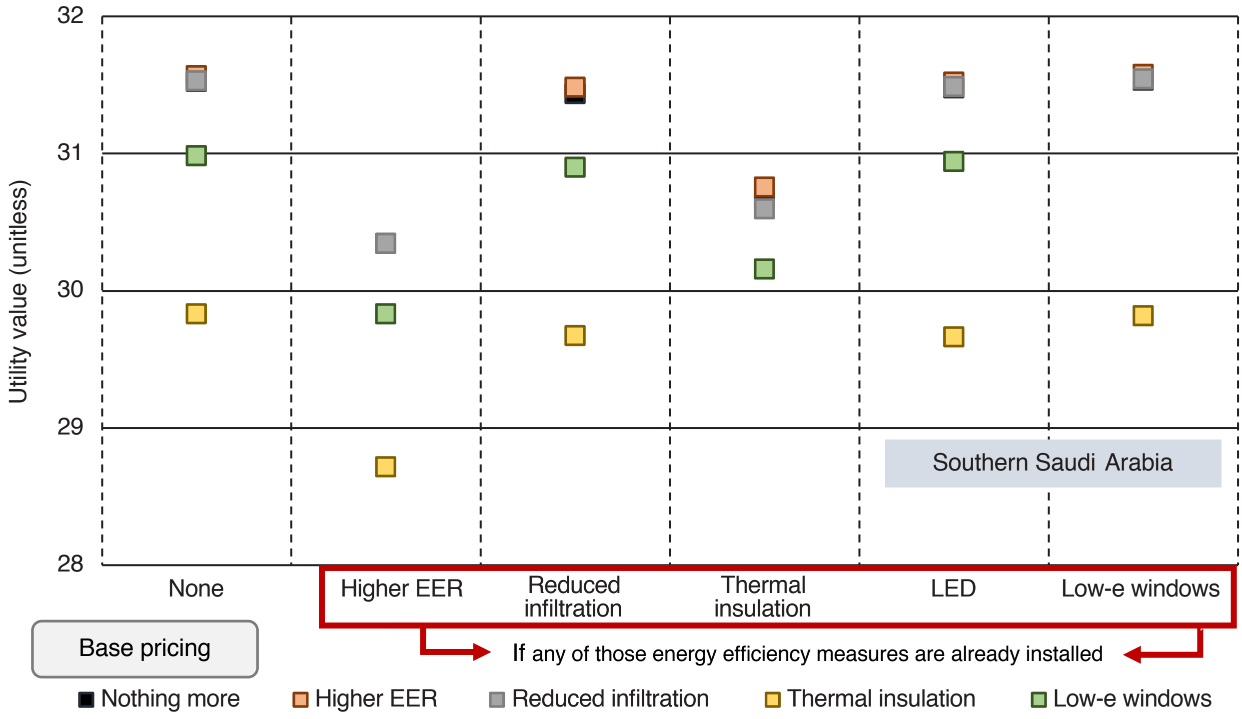
Source: Author's calculations.

Figure 6. Energy efficiency investment for a typical villa in western Saudi Arabia with ToU pricing



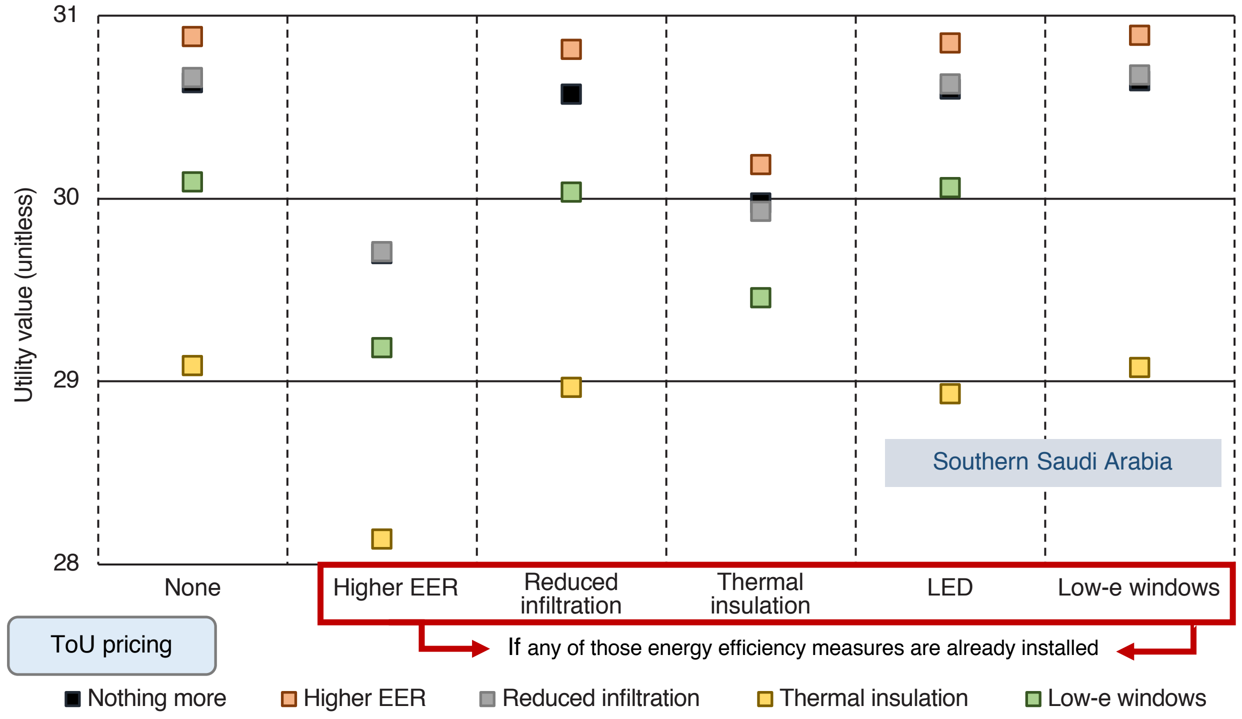
Source: Author's calculations.

Figure 7. Energy efficiency investment for a typical villa in southern Saudi Arabia with base pricing.



Source: Author's calculations.

Figure 8. Energy efficiency investment for a typical villa in southern Saudi Arabia with ToU pricing.



Source: Author's calculations.

share similar climates, marginal investment in 'improved thermal insulation' when households already have higher EER air conditioning units causes the highest loss in utility compared with when they have any other measure previously installed. The reverse is true in the southern area of Saudi Arabia. This result is consistent in both electricity pricing schemes.

In all but the southern region, the welfare of households that already have improved thermal insulation is affected differently by the electricity pricing scenarios under study. When faced with the base electricity price, households experience welfare loss when investing in any other energy efficiency beyond insulation. They would experience welfare gains when faced with the ToU electricity price.

To provide a specific example, households with pre-existing improved thermal insulation are further examined. Under base electricity pricing, households in the central region investing in higher EER experience the lowest reduction in welfare relative to 'nothing more' than if it had any other pre-existing efficiency measures. Under ToU electricity prices, however, pre-existing thermal insulation yields the lowest rise in welfare relative to all other pre-existing efficiency measures when the marginal investment is in higher EER. With the base electricity pricing scheme in place, 'higher EER' would be the most attractive second choice, whereas it would be the least attractive second choice under the ToU pricing scheme. The energy-saving benefits of both electricity pricing schemes are the same, and households in this analysis are not allowed to adapt to electricity price changes through behavioral responses – such as adjusting the indoor temperature settings or turning off lights. Hence, the only effect at play is the expenditure on electricity and its impact on the households' overall expenditure.

A plausible explanation for this is that the 5.33 cents-per-kWh bracket in the base pricing scenario is sometimes replaced by a 5 cents-per-kWh price in the ToU pricing scheme, allowing households to use the cost savings to purchase additional non-electrical goods and services. In the calibrated case, electricity use by villas in the summer averages 5.3 MWh per month in the eastern region and 4.6 MWh per month in the central region. Table 4 shows that 1.3 MWh and 0.6 MWh of summer use for the eastern and central regions, respectively, are priced at 5.33 cents per kWh in the base pricing case. A small fraction of the energy consumed in all regions is priced at 15 cents per kWh under the ToU scenario. Hence, the average electricity price in the ToU case is closer to 5 cents per kWh. In the cooler winter months, during which the demand for space cooling is subdued, typical households in all regions do not use electricity beyond the first two brackets listed in Table 4.

Furthermore, investment in 'reduced infiltration' lowers households' welfare only when more stringent thermal insulation is already installed. Welfare gains are made for all other pre-existing efficiency measures, even when compared with no more efficiency additions. Lower outdoor-to-indoor conduction heat gains lessen the satisfaction of the energy-saving benefit of a more airtight dwelling.

Changes in a typical household's utility between marginal investment decisions for a given pre-existing measure are more muted in western Saudi Arabia than in other regions. For this reason, the scaling of the vertical axes in Figures 5 and 6 is more pronounced than in the figures for other regions. In other words, subsequent energy efficiency investment has less of an impact on households' welfare. This feature could be explained by the fact that the average income in the western region is the lowest of any region in Saudi Arabia.

Expenditure avoided due to the energy-saving effect of initial energy efficiency measures is used to purchase incremental energy efficiency measures.

The net amount of money saved is used for other goods and services, but this has a more limited impact on household welfare than in higher-income regions.

Conclusion

This paper discusses the marginal net benefit of adopting higher residential energy efficiency once an efficiency measure has already been installed. It sought to answer the questions, how does already having more stringent thermal insulation influence energy efficiency investment decisions thereafter; and, how are subsequent energy efficiency investments affected by having already installed double-glazed windows? Answering these questions will improve the understanding of energy efficiency investment potential.

The paper employs a mathematical model that merges microeconomic and physical fundamentals. The households used in the analysis are characterized by their diverse socioeconomic attributes, their variable climatic conditions, and that they live in dwellings with different physical characteristics. Four typical households across Saudi Arabia are chosen to illustrate households' energy efficiency decisions.

Two electricity pricing cases are also incorporated to examine how pricing schemes may affect the results. They comprise the pricing scheme households in Saudi Arabia faced in 2017, and a ToU price that rises during peak summer demand. Higher average electricity prices in the ToU pricing scenario than in the base electricity price scenario cause welfare to fall. Higher electricity prices also make energy efficiency measures more attractive.

In all but the southern region, marginal investment in higher EER when improved thermal insulation is already installed produces the lowest welfare loss of all initial efficiency measures in the base electricity case. However, it produces the lowest welfare gain in the ToU pricing case. In the summer, households pay less for electricity, on average, under the ToU pricing scheme than in the base case. However, they pay more on average under the ToU scenario than in the base case scenario during the rest of the year. This result provides useful information for designing electricity tariffs.

In the central and eastern regions, investment in 'improved thermal insulation' when households already have higher EER air conditioning causes the highest welfare loss compared with when other measures are initially installed. This result is consistent in both electricity pricing schemes. In western Saudi Arabia, variability in the typical household's utility between marginal investment decisions for a given pre-existing measure are dampened.

Moreover, investing in 'reduced infiltration' after improving the thermal insulation of a dwelling lowers household welfare compared with no more efficiency additions. Welfare gains are made for all other pre-installed efficiency measures.

These findings highlight the complications surrounding computing the energy efficiency gap. The initial investment decision can negatively impact the viability of installing subsequent efficiency measures. To overcome this issue, energy efficiency policy could include incentives for incremental energy efficiency investments beyond the initial investments made.

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Appendix – The Residential Electricity Use Framework

A.1 Residential electricity use model

The underlying theory from which the method employed is inspired is that demand functions are derived from solving the first-order conditions of a utility-maximization problem. Those conditions are produced by writing the Lagrangian function and differentiating it according to the variables that constitute the utility function and constraints. Taken as an approximate approach, Matar (2018, 2019, 2020) proposes a linkage between a physical building energy model and a household whose decisions are consistent with microeconomic fundamentals, whereby the electricity use variables are computed by a physically compliant building energy model. These analyses explored demand response measures as a result of different electricity pricing schemes. They examined the price-induced behavioral demand response and energy efficiency investment that are exercised or installed in order to maximize a household's utility. Matar (2019) argues for using a theoretical approach as opposed to an empirical one because some countries, like those in the Gulf Cooperation Council, have not experienced frequent or large movements in their domestic electricity prices over the past decades.

This paper alters the framework described above to introduce energy efficiency investment on top of an already existent efficiency measure. The model cycles through a slew of measures that are already installed on top of the calibrated dwelling, like improved thermal insulation, more efficient lightbulbs, or higher EER air conditioners. The high energy efficiency state is accompanied by annualized long-run costs for further energy efficiency investment. The costs of the already existent measures are not considered in the households' budget constraint.

Figure A1 illustrates the updated framework. Households have utility functions with given preferences. This essentially makes the utility functions' preferences normative, or how the utility functions of the set of households 'should' be shaped. The utility's value is computed for all energy efficiency adoption states, assuming a budget constraint.

For the purposes of this paper, the model does not cycle through different behavioral price response measures, such as raising the indoor thermostat setting. Instead, it just cycles through the efficiency measures described in section 3.1.

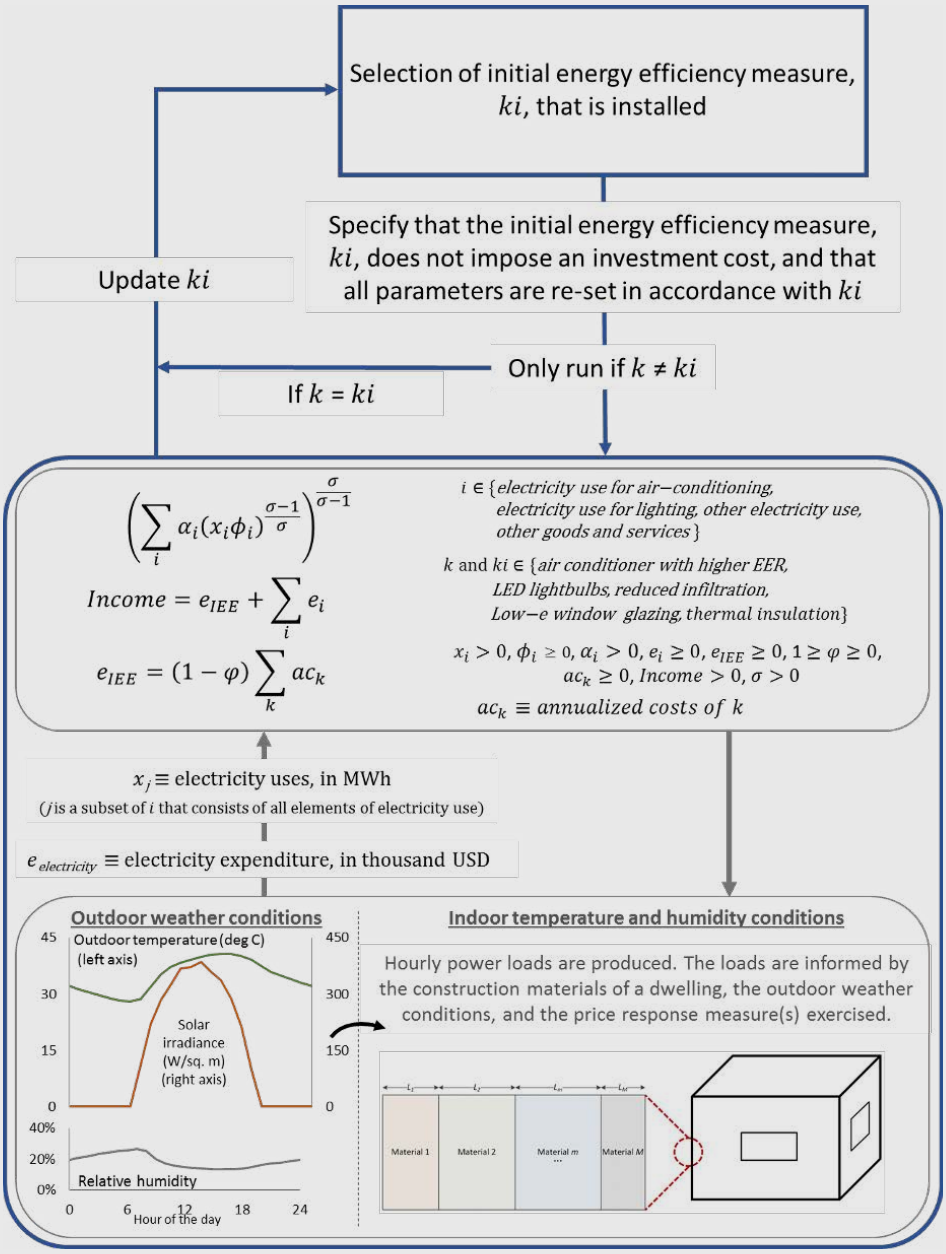
The constant elasticity of substitution (CES) utility function is shown by Equation A1. x_i consists of electricity use, in megawatthours (MWh), and the consumption of other goods and services, in monetary terms. The price of other goods and services is set to unity. The equations for the quantities of electricity used for air conditioning and lights, and the remaining electricity use, are defined in more detail by Matar (2020).

$$Utility = \left(\sum_i \alpha_i (x_i \phi_i)^{\frac{\sigma-1}{\sigma}}\right)^{\frac{\sigma}{\sigma-1}} \tag{A1}$$

The model is calibrated for various typical regional villas, apartments, and traditional houses in Saudi Arabia to match the actual electricity use data from 2017. However, the analysis is restricted in all four regions to villas. This way, the villas used in the paper have some empirical consistency with the 2017 data.

ϕ_i is an adjustment factor that approximates the satisfaction gained through the installation of energy efficiency. Although the behavioral response is not measured in this study, the value of ϕ_i is always unity for cases where only the behavioral response is studied, i.e., in cases where no energy efficiency is made. This is important to note for the purposes of calibrating the model.

Figure A1. Residential electricity use modeling framework.



Selection of initial energy efficiency measure, ki, that is installed

Specify that the initial energy efficiency measure, ki, does not impose an investment cost, and that all parameters are re-set in accordance with ki

Hourly power loads are produced. The loads are informed by the construction materials of a dwelling, the outdoor weather conditions, and the price response measure(s) exercised.

ϕ_i electricity used for air-conditioning and lighting are defined by equations A2 and A3, respectively. The values of ϕ_i are always one for the other terms in the utility function. Services such as lighting use affect the cooling load in the dwelling (non-linearly); thus, all heat gains are considered for the air-conditioning adjustment. EER is the energy efficiency ratio of the air-conditioning unit, IHG is the sum of total internal heat gains from appliances and lighting during the year, SHG is the sum of direct and diffuse solar heat gain through windows during the year, ΔT is the summed differences in temperature between the internal surfaces of the walls and roof and the desired initial indoor temperature setting, and ω is the heat gained due to infiltration. Heat gains are defined in units of power.

ΔT is incorporated to capture the effect of more stringent thermal insulation. s is the share of each type of heat gain in total cooling load at the initial, or calibrated, state for each region; it stipulates that improvements in energy efficiency are not given the same weight. EER measures the ratio of electricity use to cooling load, and thus is not part of s. Each set of values for any scenario is related to the initial state, $(\cdot)_{initial}$.

$$\phi_{AC} = \frac{EER}{EER_{initial}} \left(\frac{IHG_{initial}}{IHG}\right)^{s_{IHG}} \left(\frac{SHG_{initial}}{SHG}\right)^{s_{SHG}} \left(\frac{\Delta T_{initial}}{\Delta T}\right)^{s_{wr}} \left(\frac{\omega_{initial}}{\omega}\right)^{s_{inf}} \tag{A2}$$

$$\phi_{lighting} = \frac{N_{initial}}{N} \tag{A3}$$

In Equation A3, the power needed to meet the initial illumination requirement at the calibrated state ($N_{initial}$) is divided by the power needed for each scenario to meet that same initial requirement (N).

The values of ϕ_i are defined as unity for all the initial states of pre-existing energy efficiency measures. For example, $\frac{\Delta T_{initial}}{\Delta T}$ equals unity at the initial state when the dwelling has pre-existing thermal insulation. However, it would be greater than one if thermal insulation were installed on top of other pre-existing measures.

α_i are the preferences, and they sum to unity for all i. The households were calibrated to have preference shares for electricity ranging between 4% and 6%, depending on the region. Moreover, the calibrated value of σ, which is the elasticity of substitution, is 0.9. This calibration was performed by starting at a near-zero electricity preference setting, and slowly raising that preference until the households no longer responded to the 2017 electricity tariffs. Incidentally, the preference was calibrated to be lowest in the southern region, where the climate is less extreme, and highest in the central and eastern regions, which experience the hottest summers. The preference share devoted to electricity is further disaggregated into its various components. Estimates of the disaggregated preference shares are based on the 2011 consumption shares reported by Faruqui et al. (2011) for a household in Saudi Arabia. The preference share of other goods and services is the summed value of each preference share minus that for electricity.

The budget constraint is shown by Equation A4. *Income* is the households' average annual income by region. It is calibrated based on the average 2013 income of households in each region using data from the Central Department of Statistics and Information (CDSI 2013). The average annual income ranged from 31.71 thousand US dollars (US$) in the western region to US$40.59 thousand in the southern region. e_i are the expenditures on electricity and other goods and services. Expenditure on electricity may be computed based on hourly electricity prices or Saudi Arabia's current progressive pricing structure. e_{IEE} is the annualized investment and maintenance cost required for a particular energy efficiency measure.

$$Income = e_{IEE} + \sum_i e_i$$

Included in Equation A5 is a term that reduces the purchase cost of energy efficiency measures for households. This analysis, however, stipulates that ϕ is zero. ac_k are the annualized costs of the energy efficiency options, k, defined in the next sub-section.

$$e_{IEE} = (1 - \varphi) \sum_k ac_k$$

A.2 Data inputs and model calibration

Carried over from Matar (2020), the residential electricity use component is calibrated for typical villas, apartments, and traditional houses in four regions of Saudi Arabia: central, southern, western, and eastern. Regional weather datasets are consistent with those acquired from the National Renewable Energy Laboratory (NREL 2017). Information on construction materials, household sizes, the number of residences and their dimensions, and the space heating saturation for each type of dwelling by region is obtained or derived from the General Authority for Statistics (GaStat 2017a, 2017b). ASHRAE Standard 55-2010 is used to calibrate the acceptable indoor temperature conditions based on ranges for thermal comfort. The thermostat set points that form the calibrated villa stock are 22.5 to 23 degrees Celsius (^{o}C) for the summer, 20^{o}C to 22^{o}C for the spring and the fall, and 20.5^{o}C to 21^{o}C for the winter, depending on the region.

Air conditioner efficiency was estimated by AMAD for Technical Consultation and Laboratories (2011) to be 7 British thermal units per watthour (BTU/Wh) in 2011. Since 2014, the Saudi Energy Efficiency Center and the Saudi Standards, Metrology, and Quality Organization have legislated a minimum air conditioning performance standard of at least 11.5 BTU/Wh at T1 temperature conditions. The average EER value for a population as large as Saudi Arabia's, however, takes years to change with natural air conditioner replacement. That lag, the fact that 7 BTU/Wh is the latest documented average value for the Kingdom, and that the calibrated model produces similar 2017 electricity use values for the country as the actual values, justifies the use of around 7 BTU/Wh.

At the calibrated state, all households are estimated to have an infiltration rate of between 0.65 to 0.80 air changes per hour, depending on the region. The lighting technologies currently adopted comprise incandescent bulbs, linear fluorescent lighting, and compact fluorescent bulbs, as reported by GaStat (2017a). Windows in the calibrated dwellings are assumed to be single-glazed.

For the calibration of dwelling construction materials, GaStat (2017b) states that all villas and apartments are built using concrete, whereas 65% of traditional houses are built using adobe or mudbricks. The remaining 35% of traditional houses are made of concrete. The majority of traditional houses, built using adobe, are used to represent a single archetype to manage the model size.

Appliance saturation levels, and appliance power ratings, are carried over from Matar (2016). That paper also contains data assumptions/inputs not mentioned in this paper. Furthermore, the data for lighting used in homes by region and by technology is based on GaStat's (2017a) household energy survey. The usage times of indoor lighting are specified such that lights are turned on from sunset to 10 pm. The indoor illumination requirement is set between 130 and 190 lumens per indoor square meter, depending on the region, guided by Jefferis and Jefferis (2013). Outdoor lighting only accounts for direct use and does not contribute to the internal heat gain.

All the physical constants used to inform such things as the transmittance of heat through windows, the material thermal properties, the fractions of heat gained through radiative and convective means, as well as the trigonometric relationships that govern solar radiation on each outer surface of the house, are derived from McQuiston et al. (2005). The wall and roof materials, as given in Table 2, are modeled so that each material in the composite structure has thermal conductivity and thermal diffusivity. These thermal properties are akin to U- or R-values. Regional and seasonal wind speeds are estimated from Rehman et al. (1994).

About the author

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Walid is a research fellow at KAPSARC working on energy systems models, including the KAPSARC Energy Model, and its satellite projects such as KAPSARC's residential electricity use model. Walid holds a Master of Science degree in mechanical engineering from North Carolina State University, and a Bachelor of Science degree in the same field from the University of South Carolina.

About the Project

This project aims to develop a framework to analyze household responses to any electricity pricing scheme, especially in regions where statistical data are unavailable or insufficient. The framework combines physical and microeconomic principles. The physical side governs electricity use throughout the day, while the microeconomic side imposes a normative utility function for the household, to represent its welfare.

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