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Modeling residential electricity consumption and efficiency within an economic framework: Insights gained by using an engineering-based approach

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About KAPSARC

The King Abdullah Petroleum Studies and Research Center (KAPSARC) is an independent, non-profit research institution dedicated to researching 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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Introduction

Many countries have promoted energy efficiency and conservation in the residential sector due to its significant contribution to total demand. This paper discusses some of the wider implications of more efficient households on the overall energy system. Various efficiency options, such as thermal insulation or weather stripping, have unique effects on the power load demand throughout the day. The load-shifting potential of these measures is highly dependent on regional climate and residence characteristics. Moreover, the operational decisions made by the power sector to meet demand are contingent on the path by which load evolves during the day. Quantifying the intra-day effects of higher efficiency on total load is therefore useful in assessing the changes in equipment and fuel use decisions made by the utilities.

The consequences extend beyond power generation. Potential changes in the quantities of fuels burned for electricity, which also depend on the characteristics of the generation capacity, have cascading effects on the upstream production and refining sectors. We have developed a bottom-up approach to represent the interactions between residential electricity demand and energy sectors in the economy. The methodology involves the integration of a simulation of household electricity consumption with the KAPSARC Energy Model (KEM) for Saudi Arabia.

The effect of improved residential energy efficiency on the Saudi power sector for the year 2011 would have been, using our simulation approach, that:

- raising the average air-conditioner energy efficiency ratio (EER) from its 2011 average of 7 BTU/(W·hour) to 11 BTU/(W·hour) could have saved 225 thousand barrels per day (bpd) of crude oil or, alternatively
- increasing the share of insulated homes from 27% to 64% would have allowed the power sector to lower its use of fuel by more than 150 thousand bpd
- combining both measures in a single simulation shows incremental yet not additive reductions of about 270 thousand bpd.
- The rate of oil savings during the summer months is higher than the annual average. The efficiency measures, which lower the amount of electricity used for cooling, alleviate the large seasonal swings in domestic oil consumption for electricity generation.

All alternative scenarios result in reduced costs to the utilities and improve the average thermal efficiency for the electricity generated; the peak-shaving consequences of some efficiency measures result in forgoing the use of the least efficient turbines in the power sector, compared to a baseline case. This effect, which is difficult to capture with conventional input-output techniques, further yields differing crude oil flow between the upstream and power sectors per unit of electricity generated.

Residential electricity consumption and efficiency

According to the International Energy Agency (IEA) (2013), the residential sector accounted for more than a quarter of global electricity consumption in 2011; in some countries, like Saudi Arabia, this share is around 50%. Many countries have therefore taken initiatives to promote energy conservation and efficiency in the residential sector. Complementing price incentives, efforts aimed at mitigating the effects of controllable and uncontrollable physical factors are also important. Physical factors affecting energy demand include regional climate and housing stock characteristics.

Efficiency options may be categorized into those that impact heat transfer to and from the air-conditioned zones and those that impact the direct use of electricity. The former category dictates how much energy we use to maintain comfortable conditions at home. The amount of heat gained by an air-conditioned zone is influenced by outdoor weather conditions and solar radiation incident on the outer surfaces of the residence. It is also subject to the residence dimensions, materials selection for the walls and roof, window types, external and internal shading, and other structural characteristics. Measures mitigating the direct use of electricity address the performance features of appliances and other equipment in the home. An example of this is employing LED lighting in preference to incandescent or compact fluorescent lamps, or increasing the EER of the refrigeration cycle used for space cooling.

The implications of higher efficiency go beyond households. Ryan and Campbell (2012) have outlined the far-reaching economic benefits that could be realized by applying energy efficiency measures. The effects on the power generation and distribution sectors range from the lower consumption of fuel to avoiding future capital investment. Several other examples include reduced pollutant emissions, job creation through the implementation of efficiency programs, and potentially higher household disposable income that could be used on other goods and services.

Choosing an integrated methodology for modeling residential electricity use

Past studies have provided detailed reviews of bottom-up and top-down modeling techniques used to calculate residential energy demand, including those by Grandjean et al. (2012) and Swan and Ugursal (2009). Both approaches have their strengths and weaknesses. Top-down models are able to capture the impact of socio-economic factors, such as income, on aggregate energy consumption. It is, however, often difficult to obtain a sufficient sample size of historical data or statistically-significant price effects. Additionally, top-down models do not provide any decomposition of the aggregate energy use.

A statistical bottom-up approach, which explicitly considers end-uses, may also suffer from the lack of historical information for calibration. Engineering-based bottom-up models can remedy some of these deficiencies and represent specific technical features quantitatively. The major drawbacks of an engineering-based approach include potentially expensive computational requirements, a lack of satisfactory treatment of socio-economic variables, and having to approximate occupant behavior patterns. Typical input parameters for this class of models are weather data, structural attributes of the regional housing stock, schedules for the use of appliances, and the characteristics of the heating, ventilating, and air conditioning (HVAC) systems.

We designed an integrated methodology in which an engineering-based residential electricity demand model is used within an economic equilibrium framework. We chose this type of end-use model because it simulates the level of electricity consumption throughout the day while capturing physical factors that vary regionally. For instance, efficiency options that affect the heat gained by air-conditioned zones will have a delayed impact on electricity demand, because it takes longer for changes in external temperature to affect the interior of the building if they are better insulated. The magnitude of this delay differs based on the materials used in the buildings' construction and regional climate characteristics. In this way, we can allow for the specification of intrinsic physical characteristics of homes rather than be limited to testing arbitrary reductions in aggregate electricity use.

HVAC imposes significant effects on the demand for electricity. In Saudi Arabia, for example, 70% of residential electricity use is attributed to cooling. Our residential model constructs power load curves using the electricity consumption of HVAC systems as the foundation upon which other end uses are added. The model simulates the conductive, convective, and radiative heat gains that take place in residential enclosures of archetypes representing the regional housing stock. The required operating level of the HVAC system to achieve some desired indoor air conditions is also calculated. The framework consists of simulating hourly electricity use for representative days for four regions in Saudi Arabia by season. The calculations are performed for two types of day, weekdays and weekends/holidays. Matar (2015) provides more detail on the mathematical formulation of the model and its calibration.

The benefit of our bottom-up approach can be significant because the operational decisions of the power sector change throughout the day, depending on the level of demand. These temporal interactions between demand and electricity generation cause different fuel use and equipment ramping decisions as a result of altering the physical characteristics of the residences.

The residential approach is linked with KEM for Saudi Arabia, which is our bottom-up economic model that characterizes six sectors of the Saudi energy economy; the sectors included are:

– upstream production
– oil refining
– petrochemicals
– power
– water desalination, and cement

We have a fine representation of the technologies and production processes for each sector. We also consider regional differences in climate and housing stock through a disaggregation of the country into four regions. It is important to account for the role of climate as the four regions experience contrasting seasonal temperature and relative humidity profiles. Matar et al. (2014a) provide a detailed description of KEM for Saudi Arabia and its data inputs. Figure 1 illustrates the interactions taking place between modeled sectors and how residential demand is integrated. The residential model is run separately, and its results are input to KEM for Saudi Arabia as part of the demand the power sector has to satisfy.

The bottom-up technique we have adopted allows us to capture the equilibrium effects that may not be well represented in alternative approaches. It is normal for economy-wide studies of energy efficiency to track the flows of goods and services between production sectors using input-output coefficients. These coefficients are defined as the amount of goods and services flowing from one sector to another per unit of output by the receiving sector. Even if those models use dynamic coefficients that change over time, the values are constant for any given year. However, our approach is able to consider both the effects of lower electricity demand and changing generation efficiency on the quantities of fuels purchased by the power sector.

Models based on fixed input-output coefficients (in any year) would overlook this latter effect, which exists because changes in intra-day electricity consumption can cause the power sector to use its capacity differently. In other words, the amounts of fuels attributed to power inputs into other sectors can change, and the economy-wide input-output coefficients do not necessarily remain constant.

Summary of the power sector in KEM for Saudi Arabia:

The power sector is formulated as a cost-minimizer that currently uses chronological load demand curves for each region to make equipment and fuel use decisions. The load curves are broken up into eight discrete load segments. The considered power generation technologies are:

- conventional thermal plants
- nuclear
- photovoltaic
- concentrated solar power with thermal storage
- wind

The model structure uses variables for existing capacities, building additional plants, and the operation of the installed capacity in each load segment. The operation of non-dispatchable plants, like photovoltaic and wind turbines, is bound by physical constraints, such as the availability of solar radiation and wind. A transmission network is also represented to allow for the flow of electricity between regions. In addition to capacity balance, operation, and cost accounting constraints, reserve margin requirements may also be enforced.

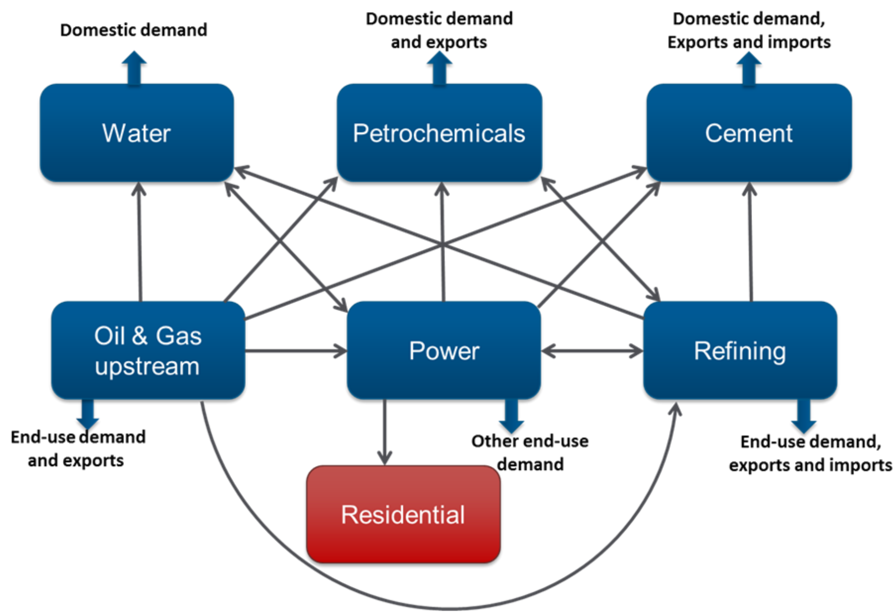

Figure 1: Flows of goods between sectors in KEM with the residential model integrated
Source: KAPSARC

An illustration: More efficient households in Saudi Arabia

We applied the integrated framework to investigate the benefits of more efficient households on the greater Saudi energy system. In addition to a Reference scenario replicating the year 2011, three alternative scenarios examine the widespread adoption of more efficient air conditioners and better insulated homes. The analysis is performed in a short -run setting where the power sector can only use its existing capacity in 2011 to meet demand. The findings of Matar (2015) are summarized as follows:

- Interfacing the residential model with KEM for Saudi Arabia quantifies the impact of the shifted system-level loads on the operating decisions of the power sector
- The increase of air conditioning efficiency, and the higher prevalence of thermal insulation in homes, lower oil consumption for electricity generation
- Raising the average EER to 11 BTU/(W.hour) from its 2011 average would have reduced crude oil burned in power plants by 225 thousand bpd
- Alternatively, if 64% of homes were insulated rather than the 27% observed in 2011, the power sector could have reduced its use of crude oil as a fuel by nearly 160 thousand bpd
- Combining these efficiency options in a single simulation resulted in incremental, yet not additive, savings of about 270 thousand bpd

The two measures have interacting features; reducing the heat gain would lower the extent to which air conditioning is utilized, thus lessening the impact of a higher EER. Also, domestic consumption of oil for power generation peaks in the hot summer months and dips low in the winter. These large seasonal swings would be mitigated by efficiency options targeting the demand for space cooling. Table 1 shows the seasonal reductions in oil consumption, in addition to a more complete set of results. The estimates of cost reduction account for

		Reference	Higher Prevalence of Thermal Insulation	Increased EER to 11 BTU/(W·hour)	Combined EER and Insulation
National residential electricity consumption (TWh)		111.4	93.6	86.0	74.1
Reduction in total cost to power sector (million USD)		-	429	608	880
Reduction in crude oil consumption by power sector (thousand barrels per day)	Summer	-	234	339	376
	Spring and Fall	-	169	229	272
	Winter	-	58	98	147
	Yearly Average	-	158	225	268
Average thermal efficiency of electricity generation		34.0%	35.0%	35.5%	36.3%

Table 1: Simulation results at the national level for a reference and alternative scenarios in a 2011 setting
Source: KAPSARC analysis

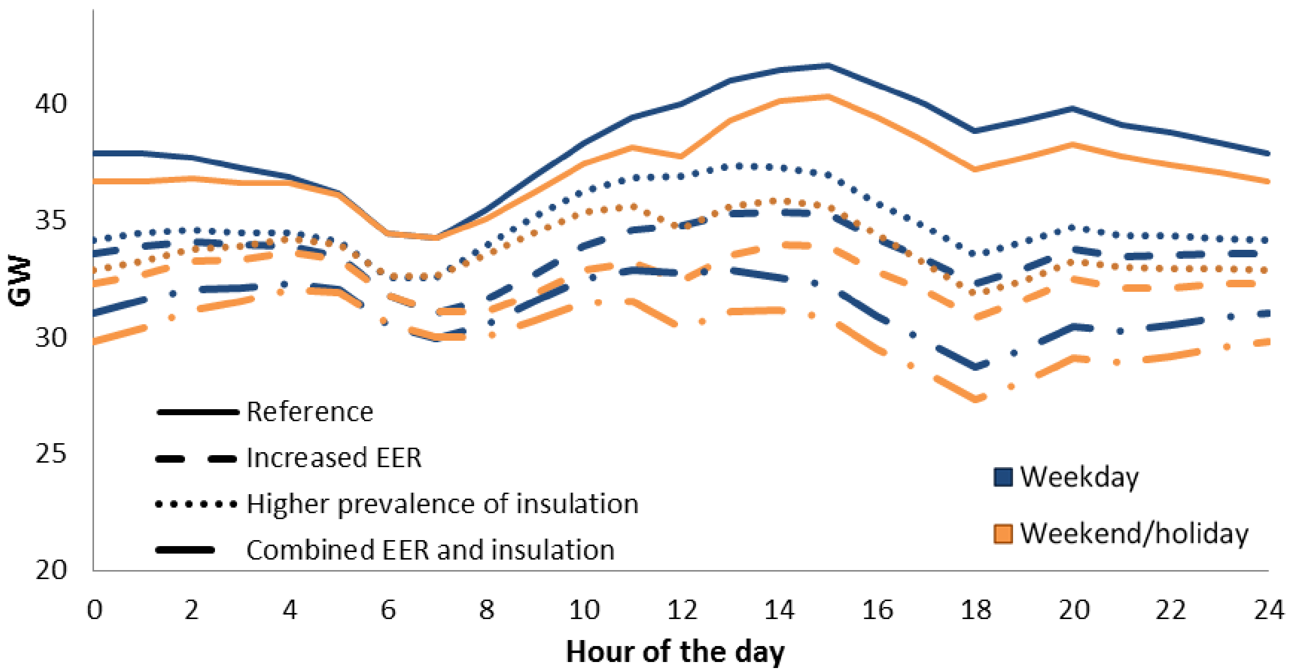

Figure 2: The system-level load curves for each scenario in the summer
Source: Electricity and Co-generation Regulatory Authority, KAPSARC analysis

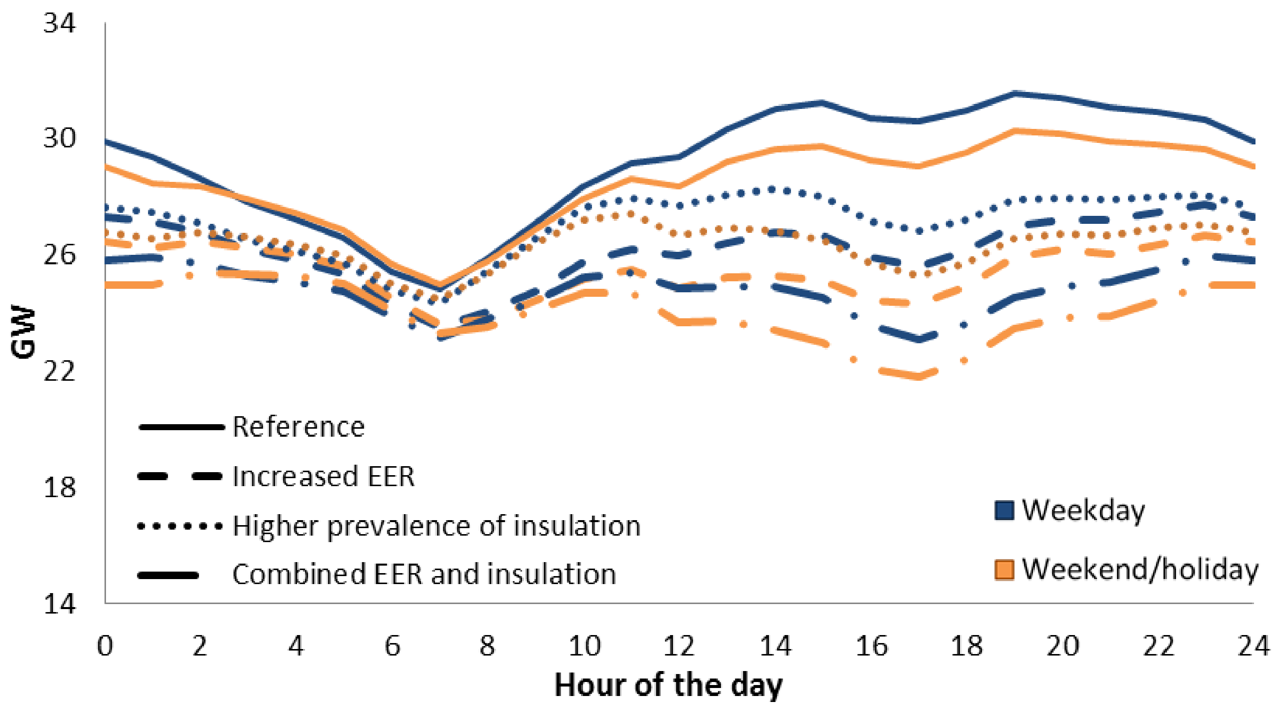

Figure 3: The system-level load curves for each scenario in the Spring and Fall
Source: Electricity and Co-generation Regulatory Authority, KAPSARC analysis

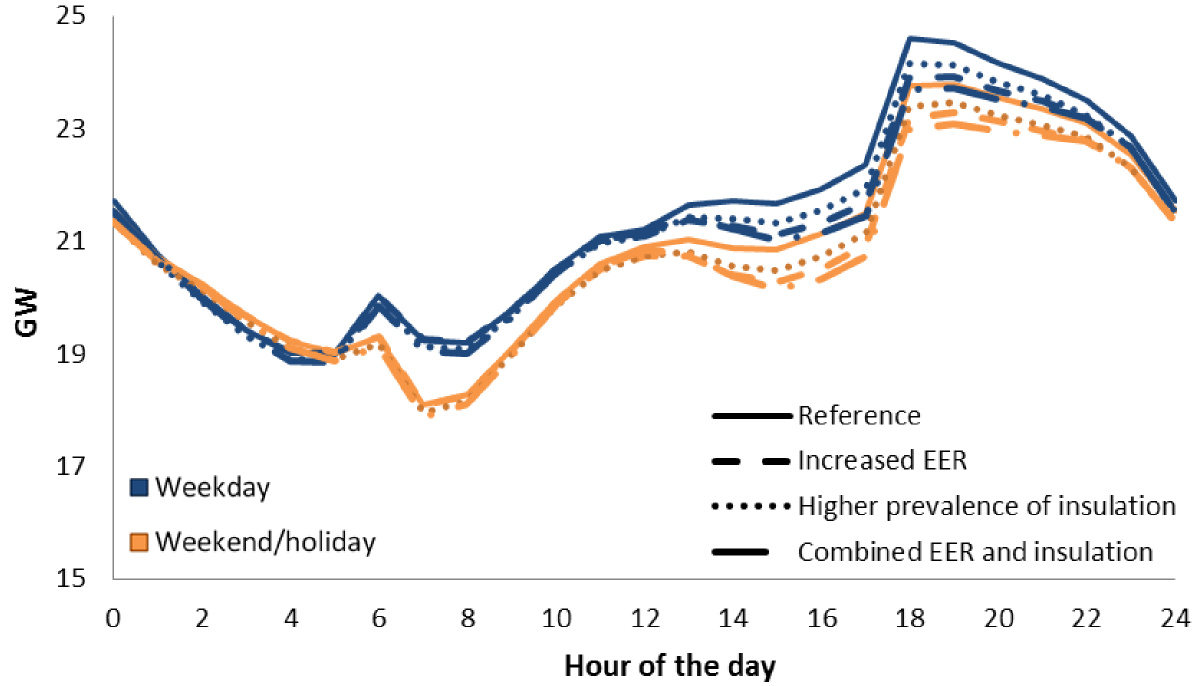

Figure 4: The system-level load curves for each scenario in the winter
Source: Electricity and Co-generation Regulatory Authority, KAPSARC analysis

the fuels purchased at the locally-administered prices, fixed operations and maintenance (O&M) costs, and non-fuel variable O&M costs.

The widespread adoption of residential efficiency measures introduces profound effects on the overall energy system. In general, different efficiency options do not uniformly shift the electricity load curves. The impact of higher thermal resistance of the building enclosure on the hourly system loads is delayed, whereas the effects of measures altering the direct use of electricity are instantaneous. This is demonstrated by the simulated load curves for the three alternative scenarios, illustrated by Figures 2 to 4 at the national level for three seasonal periods. These system-level load curves are used by KEM for Saudi Arabia in each scenario to satisfy demand.

Lowering electricity consumption during the peak load period, when the least efficient turbines are used, would result in higher fuel savings for the power sector than a reduction of the same amount during other times of the day. This would allow the utilities to lessen their reliance on the least-efficient turbines. The average thermal efficiency for the total electricity generated increases from 34% in the Reference scenario to 35% and 35.5% in the Higher Prevalence of Thermal Insulation and Increased EER scenarios, respectively. Combining the features of those two scenarios yields an average thermal efficiency of 36.3%. Table 2 decomposes the contribution of higher generation efficiency to total crude oil savings. It can be seen that neglecting the secondary factor may result in underestimating the magnitude of the economic spillovers resulting from more efficient households.

The observed change in average thermal efficiency in the alternative scenarios means that the input-output coefficients that relate to the fuel-supplying sectors and the power sector do not remain constant. Thus, the amount of intermediate consumption of fuel that is purchased from the upstream or refining sectors per unit of gross output by the power sector,

Factor	Season	Higher Prevalence of Thermal Insulation	Increased EER to 11 BTU/(W·hour)	Combined EER and insulation
Lower electricity production	Summer	199	291	334
	Spring and Fall	144	201	249
	Winter	58	97	147
Higher efficiency	Summer	34	48	42
	Spring and Fall	26	28	23
	Winter	0.6	1.1	0.9

Table 2: Decomposition of the factors contributing to lower oil use by power sector*
Source: KAPSARC analysis
* Units in thousand barrels per day. The fuel savings due to lower production are calculated as the change in electricity output using oil multiplied by the average heat rate of oil-generated electricity in the Reference scenario. Similarly, the savings due to higher efficiency are computed as the change in the average heat rate of oil-generated electricity multiplied by the quantity of electricity produced using oil in the alternative scenarios.

would not be the same. If the reduction in fuel use were in the form of refined oil products, the varying operations of the refining sector may additionally result in a change in the technical coefficient that relates it to the upstream sector.

Next steps

Our future research will turn to modeling residential energy use and the demand response to price. The approach applied in this analysis is augmented to measure the intra-day effects of reforming electricity tariff schemes.

In Saudi Arabia, for example, the residential electricity tariff starts at 0.05 Saudi Arabian Riyals (SAR) per kWh for the first 2 MWh/month and ultimately reaches 0.26 SAR/kWh for every unit consumed beyond 10 MWh/month. Altering the tiered pricing structure represents one possible approach. However, prices do not vary during the day and therefore provide no incentive for load shifting during peak hours. The implications of time -of-use, or real-time pricing, can be studied within the same economic framework and in conjunction with technical efficiency measures.

Any reform of electricity tariffs will need to chart a course between delivering the most economically efficient outcome with minimizing the economic disruption to the most vulnerable in society. This applies in Saudi Arabia as much as to other regions of the world, where the competing demands of fuel poverty alleviation and energy efficiency confront each other. KAPSARC is aiming to provide a framework for resolving such policy trade-offs.

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About the project

We developed the KAPSARC Energy Model (KEM) for Saudi Arabia to understand the dynamics of the country's energy system. As part of that work, we are now exploring the representation of end-use energy demand. End-use energy efficiency can have cascading effects on other sectors in the energy economy, and these effects can differ from one region to another. The objective of this analysis is to explore the potential impact of higher residential efficiency on an energy system. This paper introduces a framework to measure the wider system effects of implementing structural and technical efficiency options. To accomplish this, an engineering-based residential electricity demand simulation has been linked with KEM for Saudi Arabia.