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King Abdullah Petroleum Studies and Research Center

Residential energy efficiency investment and demand response under different electricity pricing schemes: a hybrid physical-microeconomic approach

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Motivation

- Empirical estimates of the own-price elasticity may not be policy-relevant. e.g.,
  - Atalla and Hunt (2016): Some countries in the Gulf Cooperation Council were found to have price elasticities of zero.
  - Similarly, South Africa had a low price regime for many years. (Deloitte, 2017)

- In regions where empirical estimates are serviceable, policymakers/researchers may want deeper insight regarding energy efficiency adoption and behavioral demand response.

Atalla, Tarek N., and Hunt, Lester C. “Modeling Residential Electricity Demand in the GCC Countries.” *Energy Economics 59* (2016): 149-158.

Deloitte. “An overview of electricity consumption and pricing in South Africa: An analysis of the historical trends and policy, key issues and outlook in 2017.” Deloitte (2017): 29.

The general idea

- Electricity consumption is governed by physical equations, as would be found by building energy models
- The household's decision-making is governed by a utility function and a budget constraint.
- The model solves for a wide range of options, and in the end determines which combination of behavioral demand response and energy efficiency adoption maximizes utility.

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

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

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

$i \in$ {*electricity use for air-conditioning, electricity use for lighting, other electricity use, other goods and services*}

$k \in$ {*air conditioner with higher EER, LED lightbulbs, reduced infiltration, Low-e window glazing, thermal insulation*}

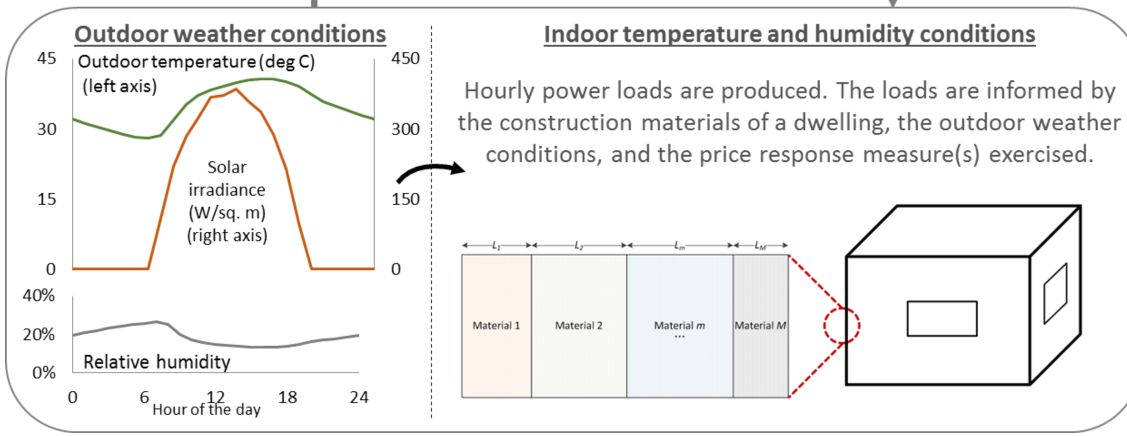
$x_i > 0, \phi_i \geq 0, \alpha_i > 0, e_i \geq 0, e_{IEE} \geq 0, 1 \geq \varphi \geq 0, ac_k \geq 0, Income > 0, \sigma > 0$

$ac_k \equiv annualized\ costs\ of\ k$

$x_j \equiv$ electricity uses, in MWh

(j is a subset of i that consists of all elements of electricity use)

$e_{electricity} \equiv$ electricity expenditure, in thousand USD



- ϕ_i are adjustment factors that estimate the utility gained by the installation of energy efficiency.

- The values of ϕ_i are unity, except for when the energy efficiency measures affect the cooling load and/or lighting in a dwelling. For example, for air-conditioning electricity use,

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

Where,

EER $\equiv$ average air-conditioning energy efficiency ratio
IHG $\equiv$ internal heat gain in the indoor environment
SHG $\equiv$ solar heat gain through windows
ΔT $\equiv$ sum of the changes in temperatures of walls/roof minus indoor setting
ω $\equiv$ the air infiltration rate

- Past analyses using this approach:
  - Matar, W. “Households' response to changes in electricity pricing schemes: bridging microeconomic and engineering principles.” *Energy Economics 75*. 2018.
  - Matar, W. “A household’s power load response to a change in the electricity pricing scheme: an expanded microeconomic-physical approach.” *The Electricity Journal*. 2019.

- They focus on short-run price response (i.e., no possibility of energy efficiency investment)

- This analysis takes a long-run view.

Assumptions and model inputs

- An analysis using archetypical villas in four regions of Saudi Arabia
- Utility function parameterization:
  - The preference share for electricity ranges between 5% and 7%, depending on region. (calibrated)
  - That is disaggregated into 70%, 5%, and 25% for the air conditioner, lighting, and other electricity uses. (using existing data)
  - Preference share for other goods and services completes the 100%.
  - σ is calibrated.

- We look at two incentive cases: no incentives, and a case where a household receives 50% reduction in costs

- Discount rate is 30% [Harrison et al (2002) and Enzler et al (2014) found similar average values for households]

- Regional annual household incomes are from Saudi Central Department of Statistics and Information (now called the General Authority of Statistics).

Assumptions and model inputs

Monthly use (MWh)	Pricing in 2016 and 2017 (US cents per kWh)	Pricing in 2018 and 2019 (US cents per kWh)
≤ 2	1.33	4.80
2 < and ≤ 4	2.67	
4 < and ≤ 6	5.33	
6 <	8.00	8.00

Time of year	TOU electricity price scheme (US cents per kWh)
In the summer months during the peak hours (from 12 pm to 5 pm)	15.00
Outside of the summer peak hours, including all other seasons	5.00

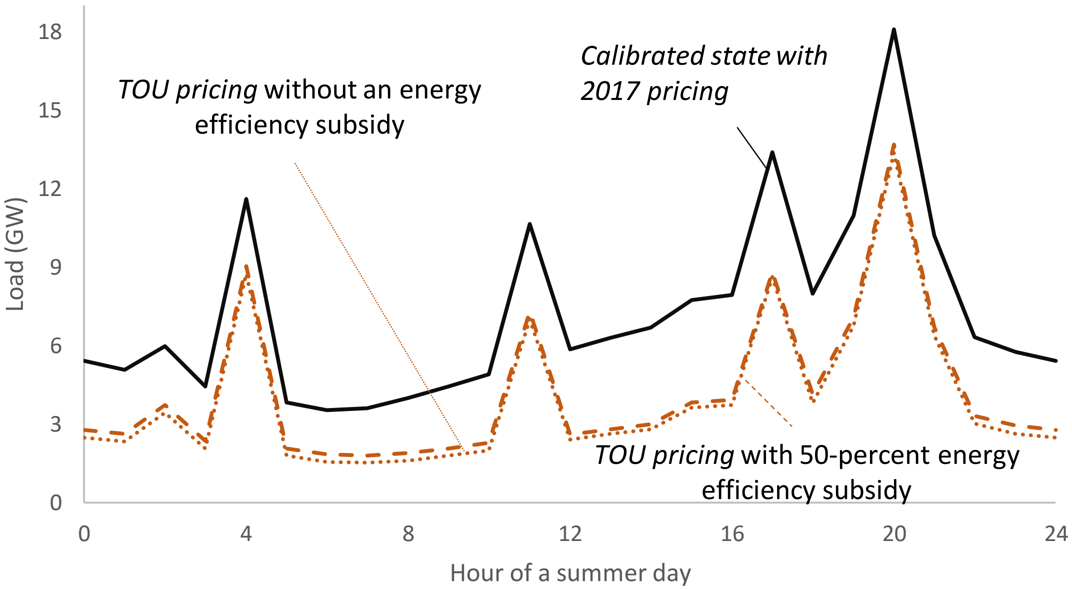
Energy efficiency measure	Full purchase cost (USD per household)
Air conditioners with average EER of 15 BTU/Wh	$c_{AC} \cdot \max(\dot{Q}_{cooling}) \cdot dt + L_{AC}$
Sealing cracks around windows, doors, power outlets, and lighting fixtures	$c_{seal} \cdot TFA$
Low-e windows	$c_{window} \cdot TGA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

Energy efficiency cases	Demand response measures			
	Thermostat set-point adjustments			
	Summer, spring, and fall	Additional adjustment during the peak in the summer	Turning off lights	Appliance load shifting
Without higher energy efficiency Air-conditioning with average EER of 15 BTU/(Wh) Reduced infiltration to 0.30 ACH Low-e windows More stringent thermal insulation 100% LED adoption The combination of higher EER, sealing cracks, and LED adoption	Incrementally raising the set-point from 0 ^{o}C to 3 ^{o}C in the summer, or from 0 ^{o}C to 1.5 ^{o}C in the spring and fall.	The household has the option to raise the thermostat set-point further from the summer setting by 0.5 ^{o}C.	Incrementally lower the lighting requirement in the dwelling.	The household may shift its appliances use based on its perceived cost, which is the sum of the monetary cost and a cost of inconvenience.

Electricity use by electricity price and incentive

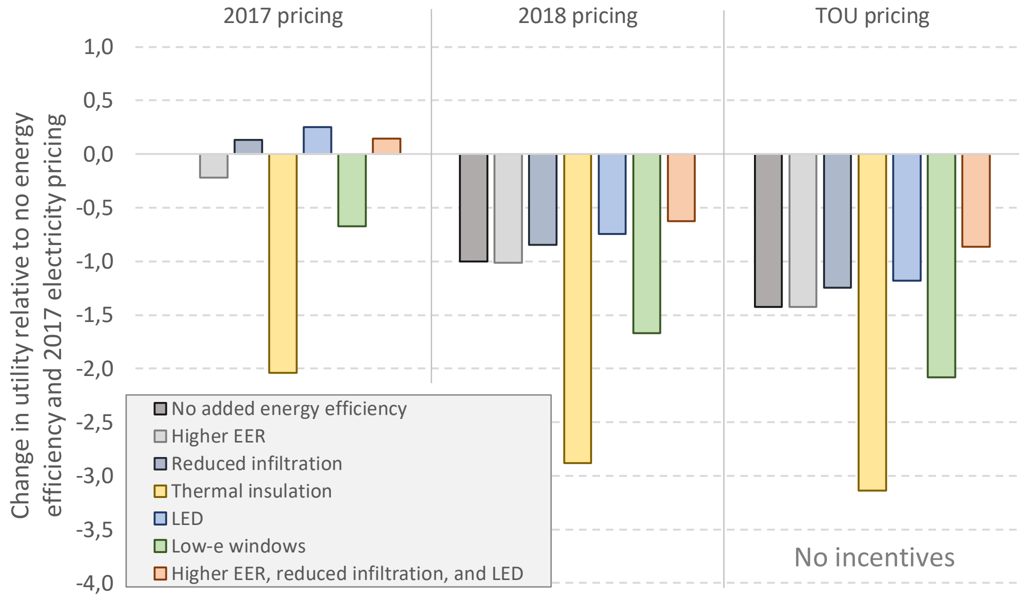
- There is some slight energy efficiency investment in the base case.
- There are some efficiency cases, like the adoption of LED lighting and sealing cracks around the dwelling, which yield a larger benefit in the long-run than their cost.
- With TOU pricing, the hourly loads are slightly higher with 50 percent incentives than a case without.
- The differences comes about because of the behavioral response, where households do not conserve as greatly when the efficiency cost is subsidized.

		Incentive level (as a percentage of the measure's purchase cost not covered by the household)	
		None	50%
Electricity price scheme	2017 pricing	46.58	29.74
	2018 pricing	29.37	29.74
	TOU pricing	29.07	29.67

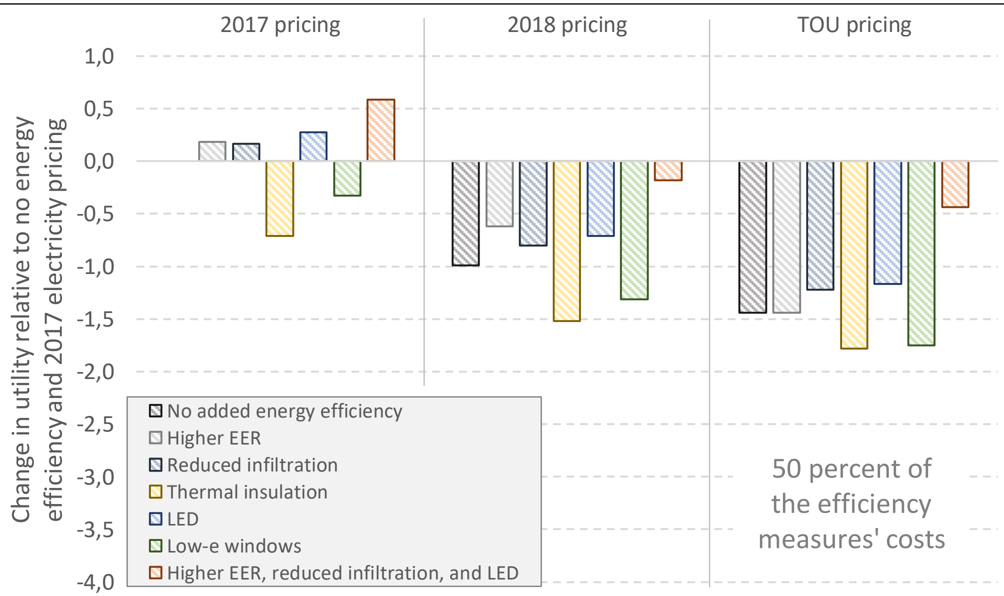


Effects of energy efficiency on household welfare

No incentives



50% of the efficiency measures' costs covered by households



Direct rebound:

- Our modeling framework makes the existence and measurement of direct rebound tricky.
- Model results suggest that with added energy efficiency, the household does not respond as aggressively to a higher electricity price. But how can we say that their adjusted response is a rebound?

Indirect rebound:

de Miguel et al (2015) say that indirect rebound in the context of higher disposable income has received little attention in the literature.

There is model evidence suggesting that as energy efficiency incentives and electricity prices increase, the expenditure on other goods and services increase as well.

de Miguel, Carlos, Xavier Labandeira, and Andreas Löschel. “Frontiers in the economics of energy efficiency.” *Energy Economics 52* (2015): S1-S4.

Summary

- The possibility for energy efficiency investment lowers the need for conservation at optimal consumer welfare.
- Raising monetary incentives that result in less personal expenditure on energy efficiency, households lessen the extent to which they practice conservation.
- There is a diminishing marginal benefit that is non-linear gained by installing energy efficiency.
- As energy efficiency subsidies and electricity prices rise, the difference in household spending on other goods and services widens between the highest efficiency case and no added efficiency. This indirect rebound effect causes a situation where firms increase their production to meet the additional demand from households, which will require more energy.

Thank you.

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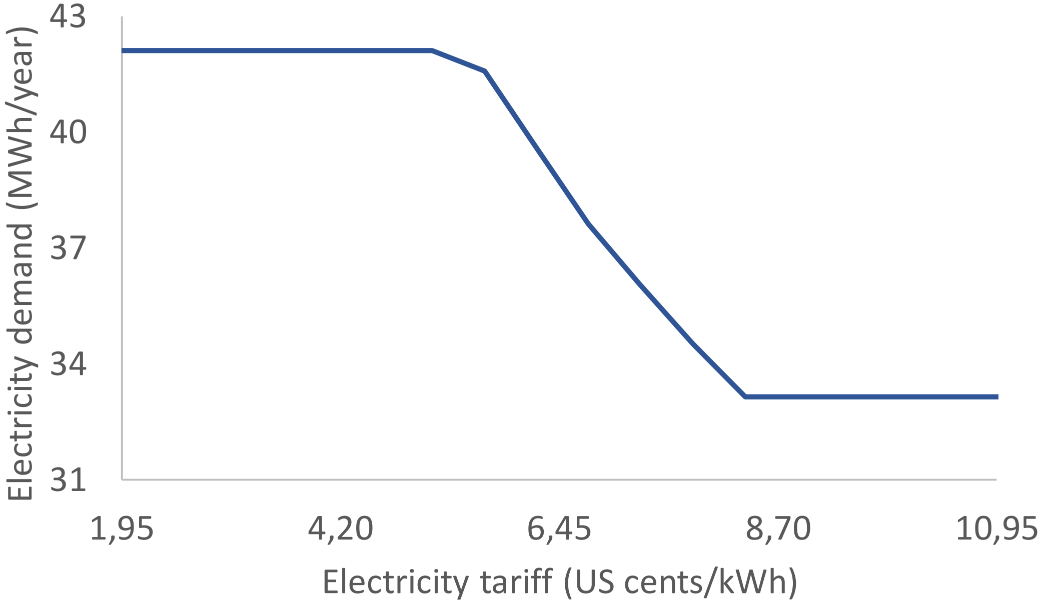
Other references

- Enzler, Heidi Bruderer, Andreas Diekmann, and Reto Meyer. “Subjective discount rates in the general population and their predictive power for energy saving behavior.” *Energy Policy 65* (2014): 524-540.
- Harrison, Glenn W., Morten I. Lau, and Melonie B. Williams., “Estimating individual discount rates in Denmark: a field experiment.” *American Economic Review 92(5)* (2002): 1660-1617.
- Central Department of Statistics and Information (CDSI). “Household Expenditure and Income Survey 1428 H.” CDSI (2013): 28.

Addendum – Threshold price to achieve a response

- Allcott (2009) suggested that there exists a threshold electricity price rise, below which a household does not respond. i.e. a non-linear function.
- Obtained from the present model, this displays the inverse short-run demand function for a particular household in a villa in the central region of Saudi Arabia:



Allcott, Hunt. "Real time pricing and electricity markets." Harvard University. (2009): 17.