Renewable Energy

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Table of Content

Gowrisankaran, Reynolds, Samano. “Intermittency and the value of renewable energy” JPE, 2016, Lee, Miguel, Wolfram. “Appliance ownership and aspirations among electric grid and home solar households in rural Kenya” AER (2016)

Introduction

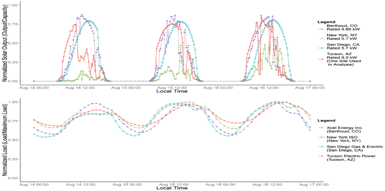
- Renewable capacity increased: falling price+ policies
- Problem is intermittency: solar generators produce only when the sun is shining
- This paper: structurally quantify social costs and reductions in carbon emissions
- Social cost depends on:
  1. variability & its correlation with demand
  2. forecastibility in its output
  3. costs of building backup generation for system reliability
- Counterfactual with real-time pricing
- Related literature: systems engineering + economics literature
- Engineers ignore re-optimizing of policies.

The Electricity Industry in the Tucson Area

- Tucson Electric Power (TEP), vertically integrated
- 91% of new fossil fuel in Arizona: combined cycle generators
- State-mandated Renewable Portfolio Standard: 3% (15%) from renewables by 2011 (2025)
- Absence wind generation in Arizona
- Scenarios 10, 15, 20 % of generation from solar
- Operating reserves: $\approx 1.5\%$ of peak load.
  - contingency reserves, used in the event of a generator failure
  - balancing reserves, used to smooth out fluctuations in load and renewable output

Solar Energy

- Intermittency:load and solar PV output



- Positive correlation between load and solar output
- Increases value of solar installations
- But, late afternoons with high load but low solar output
- ⇒ still need fossil fuel capacity
- Large fluctuations in solar over a fine time scale
- Not forecastable ⇒ increases reserve operation costs
- State mandate: 30% of renewable consist of distributed

Model-Overview

- Retail price of electricity as given
- Stage 1: system operator decides on capacity investment + a price for interruptible power contracts to customers
- Stage 2: operator decides on generator scheduling +demand-side management
- After scheduling& curtailment, solar output realized

Demand and Consumer Welfare

- Retail price (constant) $\bar{p}$
- Demand: random of weather ($\vec{\omega}$)
- $\vec{\omega}=$ cloud, temperature, time of day, day of week, sunrise
- Constant price elasticity η up to reservation value ν, scale $\bar{D}$ varies stochastically with $\vec{\omega}$ $\bar{D} \sim F^{D}(.|\vec{\omega}$

$$Q^{D}(p,\bar{D}) = \begin{cases} 0 & p > \nu \\ \bar{D}p^{-\eta} & p \leq \nu \end{cases}$$

- $F^{(}.|\vec{\omega})$ has a lower bound $D^{\bar{min}}(\vec{\omega})$
- Value of lost load (VOLL): mean value of electricity per unit for customers
- Manage demand by voluntary arrangements to curtail demand when necessary, in exchange for a payment at the time of curtailment

Demand and Consumer Welfare

- Curtailment contracts at price p_c
- If necessary, curtaile & paid a net per-unit price of $p_c\bar{p}$ as compensation
- Quantity z of demand curtailment is decided
- $WLC(z, p_c)$: welfare loss from curtailment

Generation, Transmission, and Reserves

- Generators: $j = 1, \cdots, J$
- Maintenance status $m_j \in \{0, 1\}$, $m_j = 1$ unavailable
- Maintenance with probability P_t^{maint}, iid
- System operator schedules available units for production and reserves
- let on_j denote a 0–1 scheduling indicator
- $m_j = 1$ implies that $on_j = 0$
- Marginal costs (MC) c_j and capacity k_j
- MC of reserves: fraction c^r of c_j
- Probability P_j^{fail} of failure in any hour, ii
- Maximum output

$$x_j(on_j) = \begin{cases} k_j \quad with \quad probability(1 - P_j^{fail})on_j \\ 0 \qquad\qquad\qquad Otherwise \end{cases}$$

Generation, Transmission, and Reserves

- $\vec{x}(\vec{on})$: maximum outputs for all generators
- Decide on number of new fossil fuel generators, n^{FF}, with fixed capacity k^{FF}, capacity costs of FC^{FF} per MW of capacity, operating costs of c^{FF} per MWh.
- New fossil fuel units $j = J+1, \cdots, J+n^{FF}$
- Fixed solar PV capacity n^{SL}, zero MC & maintenance & failure probabilities, capacity costs FC^{SL} per MW of capacity
- Solar production: state-contingent distribution $n^{SL}\bar{S}$, where $\bar{S} \sim F^{S}(.|\vec{\omega})$
- $\vec{F}(.|\vec{\omega})$ joint distribution$\vec{F}^{D}(.|\vec{\omega}), \vec{F}^{S}(.|\vec{\omega})$

Generation, Transmission, and Reserves

- Solar close to lines, wind far from
- d^{SL} installed in a distributed environment, lowers transmission costs
  1. Lower the fixed costs of transmission lines, function of maximum loads

$$TFC(n^{SL}) = AFC^{T} \max_{\vec{\omega}} \left\{ E[\bar{D}(\vec{\omega})\bar{p}^{-\eta} - d^{SL} n^{SL} \bar{S}(\vec{\omega})] \right\}$$

  2. . Lower line losses: Line loss: $LL = \alpha(Q + LL)^2$ solve to

$$LL(Q) = (2\alpha)^{-2}(1 - 2\alpha Q - \sqrt{1 - 4Q\alpha})$$

System Operator's Problem

- Max expected discounted total surplus, s.t. $\bar{p}$, n^{SL}
- Discount β, life span T (generators)
- First stage: n^{FF}, p_c
- Second stage: conditional on weather forecast $\vec{\omega}$, maintenance statuses $\vec{m}$
  1. Generator scheduling decisions $\vec{on}$
  2. Amount of demand to be curtailed z
- Operator chooses $\vec{on}_j$ for each unit with $\vec{m}_j = 0$
- Then, state-specific random variables are realized: may outage
- Otherwise, low mc are on and high mc as reserve
- $PC(D, \vec{x})$: ex post minimized costs of generation & reserves
- D: demand (net of curtailment) plus line loss minus solar production
- $\vec{x}$ denotes generator output realization vectors.

Simple example calculation PC

- Two scheduled generators each with capacity 1
- $c_2 > c_1$, $D = 1.6$, and no generator failures
- Demand realization ⇒ Output 2=0.6

$$PC(1.6,(1,1)) = c_1 + 0.6c_2 + 0.4c_2c^r$$

- Outage 0-1 indicator for a system outage

$$Outage(\vec{on}, z, \vec{\omega}) = 1\left\{\sum_{j=1}^{J+n^{FF}} x_j(on_j) + n^{SL}\bar{S} < \bar{D}\bar{p}^{-\eta} - z + LL(\bar{D}\bar{p}^{-\eta} - z - d^{SL}n^{SL}\bar{S})\right\}$$

- Supply less demand.
- d^{outage}: fraction lose power times number of hours

Simple example calculation PC

- System operator's problem for a second-stage

$$\begin{aligned} W(\vec{\omega},\vec{m}|n^{FF},P_c) = \quad & \max_{\vec{on},z} E\left[1 - d^{outage} outage(\vec{on},z,\vec{\omega})\right. \\ & \times \left[\bar{D}\bar{p}^{-\eta} VOLL - WLC(z,P_c)\right] \\ & \left. -PC(\bar{D}\bar{P}^{-\eta} - z - n^{SL}\bar{S} + LL(.),\vec{x}(\vec{on}))|\vec{\omega},\vec{m}\right] \\ & s.t. m_j = 1 \Rightarrow on_j = 0 \end{aligned}$$

- Expectation over $F(.,\vec{\omega})$ & $\vec{x}(\vec{on})$
- Stage 1: $P_c \& n^{FF}$ use expected value of W
- H be number of hours in a year

$$V(n^{FF}) = \max_{P_c} E\left[H \times W(\vec{\omega},\vec{m}|n^{FF},P_c)\right]$$

Simple example calculation PC

- Investment decision for system operator:

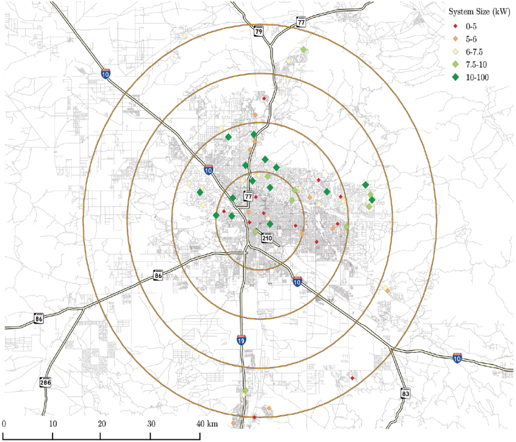
$$V^* = \max_{n^{FF}} \quad \Big\{ \tfrac{1-\beta^T}{1-\beta} V(n^{FF}) \\ -n^{SL} FC^{SL} - n^{FF} FC^{FF} - TFC(n^{SL}) \Big\}$$

- n^{SL} chosen by regulator

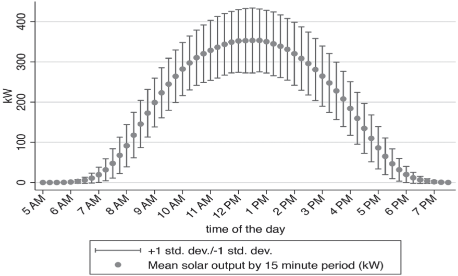
Data, Estimation, and Computation

- Data: May 2011 until April 2012
- Data on capacity, fuel source, location.
- EIA: average price & investment cost
- eGRID2010 rates on CO_2, SO_2, NO_x
- Solar: min size 2.3Kw, max size 84.2Kw
- Total capacity (58 sites) is 517 kW
- Map distances of 10, 20, 30, 40 Km from center Tucson
- Weather+forecast: National Oceanic and Atmospheric Administration
- Info at cloud cover, wind speed, temperature, relative humidity, dew point

Map of Tucson with solar sites



Solar Production by Hour of a Day



Estimation and Calibration of Parameters-Demand

- Demand parameters of base model

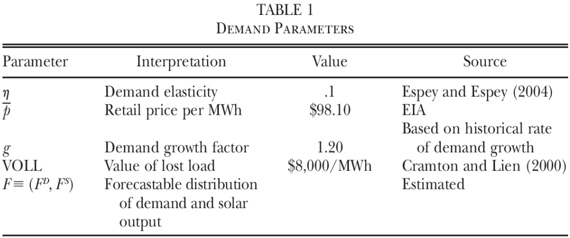


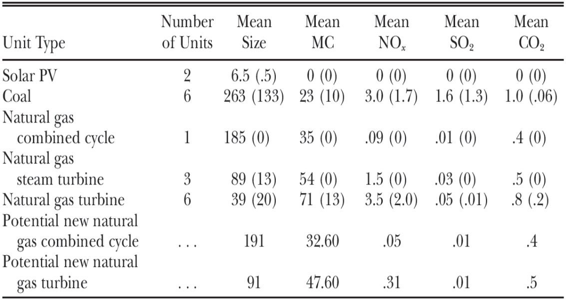
TABLE 1
DEMAND PARAMETERS

Parameter	Interpretation	Value	Source
η	Demand elasticity	.1	Espey and Espey (2004)
$\bar{p}$	Retail price per MWh	\$98.10	EIA
g	Demand growth factor	1.20	Based on historical rate of demand growth
VOLL	Value of lost load	\$8,000/MWh	Cramton and Lien (2000)
$F \equiv (F^D, F^S)$	Forecastable distribution of demand and solar output		Estimated

- F^D, F^S: seemingly unrelated regression with load and solar output as the dependent variables.
- Solar zero at night $\Rightarrow$ separate nighttime load regression
- Load estimates recovers $\bar{D}$ (demand equ)
- MC method like BBW (2002) for CA

Estimation and Calibration of Parameters-Technology

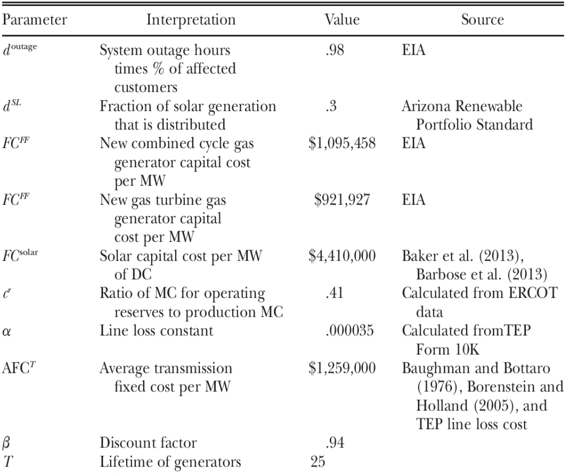
- New generators: Combined cycle w/ $k^{FF} = 191MW$



Unit Type	Number of Units	Mean Size	Mean MC	Mean NO_x	Mean SO_2	Mean CO_2
Solar PV	2	6.5 (.5)	0 (0)	0 (0)	0 (0)	0 (0)
Coal	6	263 (133)	23 (10)	3.0 (1.7)	1.6 (1.3)	1.0 (.06)
Natural gas combined cycle	1	185 (0)	35 (0)	.09 (0)	.01 (0)	.4 (0)
Natural gas steam turbine	3	89 (13)	54 (0)	1.5 (0)	.03 (0)	.5 (0)
Natural gas turbine	6	39 (20)	71 (13)	3.5 (2.0)	.05 (.01)	.8 (.2)
Potential new natural gas combined cycle	...	191	32.60	.05	.01	.4
Potential new natural gas turbine	...	91	47.60	.31	.01	.5

Estimation and Calibration of Parameters-Technology

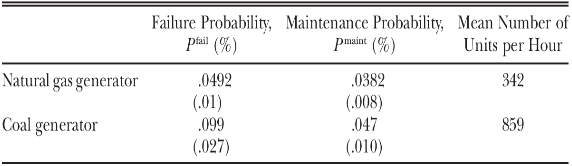
- Cost for PV and other sources



Parameter	Interpretation	Value	Source
d^{outage}	System outage hours times % of affected customers	.98	EIA
d^{SL}	Fraction of solar generation that is distributed	.3	Arizona Renewable Portfolio Standard
FC^{FF}	New combined cycle gas generator capital cost per MW	$1,095,458	EIA
FC^{FF}	New gas turbine gas generator capital cost per MW	$921,927	EIA
FC^{solar}	Solar capital cost per MW of DC	$4,410,000	Baker et al. (2013), Barbose et al. (2013)
c^{r}	Ratio of MC for operating reserves to production MC	.41	Calculated from ERCOT data
α	Line loss constant	.000035	Calculated fromTEP Form 10K
AFC^{T}	Average transmission fixed cost per MW	$1,259,000	Baughman and Bottaro (1976), Borenstein and Holland (2005), and TEP line loss cost
β	Discount factor	.94	
T	Lifetime of generators	25	

Estimation and Calibration of Parameters- Technology

- Line losses 6.6% for all year
- Using using $LL(Q)$ equation to find in any hour that match annual loss
- d^{outage}: in 2008, 21 outrage $\Rightarrow=$ duration × percentage of customers affected
- Mean hourly maintenance and failure probabilities



	Failure Probability, P^{fail} (%)	Maintenance Probability, P^{maint} (%)	Mean Number of Units per Hour
Natural gas generator	.0492	.0382	342
	(.01)	(.008)	
Coal generator	.099	.047	859
	(.027)	(.010)	

Computation of the System Operator's Problem

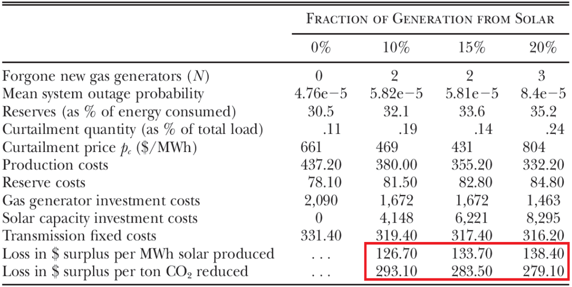
- Find n^{FF}, P_c given n^{SL}
- Given (long-tun) $(n^{FF}, P_c, \vec{\omega}, \vec{m})$, operator chooses $\vec{on}, z$
  - For each value of $(n^{FF}, P_c, \vec{\omega}, \vec{m}, \vec{on}, z)$, simulate generator failures $\vec{x}(\vec{on})$, demand and solar output $F(., \vec{w}) \Rightarrow$ solve for social welfare
- Short-run simplification assumptions:
  - Operator schedules in ascending order of MC
  - Operator curtails demand only if MC available generators ¡ marginal cost of curtailment ($\frac{dWLC(z)}{dz}$)

Results-Forecast Estimation Results

- U-shaped relation forecasted temperature and load
    - electricity for both heating and cooling
- Solar output negative on forecasted cloud
- Correlation in residuals load & solar output=.093 (significant)
- Forecast with perfect fit

Social Costs of Large-Scale Solar Energy

- Social costs of large scale solar generation

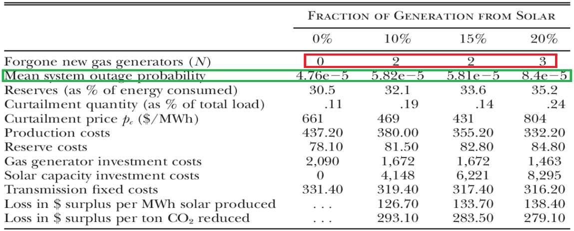


	Fraction of Generation from Solar			
	0%	10%	15%	20%
Forgone new gas generators (N)	0	2	2	3
Mean system outage probability	4.76e−5	5.82e−5	5.81e−5	8.4e−5
Reserves (as % of energy consumed)	30.5	32.1	33.6	35.2
Curtailment quantity (as % of total load)	.11	.19	.14	.24
Curtailment price p_c (\$/MWh)	661	469	431	804
Production costs	437.20	380.00	355.20	332.20
Reserve costs	78.10	81.50	82.80	84.80
Gas generator investment costs	2,090	1,672	1,672	1,463
Solar capacity investment costs	0	4,148	6,221	8,295
Transmission fixed costs	331.40	319.40	317.40	316.20
Loss in \$ surplus per MWh solar produced	. . .	126.70	133.70	138.40
Loss in \$ surplus per ton CO_2 reduced	. . .	293.10	283.50	279.10

- Paper: Social cost of large-scale solar \$126.70 to \$138.40 per MWh.

Foregone new gas generation+outrage probability

- Engineering calculation:
  - Solar average cost \$181.20, combined cycle \$66.30 per MWh
  - Simple average, solar PV additional per-unit cost of \$114.90 per MWh
- Paper endogenizes choices ⇒ higher solar cost by \$23
- Higher solar ⇒ weakly monotonically & nonlinear decreasing new natural gas



	FRACTION OF GENERATION FROM SOLAR			
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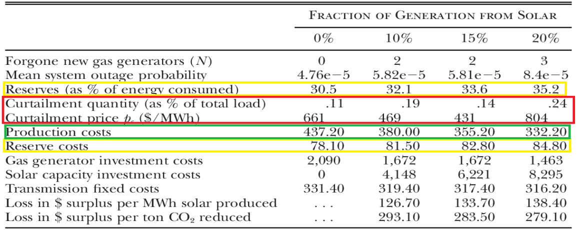
Reserve, production cost, curtailment

- Reserve increase is minor by solar 20%
- Cost adds only $6.7 million annuallly
- While decrease in production costs $105 million
- Demand curtailment in (July at 6 pm) rises 9.7 % to 58 %
- Curtailment at noon goes down monotonically
- Aggregate curtailment non-linear



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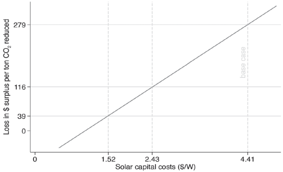
Environment, capital cost

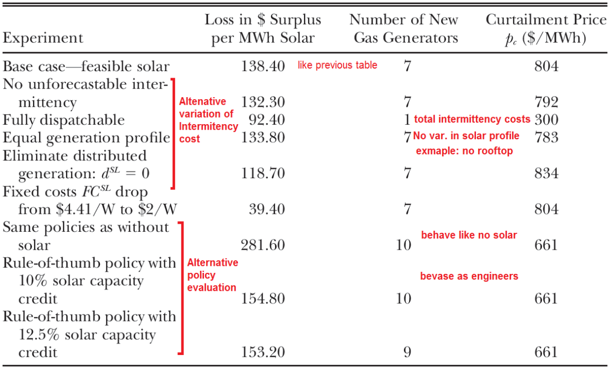
- US government value for social cost of CO_2 in 2015 is \$39 per ton
- Solar capital costs is the major source of valuation
- Social break-even point for 20% solar as solar capital costs.



- Solar capacity costs =\$1.52 & 20% solar ⇒ welfare neutral
- Model w/ start-up raise social cost of solar from \$138 to \$143

Components of Social Costs for Solar

- Decomposition social costs of 20 percent solar



Experiment	Loss in $ Surplus per MWh Solar	Number of New Gas Generators	Curtailment Price p_c ($/MWh)
Base case—feasible solar	138.40	7	804
No unforecastable intermittency	132.30	7	792
Fully dispatchable	92.40	1	300
Equal generation profile	133.80	7	783
Eliminate distributed generation: $d^{SL} = 0$	118.70	7	834
Fixed costs FC^{SL} drop from $4.41/W to $2/W	39.40	7	804
Same policies as without solar	281.60	10	661
Rule-of-thumb policy with 10% solar capacity credit	154.80	10	661
Rule-of-thumb policy with 12.5% solar capacity credit	153.20	9	661

like previous table

Altenative variation of Intermitency cost

total intermittency costs

No var. in solar profile
exmaple: no rooftop

behave like no solar

Alternative policy evaluation

bevase as engineers

Components of Social Costs for Solar

- Unforecastable component lower SC, small effect (b/c good forecast of intermittency)
- Compare w/ perfectly dispatchable (total intermittency costs
  - = difference in social costs between large-scale solar and a energy source with same capacity
  - lower the social cost of 20%
- Solar facility that always produced at its mean output: better \$4.60 per MWh
- Distributed generation (rooftop solar) is also costly, raising the cost of solar by \$19.70 per MWh
  - ⇒ Transmission cost savings from distributed generation are small relative to extra capacity costs
- Main saving: fixed cost of solar
- With \$3.00/W in 2012 as in table
- If cost drops to \$2 social costs drop by \$99 per MWh

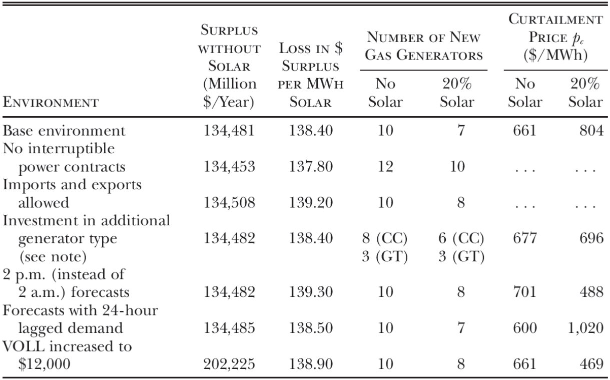
Components of Social Costs for Solar

- Test of alternative policies (n^{FF}, P_c)
  1. As no solar: higher social cost \$281.60 vs \$138.40 (too many new generators+much higher outage)
  2. Rules of thumb as systems engineering literature for n^{FF}
     - 2.1 meet load during peak demand periods
     - 2.2 meet specific outage, equal to paper benchmark

     both rule-of-thumb policies \$15 higher social cost than optimum
- Importance of reoptimization for large-scale solar to mitigate intermittency cots.

Robustness to Environment

- Social cost across different environments

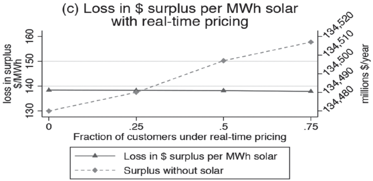


Environment	Surplus without Solar (Million $/Year)	Loss in $ Surplus per MWh Solar	Number of New Gas Generators		Curtailment Price p_c ($/MWh)	
			No Solar	20% Solar	No Solar	20% Solar
Base environment	134,481	138.40	10	7	661	804
No interruptible power contracts	134,453	137.80	12	10	. . .	. . .
Imports and exports allowed	134,508	139.20	10	8	. . .	. . .
Investment in additional generator type (see note)	134,482	138.40	8 (CC) 3 (GT)	6 (CC) 3 (GT)	677	696
2 p.m. (instead of 2 a.m.) forecasts	134,482	139.30	10	8	701	488
Forecasts with 24-hour lagged demand	134,485	138.50	10	7	600	1,020
VOLL increased to $12,000	202,225	138.90	10	8	661	469

- Environment rules no substantial effects

Real Time Pricing

- Adds to the social value.
- Without solar, 75% customers on real-time pricing contracts: adds $36 million to annual social surplus relative to having no real-time pricing (the dashed line)
- Real-time pricing has a negligible effect in changing the social costs of large-scale solar.



Introduction

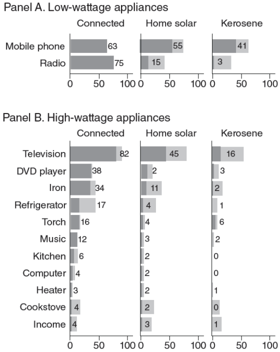
- Lee, Miguel, Wolfram. "Appliance ownership and aspirations among electric grid and home solar households in rural Kenya" AER (2016)
- Universal energy access major policy goal in sub-Saharan Africa
- large-scale infrastructure (grid connections) OR small-scale decentralized (solar, solar lanterns, solar home systems)
- Microfinance for home solar by mobile phone! in Kenya
- Solar: short-term benefit, make it more difficult to meet the soaring increase in energy demand (out poverty)
- ⇒ type of energy supply is matter
- Paper: household appliance survey in Western Kenya

Data and Setting

- Low electrification rates: 5% for rural HH
- Unconnected HH, sources of energy: kerosene (92.4%), solar lanterns (3.6%), solar home systems (2.2%)
- Sample into three categories
  1. connected to national electric grid (n = 215);
  2. not connected to the grid but use solar (n = 198)
  3. not connected to the grid, rely on kerosene (n = 2,091)
- Solar lanterns (cost $10 to $100) less than 10 watts of power, lighting and mobile charging services
- Solar home systems (cost $75 to $2,000) up to 1,000 watts of power, televisions, fans, and limited motive and heating power
- M-KOPA (solar)(costs over $200) 8 watt panel, two LED bulbs, an LED flashlight, a rechargeable radio, and mobile charging adaptors

Patterns of Electrical Appliance Ownership and Aspirations

- Solar HH higher living standards than kerosene HH, but differences in appliance ownership are not large
    - More educated, politically aware, have bank accounts, high quality walls, more land



Patterns of Electrical Appliance Ownership and Aspirations

- Strong desire to own high-wattage appliances
  - kerosene: televisions (39%), irons (16%)
  - solar: televisions (37%), irons (26%), refrigerators (24%)
- All HH spend a similar mean amount on kerosene
- Portion not spend on Kerosene: 33.4 % of connected HH, 23.7% and 2.5% of home solar and kerosene HH
  - Connected HH: problems with grid, such as blackouts
  - Solar HH: solar not provide sufficient lighting points within the home and must be complemented with kerosene lanterns

Discussion and Conclusion

- Solar for basic appliances, mobile. lighting
- Next level needs grid connections
- Sub-Saharan countries move to less non-fossil