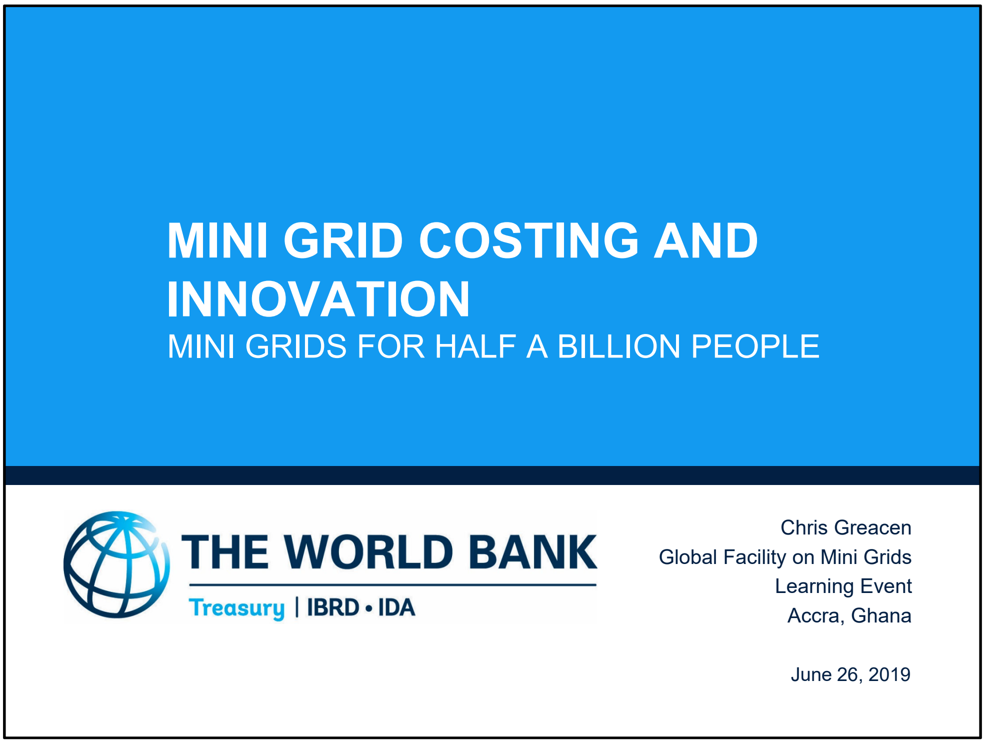


Connecting 490 million people by 2030 will require utilities and private companies to develop and operate more than 210,000 mini grids.

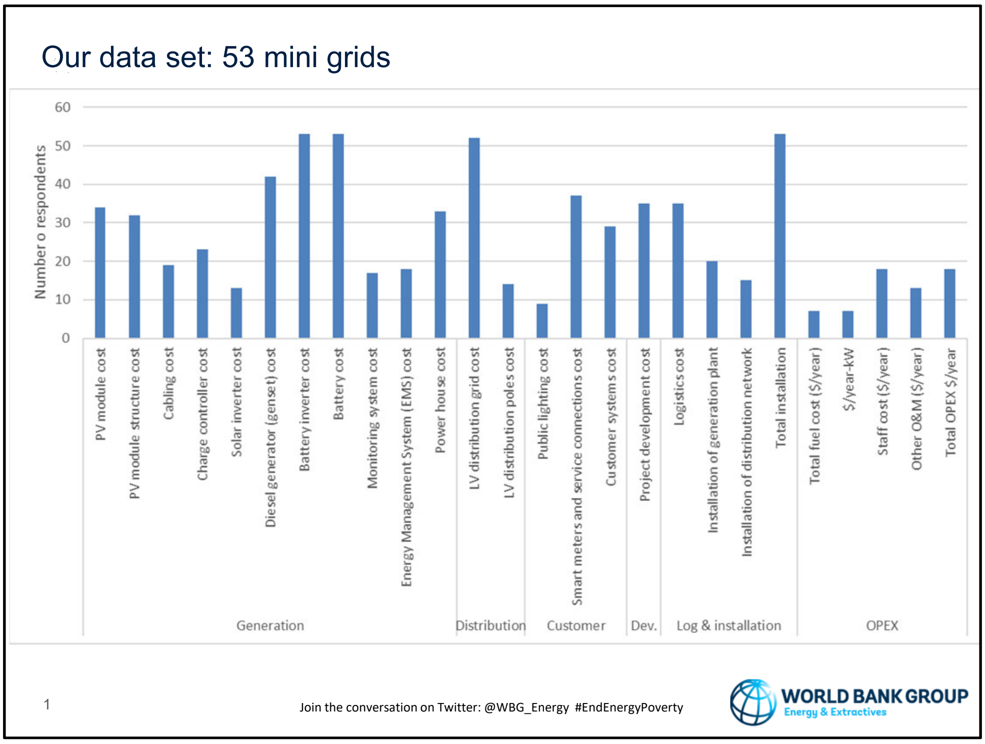
As we're well aware the solar mini grid industry is in the early stages of scale-up. Solar and solar-diesel mini grids installed and operating in the thousands and serve populations of hundreds of thousands—far from the hundreds of millions projected in little more than a decade.

Whether this thousand-fold scale up happens depends crucially on mini grid costs.

What are mini grid costs?

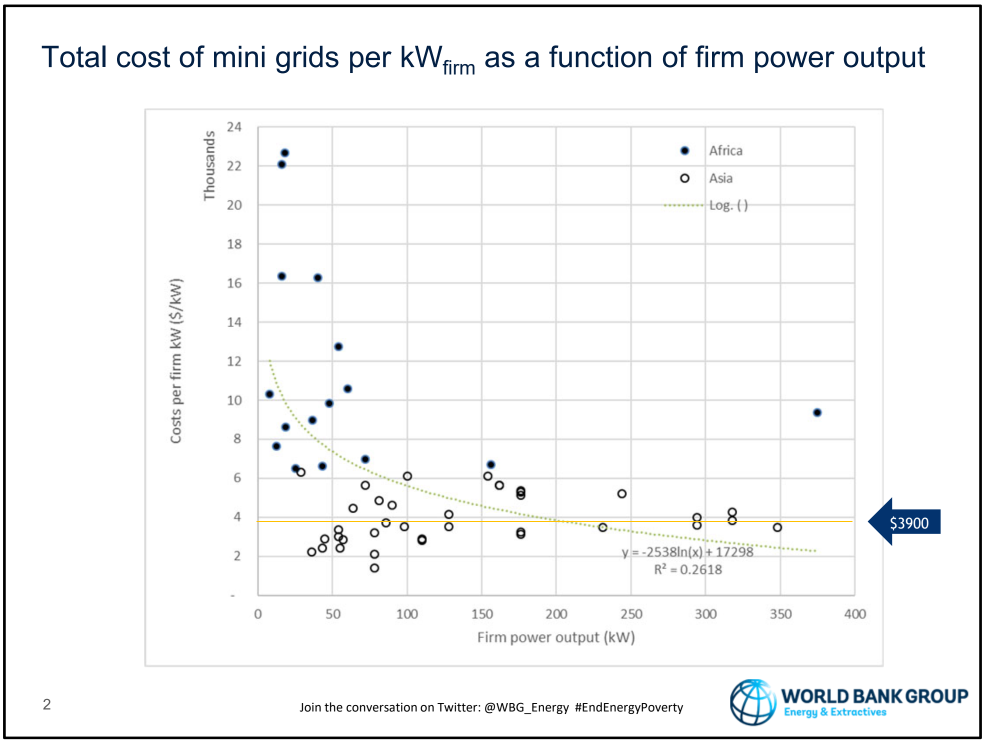
What are the costs of constituent parts of mini grids, and estimates of future costs? What are the drivers of mini grid costs? What opportunities exist for cost savings? These are topics we'll be exploring in the costing and innovation session.

(90 sec)



The ESMAP global facility on mini grids is building and analyzing a comprehensive database of detailed cost information on solar mini grids. Currently the database comprises detailed of cost of 53 mini grids in Asia and Africa. This chart shows some of the cost categories and the number of mini grids in each case for which we have information. Of the 53 mini grids, 38 were PV-diesel hybrids. The rest were solar-only. 37 were in Asia, and 16 in Africa.

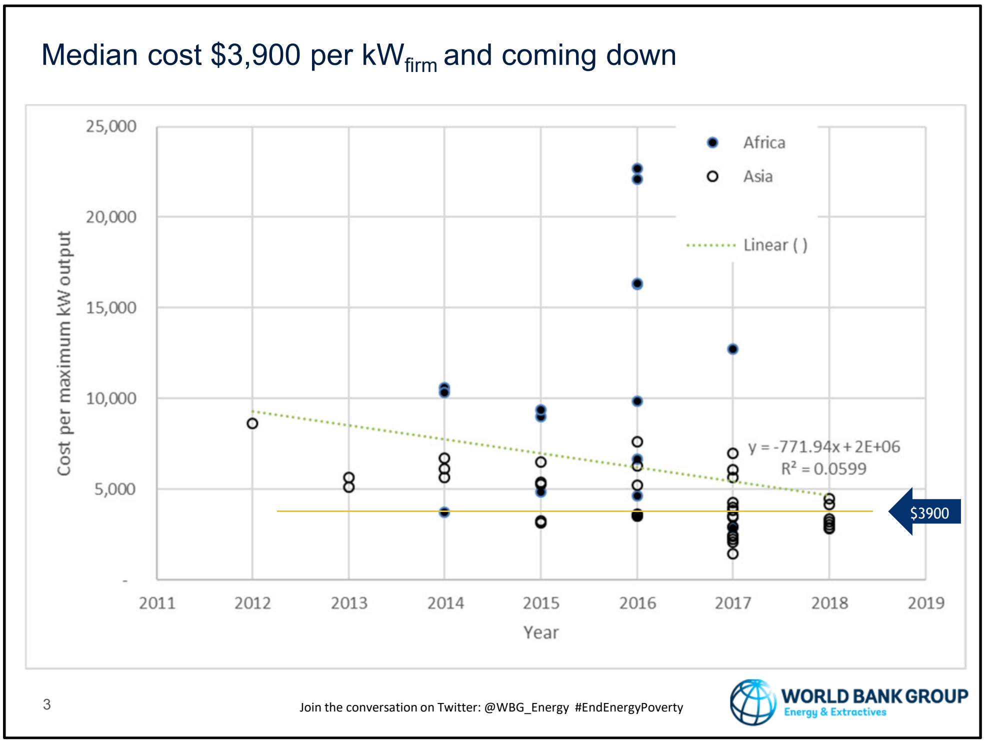
(58 sec)



The variation of costs per unit of firm kW is large, ranging from about 1,400 dollars to over $22,000. The average was about $6200. The median, $4,800. Firm kW mans that largest power output that the system can sustain. In this context, we define firm kW as the sum of the mini grid's battery inverter and the system's diesel generator capacity.

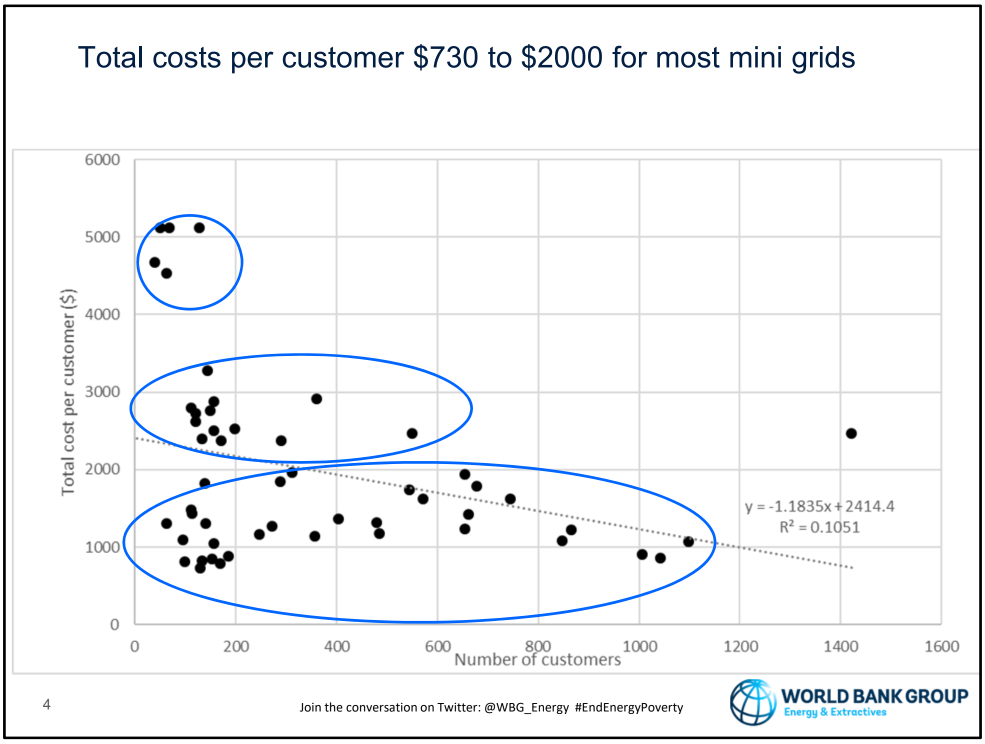
(space) If projects above $8,000 per kW are removed, the average cost per kW falls below $4,300, with a median of about $3,900.

(28 sec)



The data suggests that costs are coming down – an average of nearly $800 per kW per year. But low R-squared for this trendline indicates data should be interpreted with caution. These [point to 2017 cluster] do a lot to drive down the trendline, and are comparatively lower-cost mini grids installed in Myanmar and B'desh in 2017 and 2018.

(25 sec)



The total cost per customer varied from $730 per customer to over $5,000. Most mini grids were in the range of $1,000–$2,500. The average was $2000 while the median was $1,600.

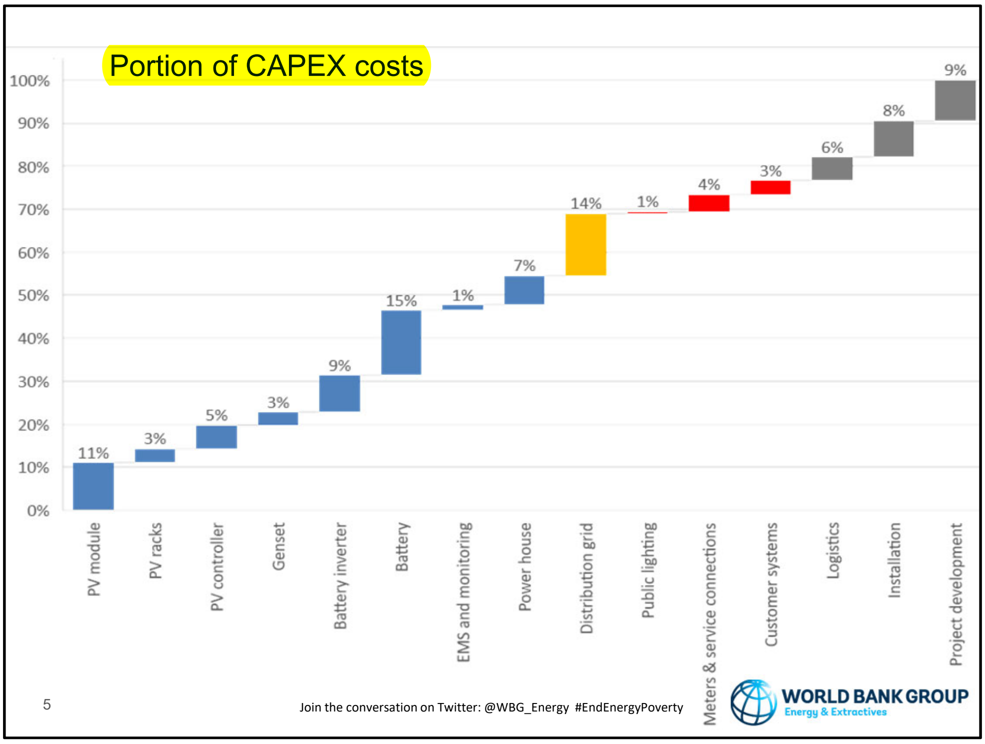
[SPACEBAR] The highest-cost cluster -- $4,000–$5,000 per customer -- comprises five mini grids with less than 70 customers each. These were early mini grids in Palestine and sub-Saharan Africa. The firm power output averages 460W per customer.

The middle cluster -- $2,400–$3,300 per customer -- comprises 16 mini grids mostly serving 200 customers or fewer, mostly in Africa, with an average per customer firm power output of 530W.

The lowest cost cluster -- $730–$2,000 per customer -- comprises 32 mini grids (28 of which are in Asia), most of which have <u>more</u> than 200 customers, which have an average maximum power output of only 320W.

If the highest cost clusters are removed, the average and median cost per customer are $1,670 and $1,430, respectively. A trendline suggests that if a mini grid is built to serve 100 more customers, its per customer costs will be about $68 lower.

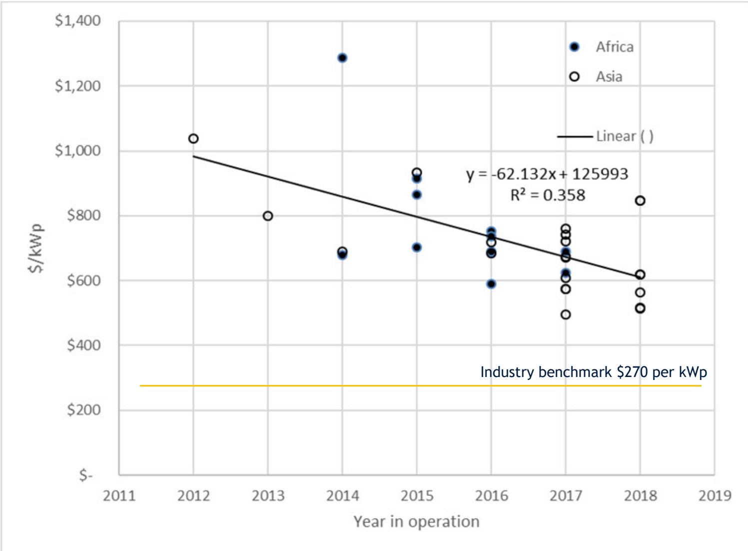
(110 sec)



The biggest contributors to mini grid costs were solar PV modules, batteries, and the distribution grid averaging 11%, 15% and 14%, respectively. There was considerable variation among grids. In one, the battery accounted for 39% of costs. In a few mini grids distribution comprised about a third of costs.

(20 sec)

PV module costs declining



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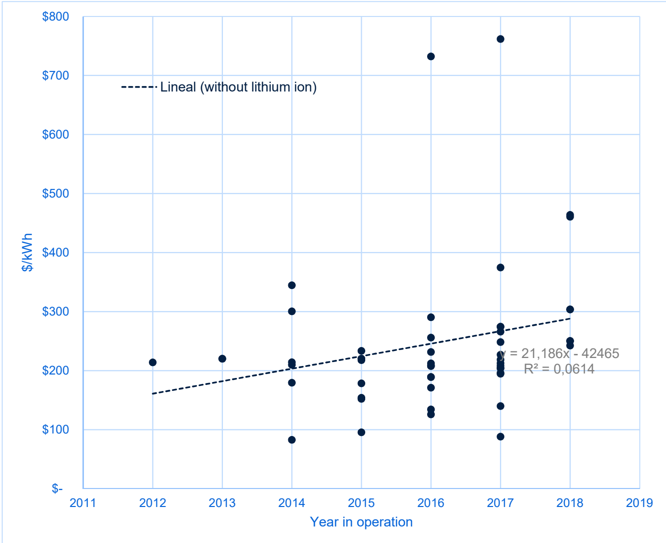
Solar module costs in the mini grids we investigated declined at a rate of about $62 per kWp per year. Consistent with this trend, an October 2018 study of Nigerian mini grids benchmarked solar modules at $402 per kWp.

The December 2018 EU spot market price for mainstream modules was $270 per kWp is shown as a benchmark comparison in orange. As a global commodity, module prices have been consistently falling 18 to 22 percent for every doubling of production. Production doubles about every 1.8 years and module prices are expected to reach $220 per kWp by September 2020.

(45 sec)

Cost of (lead acid) batteries increasing…



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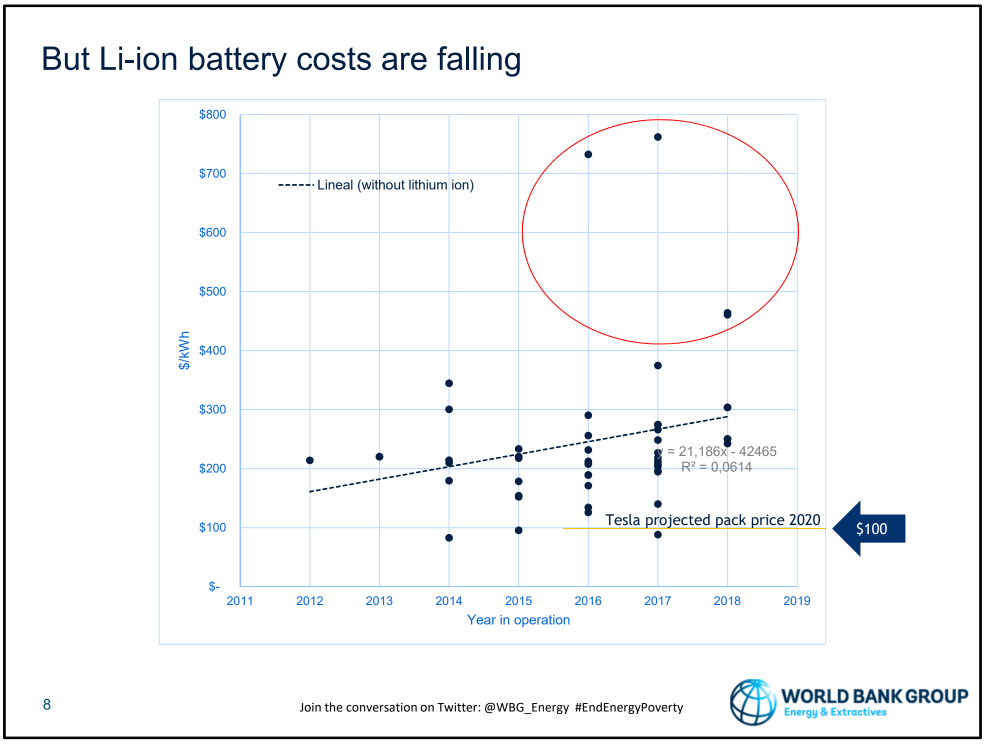
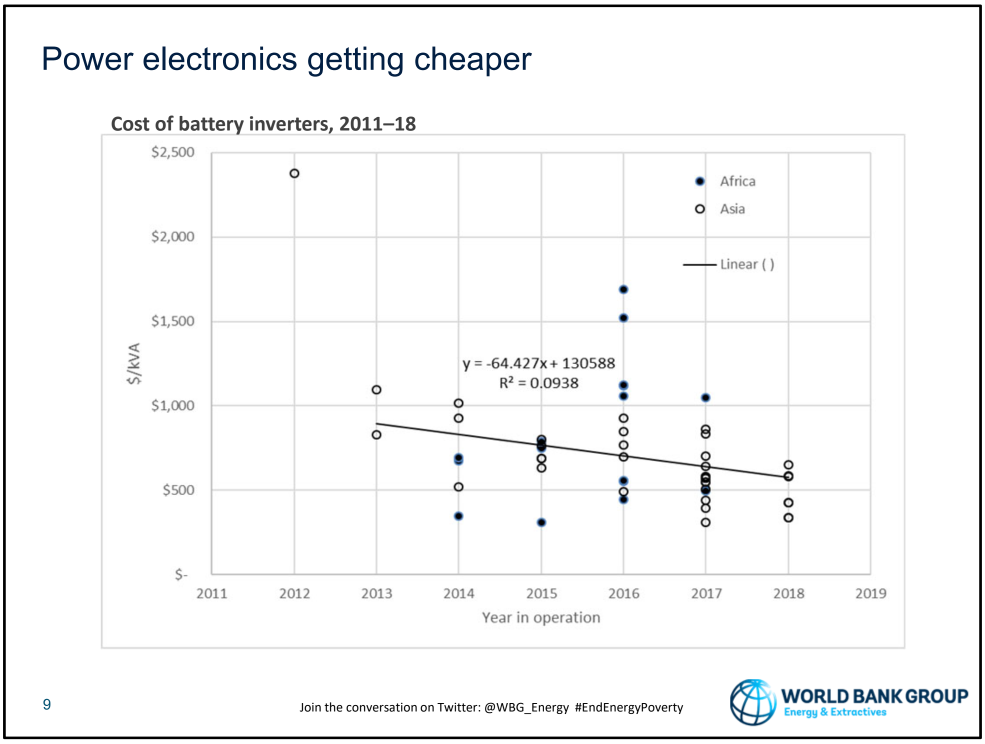
The cost of lead acid batteries has been increasing, driven by increases in the price of lead.



However, lithium ion battery costs appear to be decreasing, at least if we look at the larger industrial users of lithium ion batteries. While mini grids reported lithium ion battery costs at more than $400 per kWh, the industry benchmark for electric vehicles is $209 per kWh and Tesla predicts a pack price of $100 per kWh by 2020.

kWh capacities of lead acid and Li-ion batteries are not strictly comparable. Li-ion batteries can be more deeply discharged and thus have a larger usable kWh capacity for a given kWh nameplate capacity. Moreover, Li batteries have superior cycle lifetimes as well as decreased temperature-related degradation, which plagues lead acid batteries in tropical countries.



Battery inverter costs are trending downward at about 11% per year, albeit with strong variations across projects.

PV inverters are dropping in price even more quickly: a U.S. National Renewable Energy (NREL) study found that the price of PV inverters dropped from $320 per kWp in 2010 to $90 per kWp in 2017, a decline of about 16 percent per year.

Geospatial technologies have decreased the cost of preparation and planning by an order of magnitude

10

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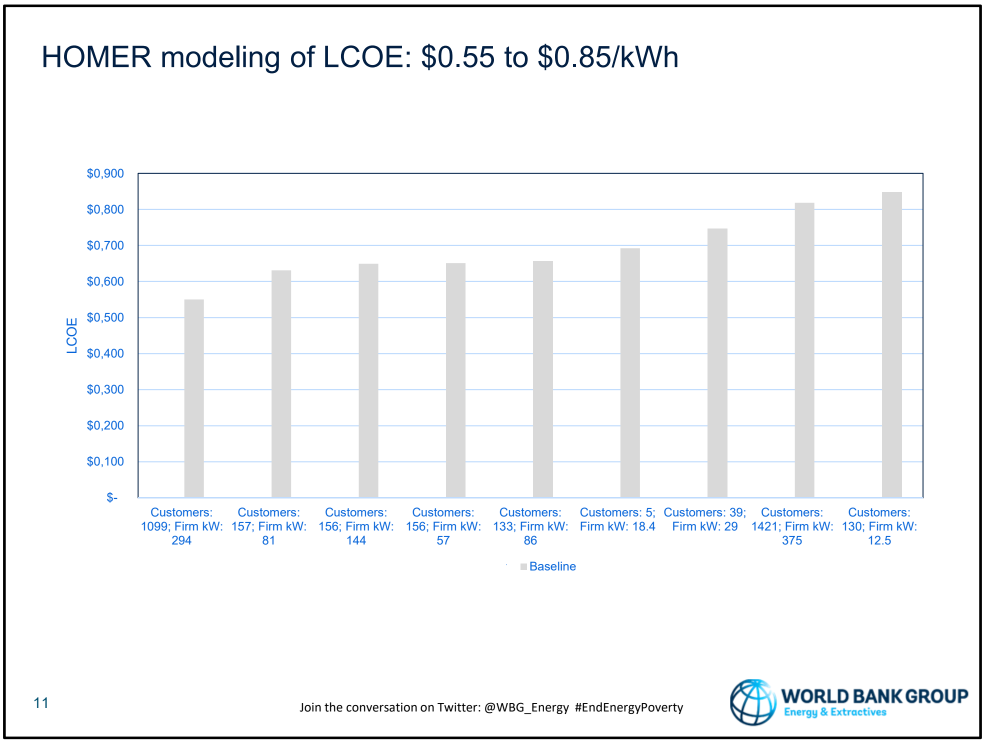
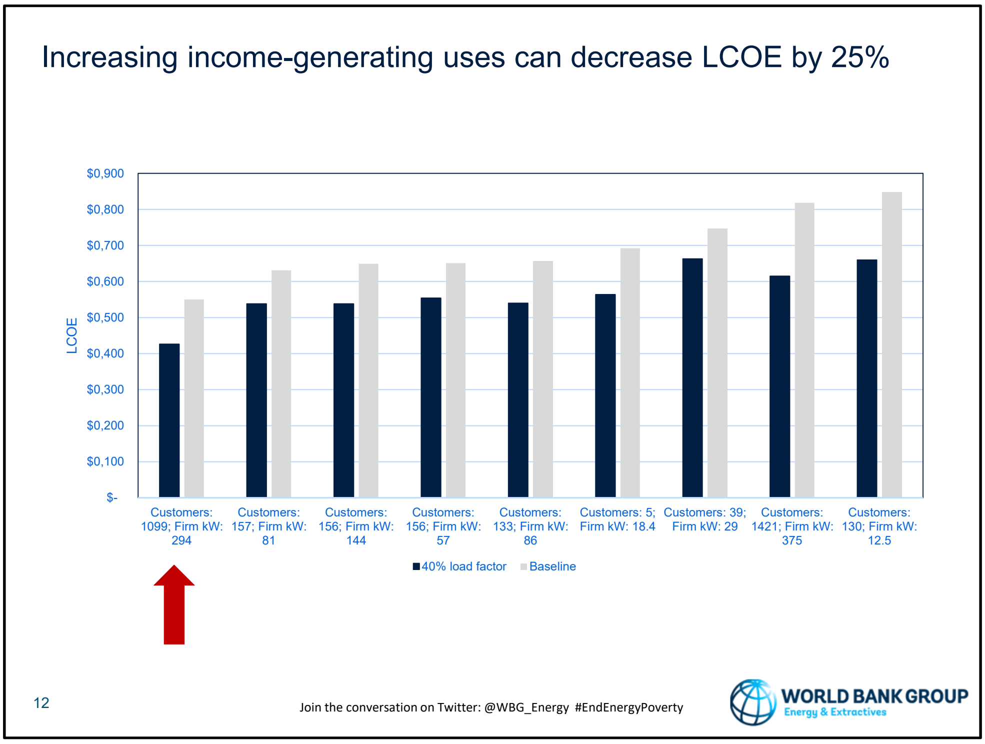
In the past, site selection and analysis required many expensive trips to rural areas, costing around $30K per site. Today tools like Odyssey integrate satellite and demographic data, and coordinate the site bidding process. It also aggregates projects and exposes them to potential investors. Scale and experience have reduced the remaining feasibility study and community engagement to around $2.3K per site based on the World Bank's experience in Nigeria.



Taking all of the information on investment costs, costs and lifetimes of equipment, GPS coordinates for solar resource data, O&M costs, fuel costs, and annual kWh, we modeled nine mini grids from the database in HOMER to determine a baseline levelized cost of energy in each.

Then we varied assumptions to model the impact of CAPEX subsidies, high productive use such as daytime electric powered agricultural processing, and a case that combined productive use and lower future equipment cost estimates.

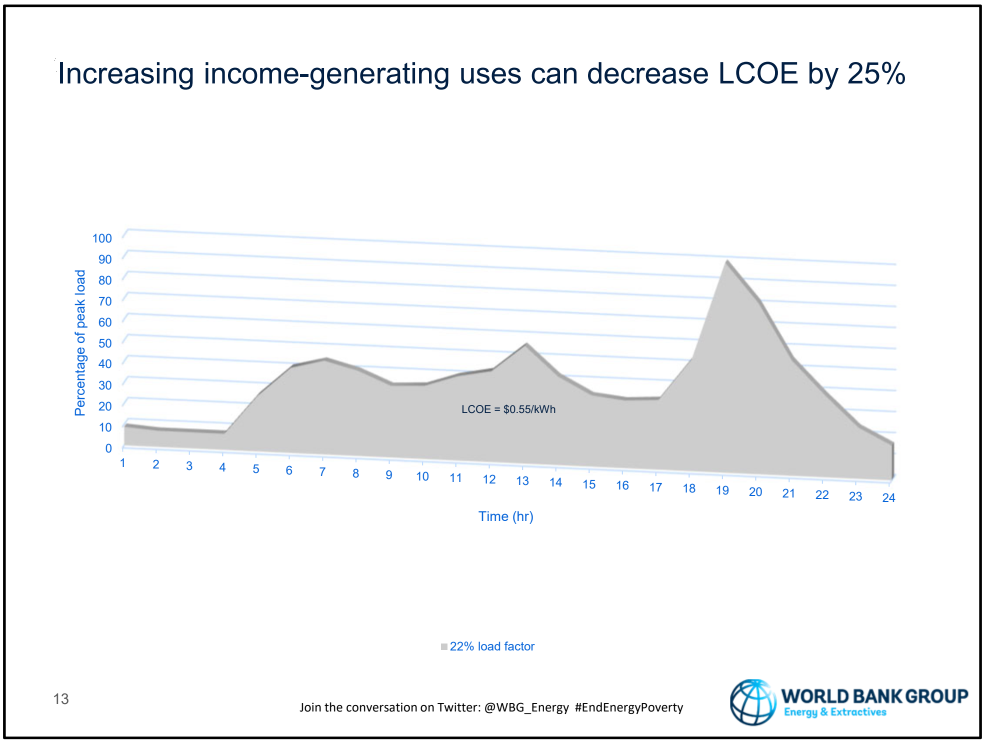
The base case results are shown in grey – LCOE varying from a low of $0.57 to $0.85 per kWh with a mean $0.66, respectively.



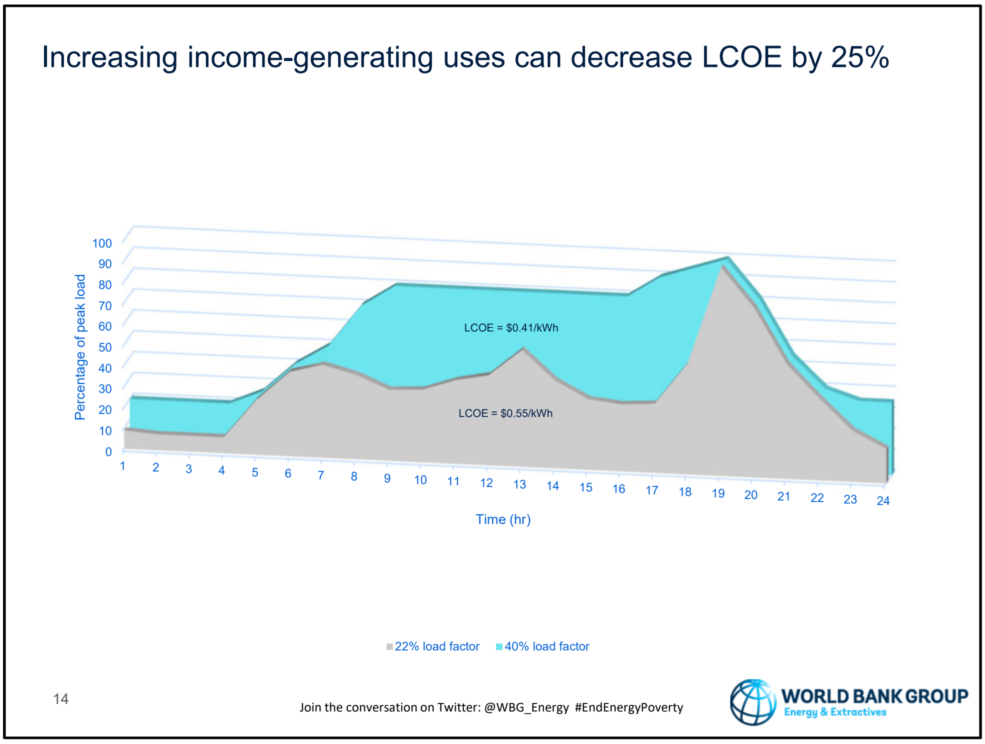
Productive use loads such as agricultural milling or water pumping generally occur during daytime hours, adding diversity to residential loads that occur primarily in the evening.

Adding productive load to shift from a 22% to a 40% load factor reduces LCOE 11–25 percent through better asset utilization.

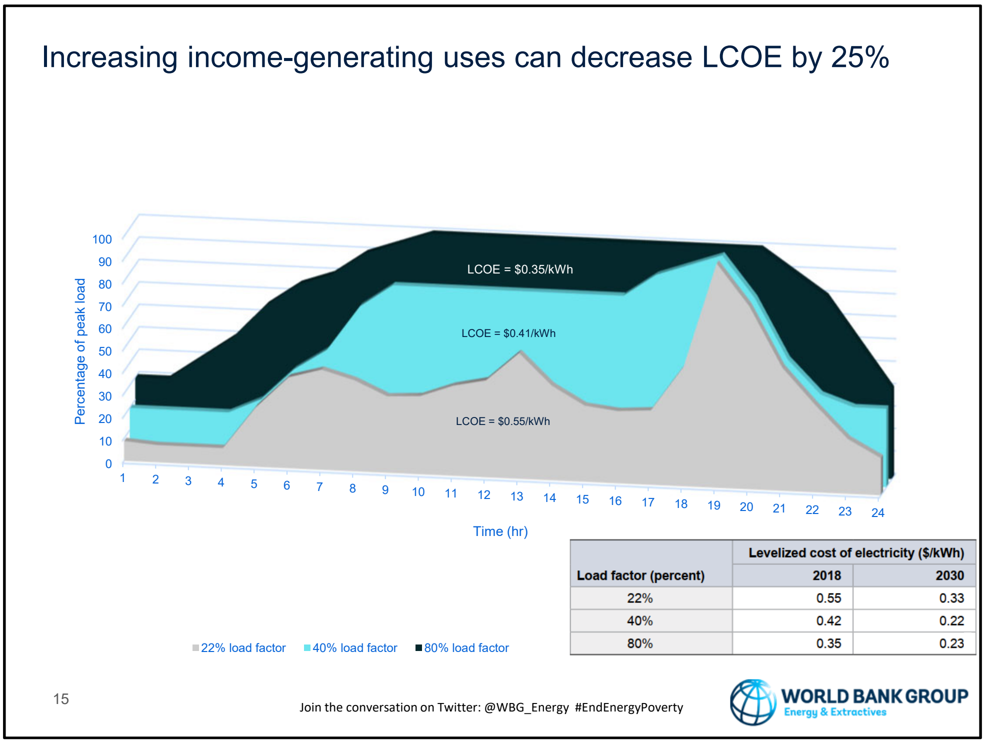
(space)
Let me dive a little deeper into the load factor discussion, focusing on this lowest LCOE project on the left.



This is a typical village residential profile, with a small peak in the morning, a small peak in the early afternoon, and a large evening peak as people come home, watch TV, and turn on lights, and prepare the evening meal. Using this load profile, which has a load factor of 22%, the LCOE is about $0.55/kwh.



Adding daytime productive use loads such as milling or water pumping can raise the load factor to 40% and take better advantage of daytime electricity from the solar panels.



An 80% load factor is very optimistic, and reduces LCOE further, to $0.35 per kWh.

The combination of increased load factor and future expected costs (using benchmark costs for solar PV, batteries, etc.) lowers LCOE even further, down to $0.22/kWh in the 40% LF case.

Summary

- Solar hybrid mini grids median price: $3,900/kW_{firm}$
- Component costs vary significantly
- Capital costs falling
  - PV
  - Battery
  - Power electronics
- Preparation and planning costs falling
- LCOE varied from $0.55 to $0.85/kWh (median $0.66) with 22% load factor
- Increasing income-generating uses can decrease LCOE by 25% or more
- LCOE mini grid with high productive use can drop to $0.22/kwh by 2030

Questions / Discussion

Any mini grid cost data you can share?

chrisgreacen@gmail.com

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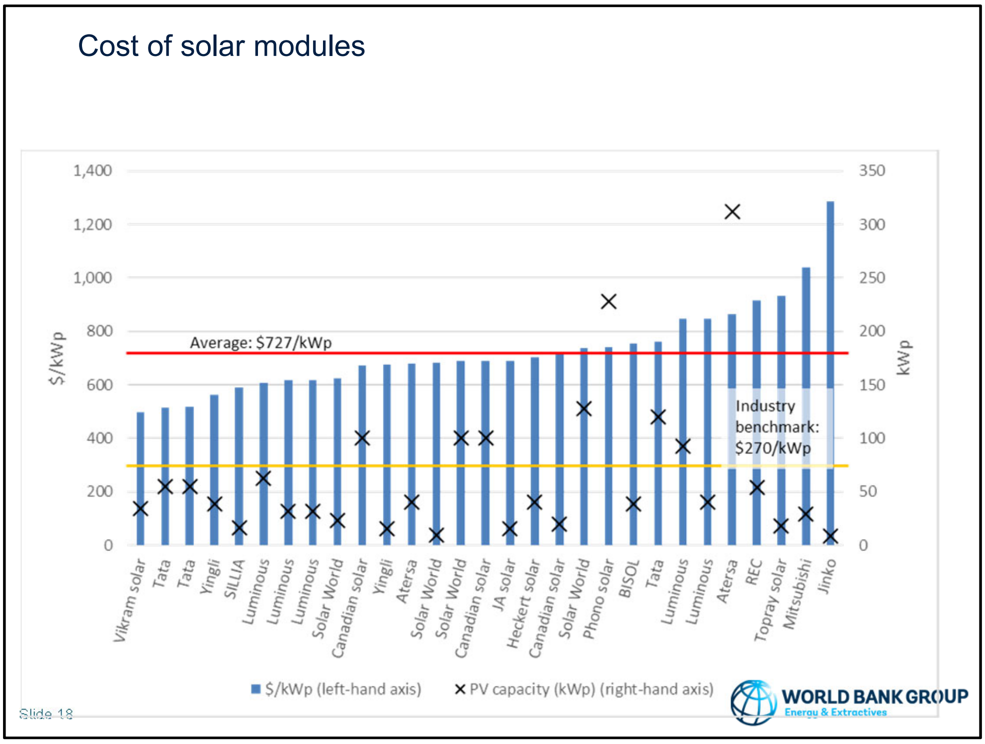
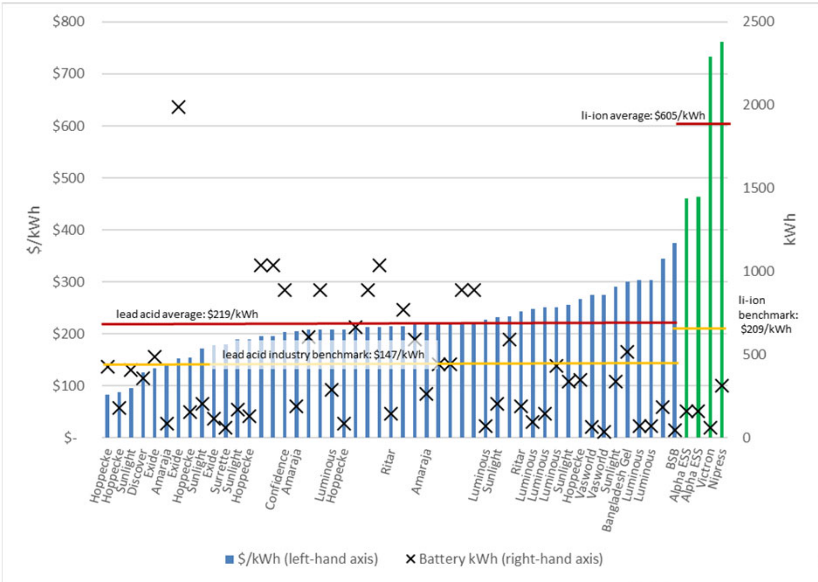


Solar modules ranged in cost from about $500 per kWp to nearly $1300, with an average of just over $730. The December 2018 EU spot market price for mainstream modules was $270 per kWp is shown as a benchmark comparison in orange.

The X's indicate the capacity of the solar array at each mini grid.

(30 sec)

BATTERY COSTS



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ROUP

Batteries ranged in cost from $83 per kWh for a mini grid with lead acid batteries in Chad to $760 for a Li-ion battery in an Indonesian mini grid. All but 11 of 53 mini grids reported battery costs between $100 and $300 per kWh. Consistent with this range, a benchmarking study found batteries in Nigeria cost $197 per kWh in 2018. The X's in the graph represent the battery capacity. Mini grids with smaller batteries tended to have higher unit costs.

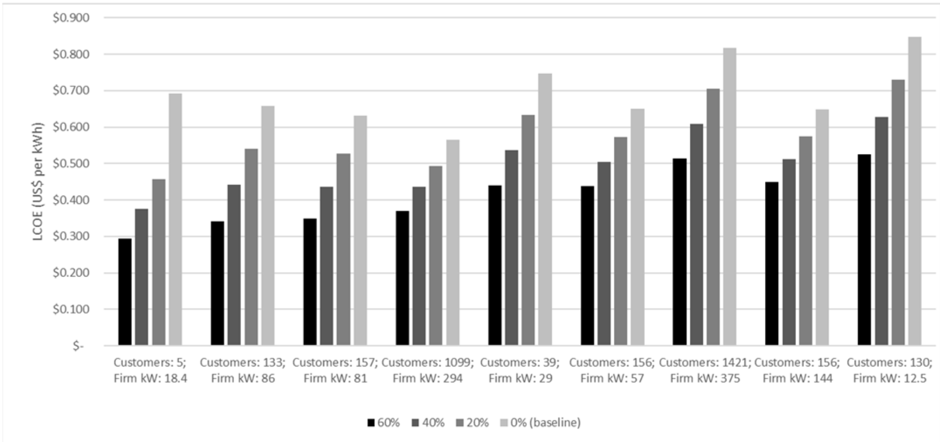
Li-ion batteries are the green bars on the right. They are a new addition to the mini grid toolbox, with the first installation in 2016 in Indonesia, another in 2017 in Tanzania, and two more in Myanmar in 2018. In the mini grids surveyed, Lithium ion batteries were installed on smaller mini grids, as developers tested this promising but higher initial cost technology. Li batteries averaged $605 per kWh, while lead acid averaged $219. kWh capacities of lead acid and Li-ion batteries are not strictly comparable. Li-ion batteries can be more deeply discharged and thus have a larger usable kWh capacity for a given kWh nameplate capacity. Moreover, Li batteries have superior cycle lifetimes as well as decreased temperature-related degradation, which plagues lead acid batteries in tropical countries.

Outside of mini grids, a global industry benchmark cost for lead acid batteries is $147 per kWh and $209 for lithium. Industry analysts predict further substantial declines in Li battery costs, driven largely by the demand for lithium-ion batteries in electric vehicles.

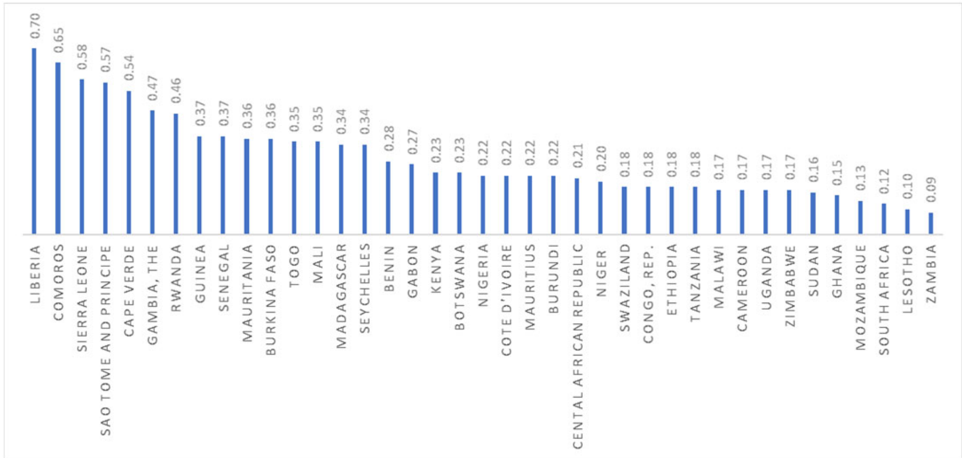
Tesla predicts $100 per kWh by 2020, which we estimate translates to $150 for mini grids.

(135 sec)

LEVELIZED COST OF ENERGY (LCOE): IMPACT OF CAPEX SUBSIDIES



The impact of performance-based grants is substantial, with a 60 percent grant reducing LCOE of the lowest mini grid to just over $0.29 per kWh, compared to nearly 70 cents in the base case.



World Bank 2016. *Making Power Affordable for Africa and Viable for Its Utilities*. https://www.esmap.org/node/57463

The data

Inclusion of diesel generator	PV/diesel hybrids: 38 Solar PV only: 15
Region	Asia: 37 Africa: 16
Business model (for 24 projects for which data was available)	Private: 10 Public utility: 8 Community: 5 Private-public partnership: 1

Feature	Average	Minimum	Maximum
Installed "firm" capacity (kW)	115	8	375
Installed solar capacity (kWp)	88	9	312
Number of customers	253	39	1,421

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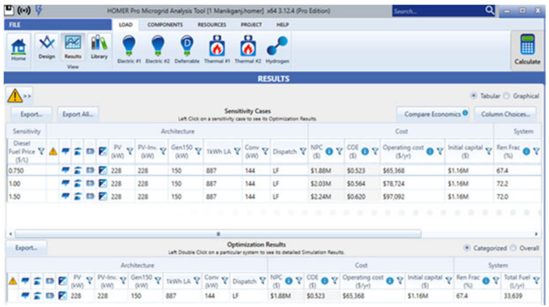
Of the 53 mini grids, 38 were PV-diesel hybrids. The rest were solar-only. 37 were in Asia, and 16 in Africa. Business models varied, with 10 operated by private companies, 8 by public utilities, 5 community run systems, and 1 PPP.

Firm capacity, defined in our study as the sum of the battery inverter and diesel generator capacities, averaged 115 kW, with a broad range from 8 to 375. Installed solar capacity averaged 88 kWp, and the average number of customers was 253.

(45 sec)

Levelized cost of energy (LCOE) modeling

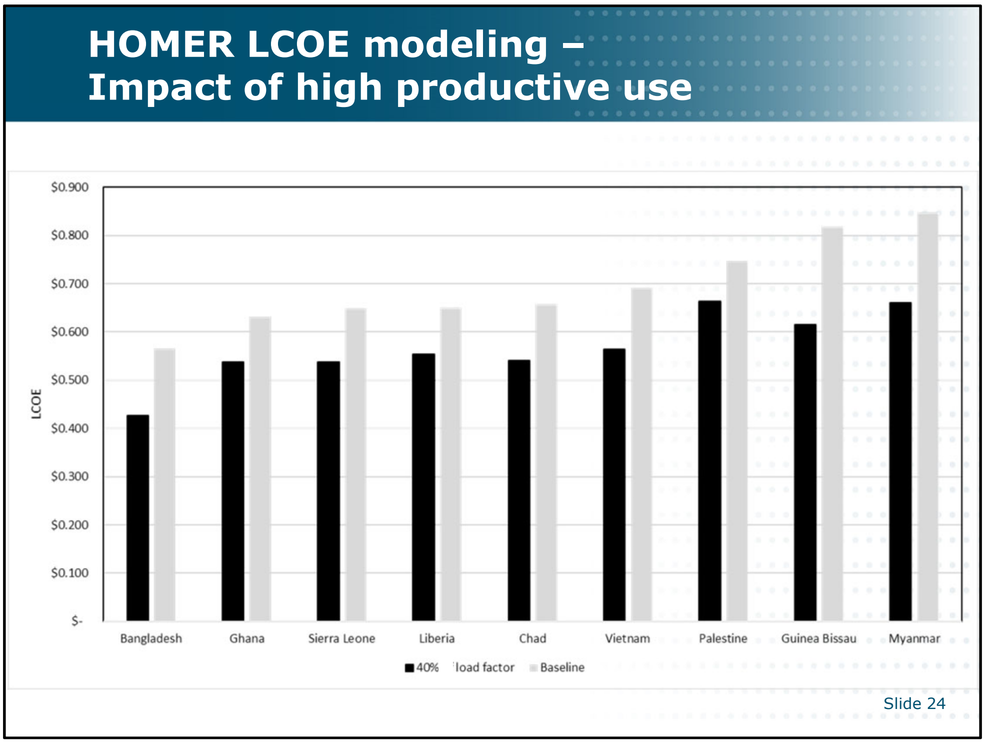
- **Base case**
- **High productive use**
  - Load factor 22% → 40%
- **High productive use & 2020 equipment cost**
- **CAPEX subsidies**
  - 20%
  - 40%
  - 60%



Slide 23

Taking all of the information on investment costs, costs and lifetimes of equipment, GPS coordinates for solar resource data, O&M costs, fuel costs, and annual kWh delivered, the HOMER team modeled nine mini grids from the database to determine a baseline levelized cost of energy in each.

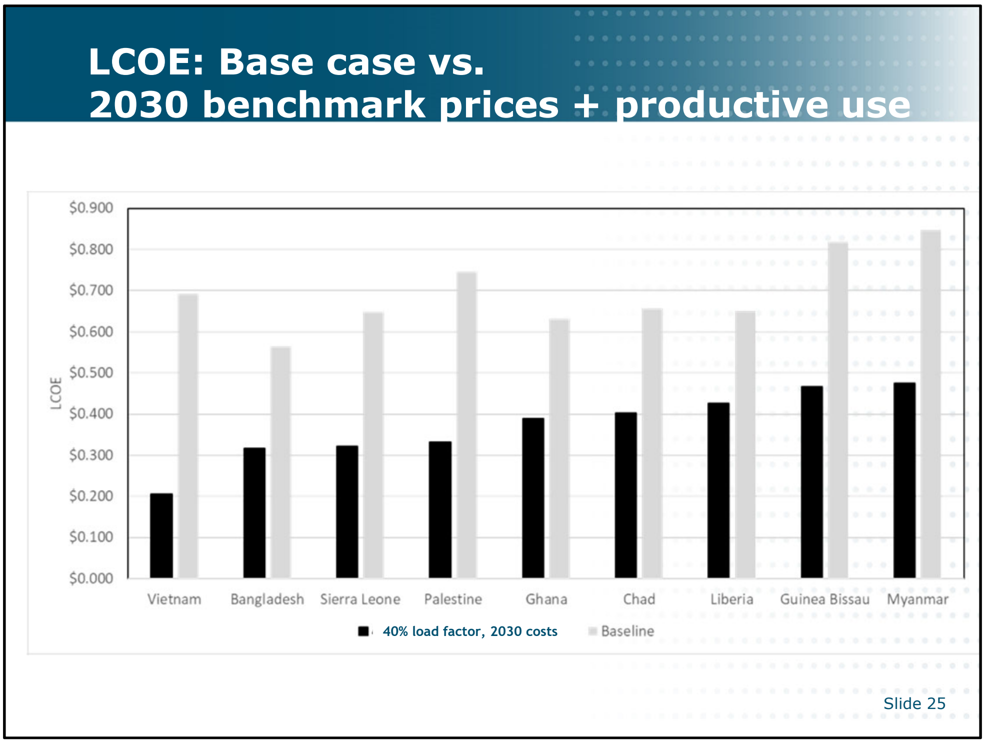
Then we varied assumptions to model the impact of CAPEX subsidies, high productive use such as daytime electric powered agricultural processing, and a case that combined productive use and 2020 equipment cost estimates.



The base case results are shown in grey – LCOE varying from a low of $0.57 to $0.85 per kWh with an average and mean of $0.69 and $0.66, respectively.

Productive use loads such as agricultural milling or water pumping generally occur during daytime hours, adding diversity to residential loads that occur primarily in the evening.

Adding productive load to shift from a 22% to a 40% load factor reduces LCOE 11–25 percent through better asset utilization



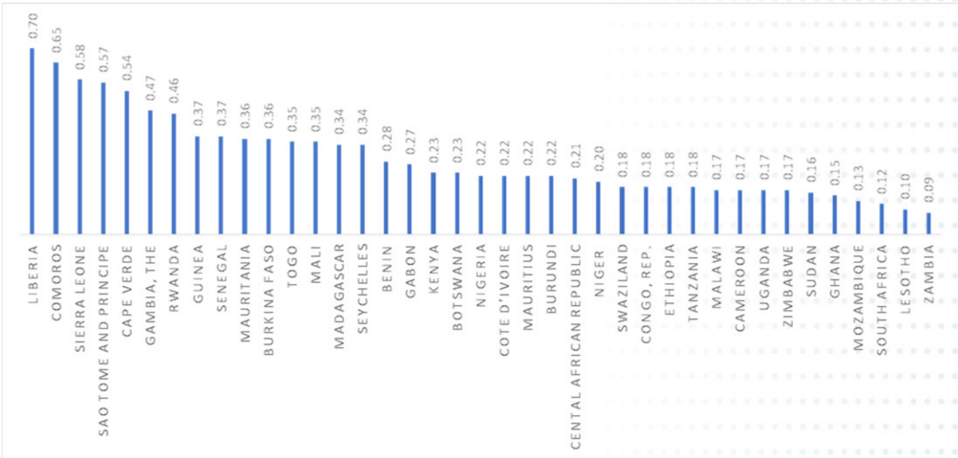
What if the mini grids we know about were built with expected 2020 reduced component prices and were operated at 40% load factor?

This slide shows that scenario in black, compared to current mini grid LCOE in grey.

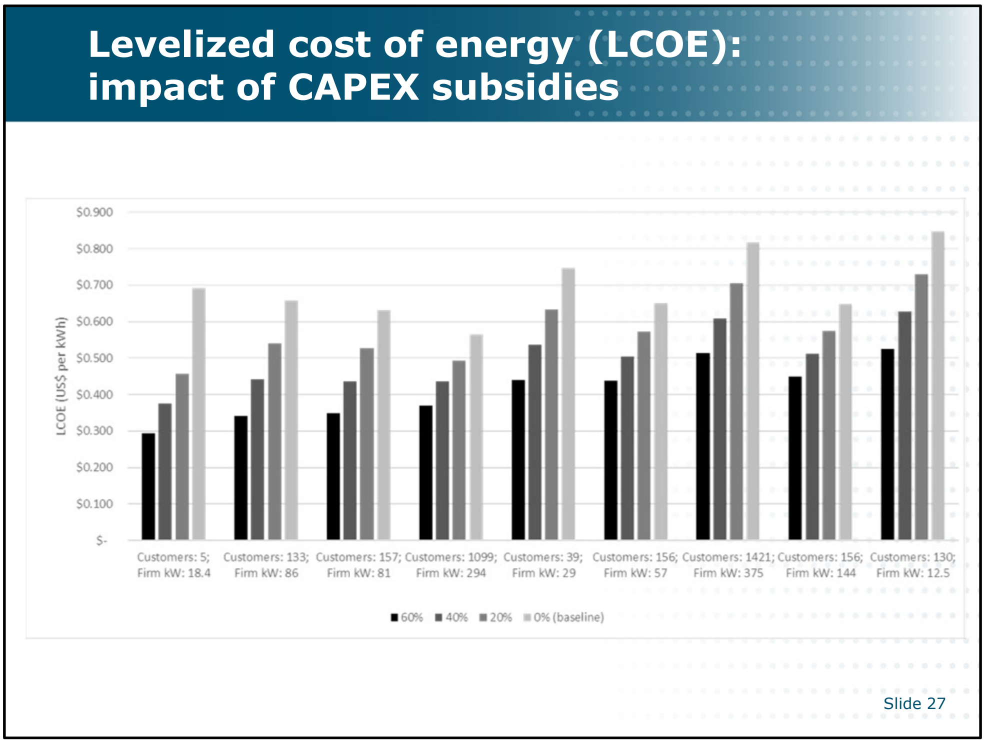
The modeling indicated that if dispatchable loads (for example, water pumping with significant storage) is employed, LCOEs as low as $0.21 per kWh are possible.

Cost of Utility Electricity in Africa

($2019 per kWh)

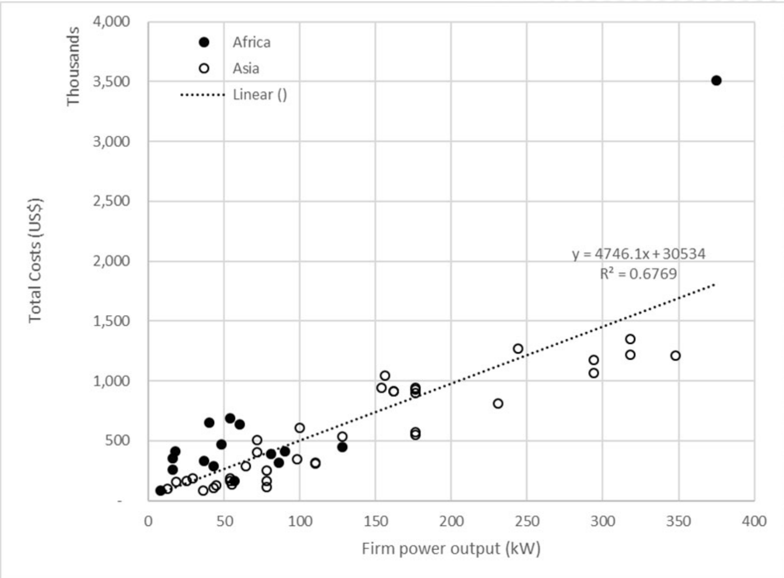


World Bank 2016. *Making Power Affordable for Africa and Viable for Its Utilities.* https://www.esmap.org/node/57463



The impact of performance-based grants is substantial, with a 60 percent grant reducing LCOE of the lowest mini grid to just over $0.29 per kWh, compared to nearly 70 cents in the base case.

Total cost of mini grids as a function of total firm AC power output



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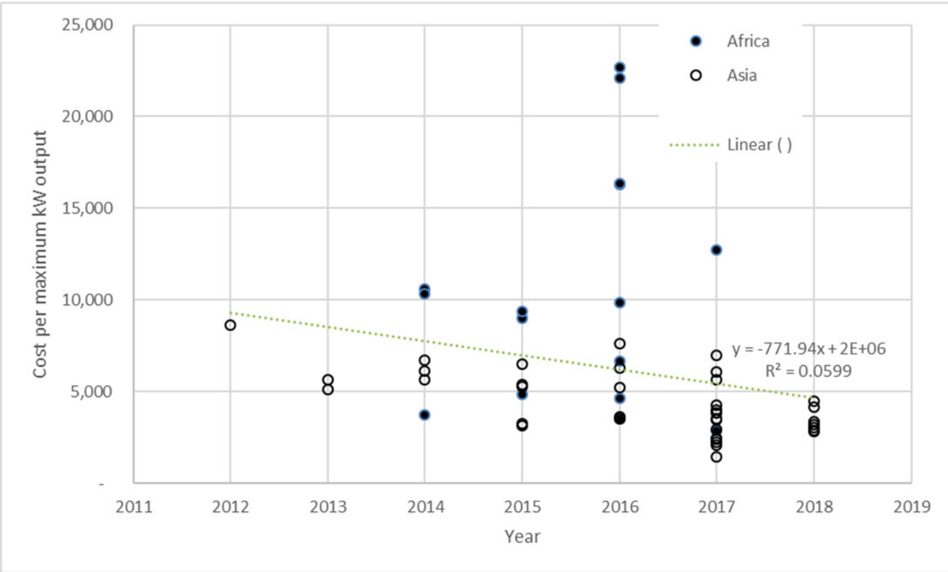
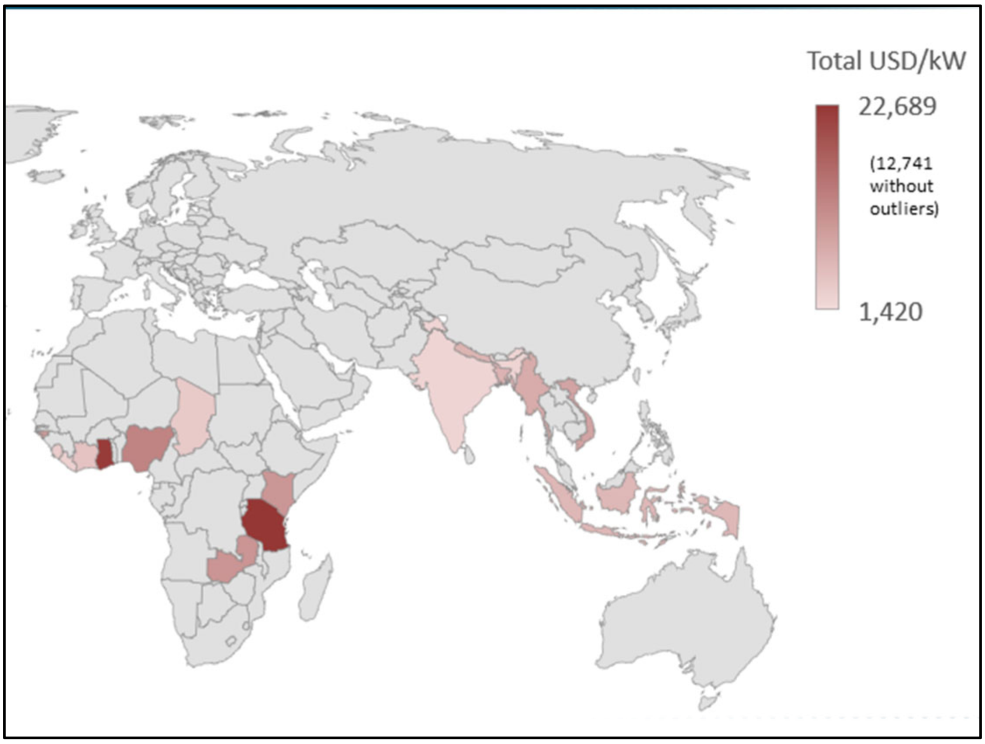
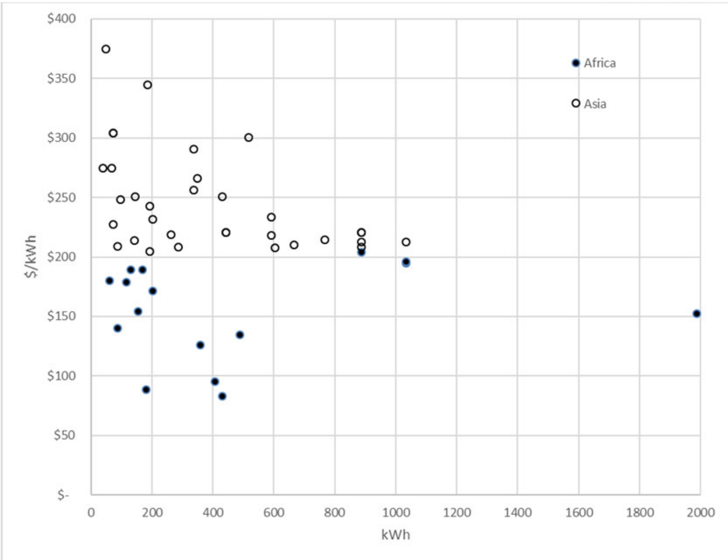
Mini grid cost per kW of firm output, 2011–18



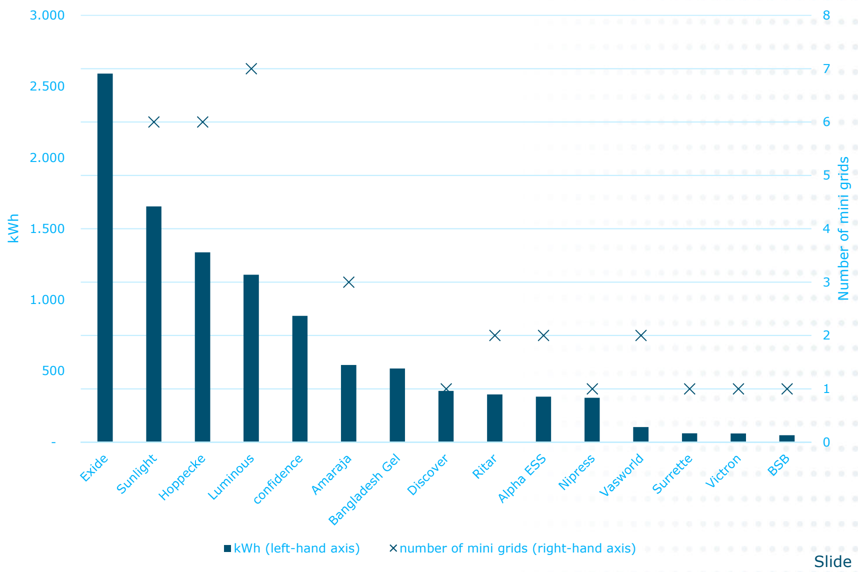

Total USD/kW
22,689
(12,741
without
outliers)
1,420

Cost of lead acid battery as a function of battery capacity



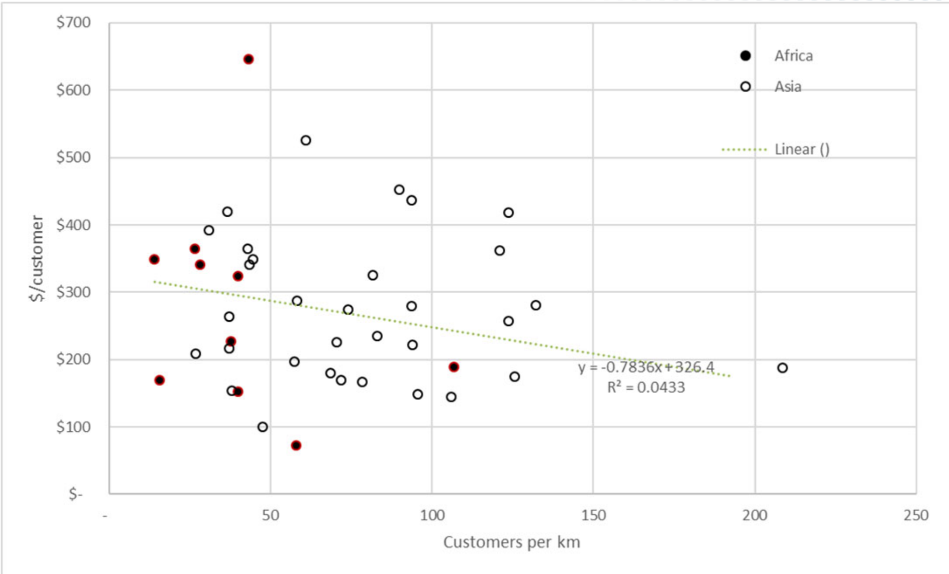
Slide 31

Market share of batteries by manufacturer

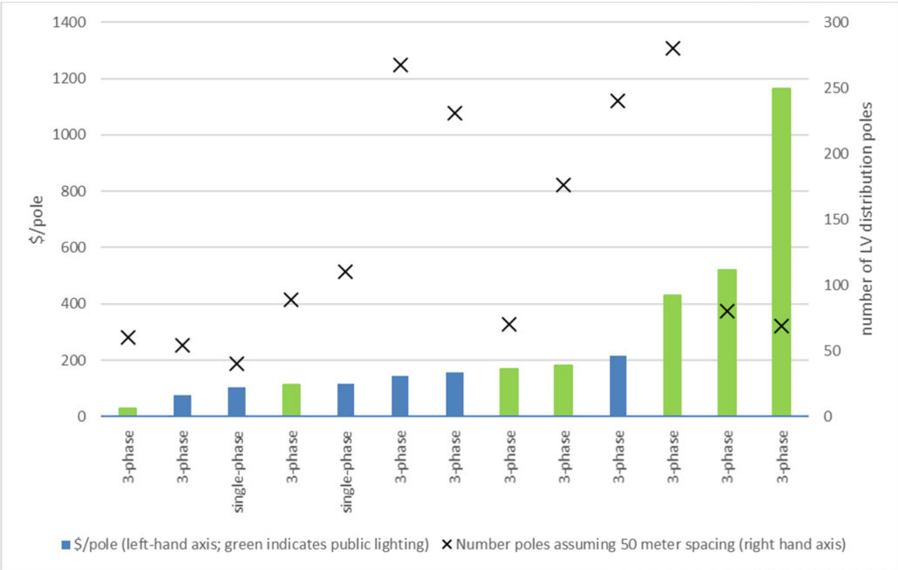


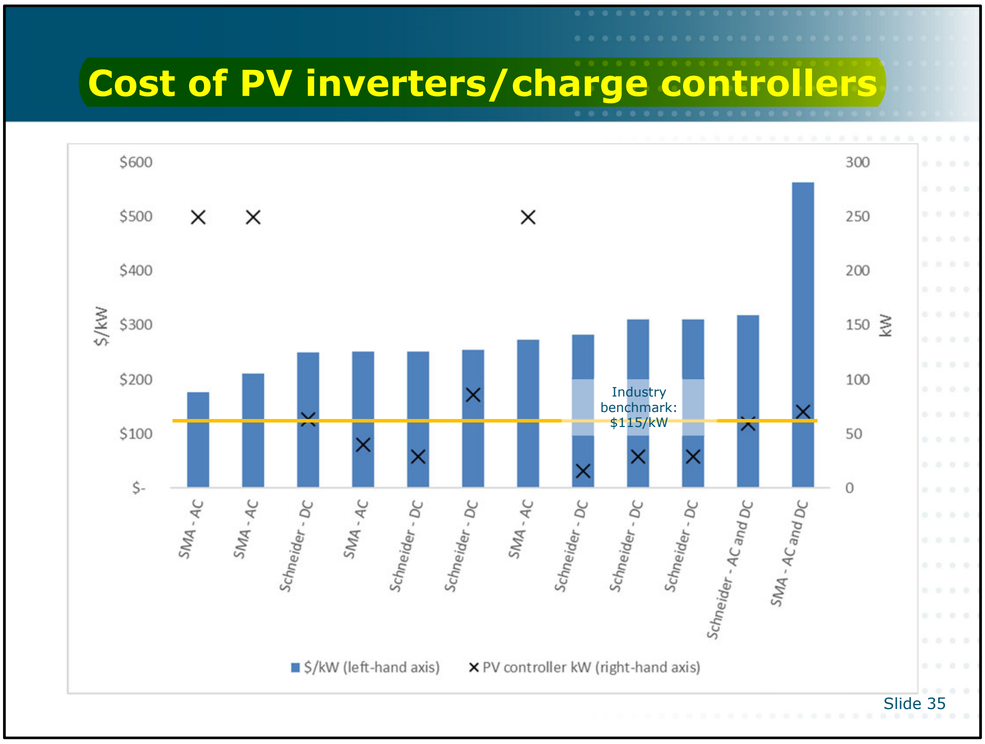
Slide 32

Correlation between cost per customer and the number of customers per kilometer



Cost of low-voltage distribution poles, by line type

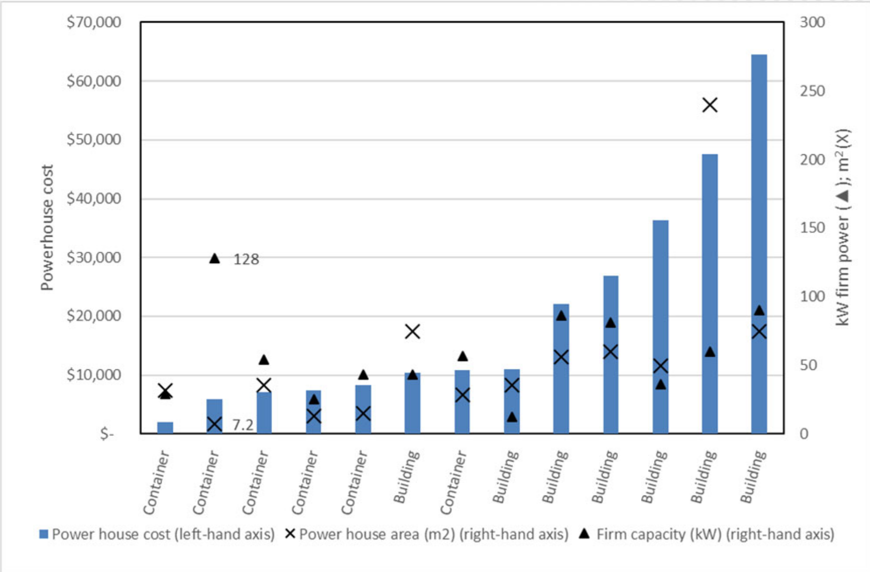




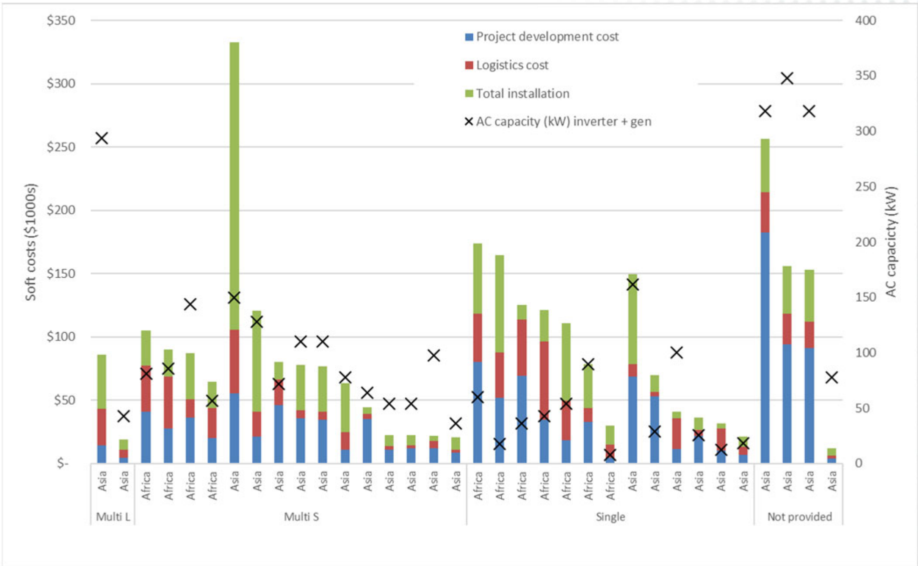
mini grids on which data are available, 24 are DC coupled (using PV controllers), 20 are AC coupled (PV inverters), and 9 are both AC and DC coupled (using both controllers and PV inverters). Sites with AC coupling had the eight highest capacities. Sites with both AC and DC coupling had the highest average controller/PV inverter costs ($441 per kW), followed by DC-coupled systems ($277 per kW). AC-coupled systems ($228 per kW) spent the least on charge controller functionality.

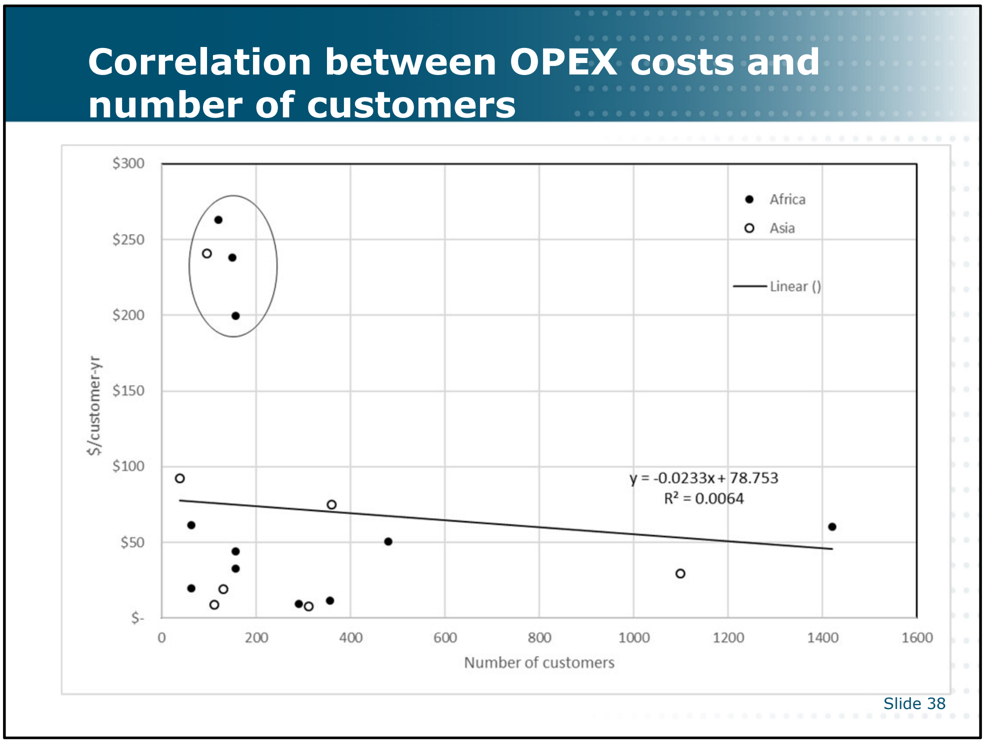
SMA accounted for the largest installed cumulative capacity, at 2,431kW. Its installed capacity was nearly five times greater than its closest competitor, Schneider, with 500kW. SMA was also the most popular brand in terms of numbers of sites, with 18 mini grids reporting using the brand

Cost of power houses



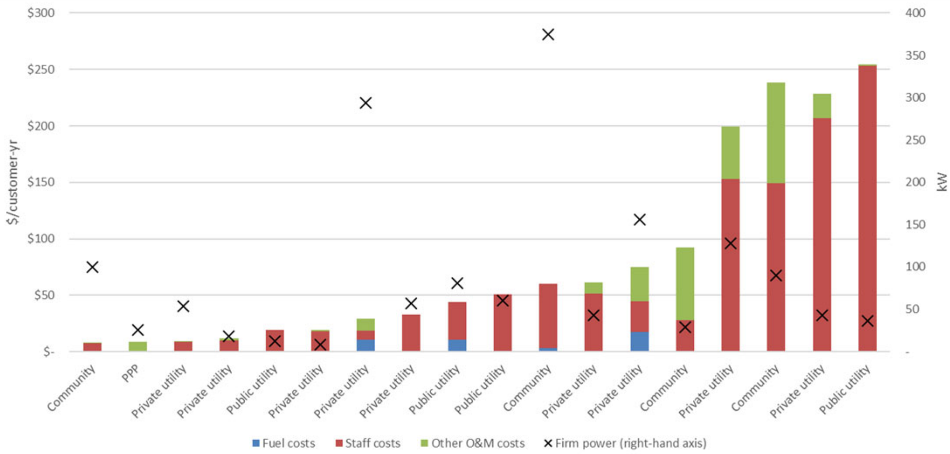
Cost of project development, logistics, and installation



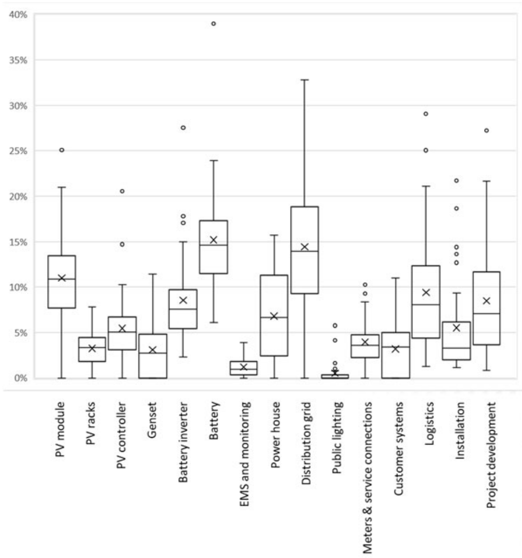


Averages were similar in Africa and Asia at $90 and $68 a year, respectively, but with extreme variation (from a low of $8 to a high of $263 per customer per year). The high per-customer OPEX expenses in the circled cluster of four projects reflect high staff costs.

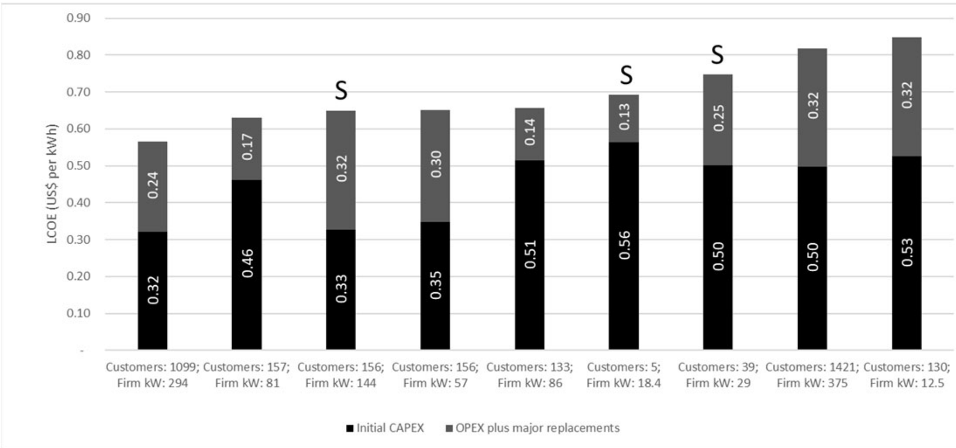
Fuel, staff, and other operations and maintenance costs



Portion of mini grid cost attributable to different components

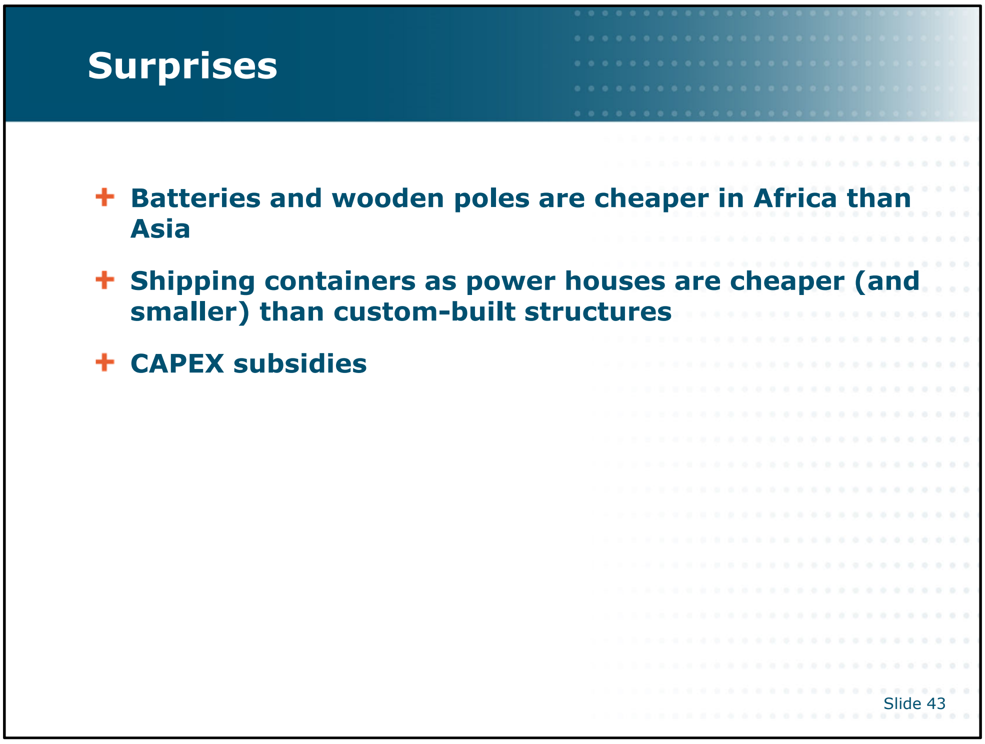


LCOE attributable to initial CAPEX vs OPEX and major replacements



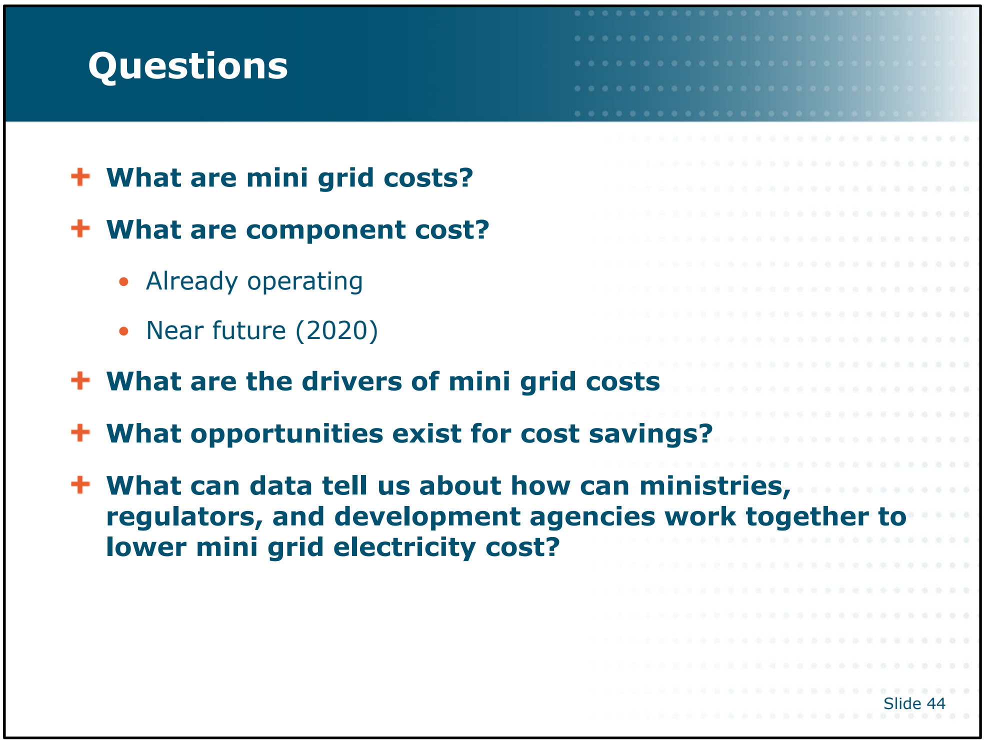
Industry benchmarks and 2020 cost projections

Mini grid component	Average cost	Minimum cost	Maximum Cost	Mainstream industry benchmark	Price estimate by 2020	Cost drivers and Innovations
PV module ($ per kWp)	719	497	2,652	290[a]	240 [b]	Solar farms & rooftop solar
PV inverter ($ per kWp)	228	176	564	115[c]	80[d]	Solar farms and rooftop solar
Battery inverter ($ per kVA)	729	311	2,377	203[e]	142	EV
Lithium Ion battery ($ per kWh)	605	461	762	209[h]	150[i]	EV
Lead Acid battery ($ per kWh)	240	126	348	147	127	



Battery inverter costs are trending downward, albeit with strong variations across projects. The trendline indicates that each year the cost drops about $64 per kVA (figure 3.15). The *R*-squared is low, however, and it is noteworthy that most of the cost figures for 2017 and 2018 come from mini grids in Myanmar and Bangladesh that have lower costs than other countries in the data set.

Decreasing battery inverter costs are consistent with broader trends, driven by synergies with PV inverters, electric vehicle motor drives, and other power electronics. A U.S. National Renewable Energy (NREL) study found that the price of PV inverters dropped from $320 per kWp in 2010 to $90 per kWp in 2017 (all measured in constant 2010 dollars) (Fu and others 2017). This decline of about 16 percent a year is somewhat larger than the roughly 11 percent annual decrease for battery inverters indicated in the dataset.



What are mini grid costs? In terms of cost per mini grid, cost per customer, and cost per installed firm kW.