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BALANCING OPPORTUNITIES AND COSTS IN HAWAII'S INCREASINGLY GREEN GRID

BY

KARL JANDOC AND MICHAEL ROBERTS

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Karl Jandoc
Department of Economics, University of Hawai`i at Manoa

Michael J. Roberts
Department of Economics, Sea Grant, and UHERO
University of Hawai`i at Manoa

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Hawai`i's tourism-dependent economy and oil-fired power plants make it the most oil dependent state in the United States. It also has the nation's highest electricity prices, often between 3 and 4 times the national average over the last decade. These high prices, the state's sunny and windy climate that make it amendable to increasingly economical renewable energy, plus a relatively progressive political culture have pushed the state to adopt an ambitious goal of being 100 percent renewable by 2045. Focusing mainly on the state's largest grid on Oahu, where most people live, we discuss the cost structure of the current electricity system, the potential benefits and challenges of growing the share of renewable energy, and make a few policy suggestions. In particular, we argue that all homes and businesses should be given an opportunity to buy and sell electricity at the marginal cost of generation. Variable pricing could greatly reduce the cost of renewable energy, and perhaps seed development of Hawai`i as a technology center focused on batteries and smart machines that can help shift electricity demand to align with the variable supply of solar and wind energy.

Introduction

If, as Justice Louis Brandeis famously said, states can choose to be laboratories of democracy by trying "novel social and economic experiments," then Hawai`i has chosen to be this nation's laboratory for renewable energy. Each island's situation is a little different, but all are rich in renewable energy potential, while oil, our traditional fossil fuel, is comparatively expensive. Today solar and wind are nominally competitive with fossil fuel and especially attractive in Hawai`i. Add generous subsidies to the mix, and renewable energy now looks like a veritable goldmine to opportunistic investors.

The natural variability and intermittency of solar and wind do present new challenges for storage and grid management. While battery costs appear to be falling, it could be some time before they are cost effective for storing electricity over hours or days. In the meantime, renewable energy probably makes more sense if integrated with the existing grid, managed by our privately owned and publicly regulated utilities, HECO, MECO and HELCO, all subsidiaries of Hawaiian Electric Industries. NextEra Energy has put forward a bid to buy Hawaiian Electric. NextEra is a much larger power company with a wide mix of fuels and is the nation's largest proprietor of wind and among the larger solar generation. NextEra wants to be the North American leader in renewable energy and sees Hawai`i as a strategic part of its plan. Also, given current pricing structures, NextEra may have a lot to gain by owning both the utility and a substantial share of the State's renewable energy generation capacity.

Renewable energy has found its time and place, which could be a remarkably positive development. At the same time, at least in Hawai`i, a state that is understandably skeptical of outsiders seeking economic opportunity, there is a palpable fear that the benefits of renewable energy will not be widely shared.

In this paper we review some of the basic data on costs surrounding alternative forms of electricity generation. We focus mainly on O`ahu, because it uses the bulk of electricity, and in part because more public data is available on its larger grid. We also discuss how some of the basic challenges with intermittency and storage could be resolved in a simple and transparent manner with variable time-of-day pricing (e.g., hourly). Finally, we discuss some potential auxiliary benefits to Hawai`i's economy from the state's renewable energy transformation.

Oil-based generation

Historically, and still today, Hawai`i electricity prices are closely connected to oil prices. We unpack some of the details of this link and show how Hawai`i's oil prices compare to world market prices. Electricity prices have otherwise drifted

up due to factors besides oil prices. We use data reported to the Federal Energy Regulatory Commission and the Energy Information Administration to critically evaluate generation costs in relation to revenues. These data also give telltale indications of the changing energy landscape, including improvements in energy efficiency and the rapid growth of rooftop solar, that has pushed down daytime loads and may have caused a recent increase in nighttime load.

Excluding rooftop solar, Hawai`i residential consumers paid an average of about 37.5 cents per kilowatt-hour of electricity in 2014, which is about 3.5 times the national average, and far more than any other state. Larger scale commercial and industrial customers paid less, 34.5 and 30.4 cents respectively (Figure 1.) Taking refrigerators, water heaters, stoves, air conditioning and other uses into account, the average Hawai`i household uses about 18.5 kWh each day, for a monthly bill of about $208.
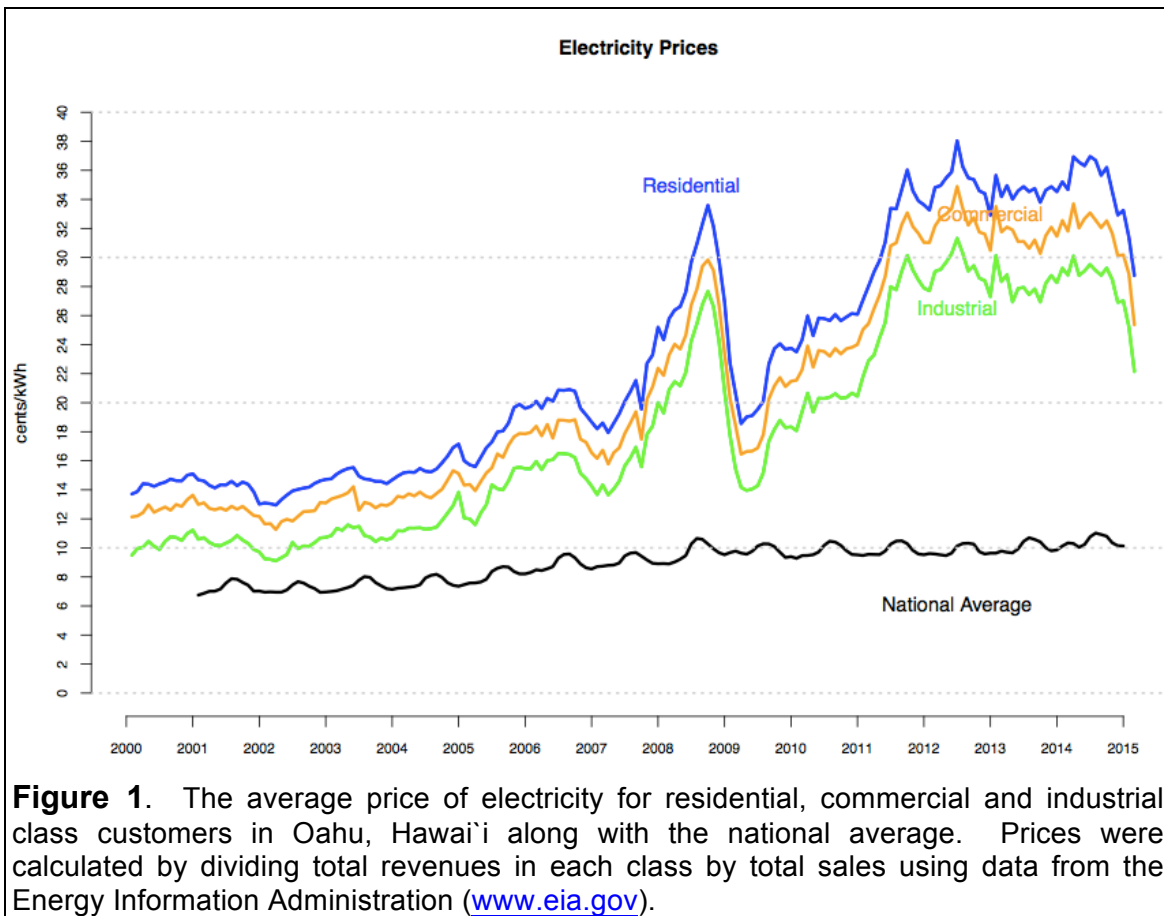

Figure 1. The average price of electricity for residential, commercial and industrial class customers in Oahu, Hawai`i along with the national average. Prices were calculated by dividing total revenues in each class by total sales using data from the Energy Information Administration (www.eia.gov).

Thankfully, high electricity prices hurt a little less here than on the mainland, because our mild climate means we don't have heating bills and residents can often get by without air conditioning. But hotels and other businesses are unlikely to skimp on air conditioning like some residents will. And while their prices are slightly lower, electricity is still a considerable expense.

Today over two thirds of the state's generated electricity is used by commercial businesses and industry, which factors greatly into the prices we pay and wages we earn. It's easy to see how high electricity prices are a burden on Hawai`i's economy.

Electricity prices can be roughly boiled down to the price of oil, which is used to generate most of our electricity, plus the price we pay for fixed costs like power plants, the grid and its management. These costs are "fixed" in the sense that they don't vary with the amount of electricity generated and consumed. We have high electricity prices because oil prices have been high, and because the fixed price of our infrastructure, averaged over the amount of electricity we use, is high and growing. The fixed-cost component of electricity prices has risen from around 10 cents/kWh in 2000 to almost 18 cents/kWh today (Figure 2). Fixed costs alone are about 50% higher than mainland retail prices. To some extent, high fixed costs can be explained by the State's isolation and small scale, which means fixed costs need to be averaged over fewer kilowatt hours of generation. Increased efficiency and growing penetration of distributed solar have acted to reduce total net generation, further increasing fixed costs.
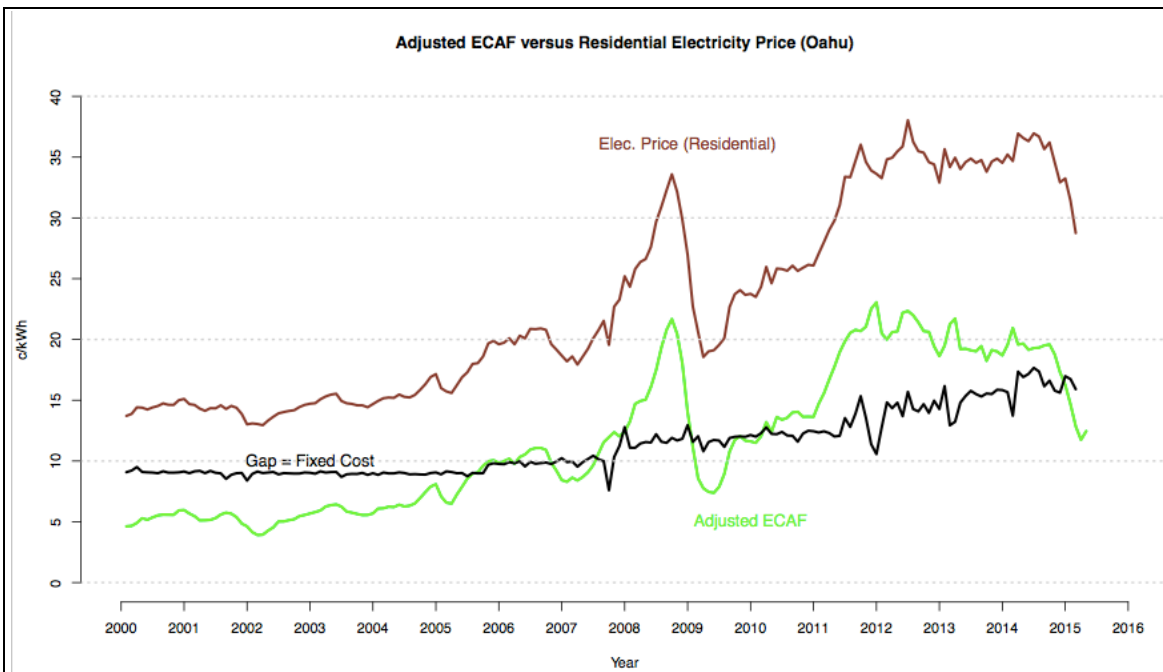

Figure 2. **ECAF and the average price of electricity.** The energy cost adjustment factor (ECAF) reflects the fuel cost (mainly oil) used in generating electricity. We adjusted the official ECAF to account for periodic changes in the baseline. The difference between the ECAF and the electricity price ("Gap" in the figure), indicates rising fixed costs.

Statistical analysis of the price Hawaiian Electric Company (HECO) pays

for oil[1] indicates that it is closely associated with the Brent crude oil prices averaged from 14 to 141 days prior to the first of each month.[2] For example, the oil price HECO uses to calculate electricity prices for January 2015 is most closely connected to the average price of Brent from August 13, 2014 through December 18, 2014. This moving average is plotted in Figure 3, along with HECO's low-sulfur fuel oil (LSFO) inventory price, the oil-equivalent price for all fuels (general composite cost) and the energy cost adjustment factor (ECAF) applied to customers' bills in cents per kWh. The ECAF allows the utility to adjust prices in response to changing costs of generation—mainly oil prices—-since these costs can vary a lot between rate cases.
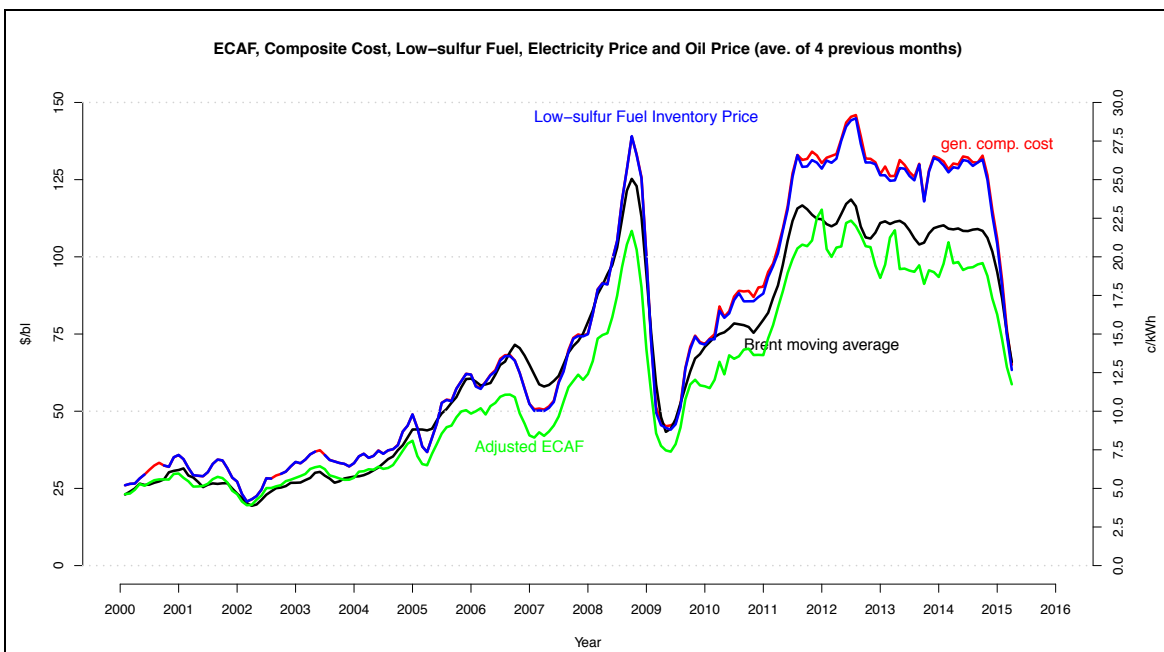

Figure 3. **Different measures of fuel costs.** The energy cost adjustment factor (ECAF) drives most variation in electricity prices and reflects the fuel cost (mainly oil) used in generating electricity. The graph shows ECAF together with HECO's fuel cost (low sulfur oil and a general composite cost that includes diesel) and a moving average of historical Brent crude: the price averaged from 141 to 14 days prior to the first of each month. Note the ECAF has been adjusted to include different baselines from each rate case by the Public Utilities Commission.

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[1] As reported each month to the Public Utilities Commission in the Energy Cost Adjustment filing. See   http://www.Hawai`ianelectric.com/heco/_hidden_Hidden/EnergyServices/Energy-Cost-Adjustment-(ECAC)-for-Hawai`ian-Electric
[2] Brent crude oil serves as a major benchmark for world oil prices. We found this by searching over all possible moving averages starting from as early as six months prior and ending as recently as the current day.

Another perspective on oil prices and ECAF is shown in Figure 4, which shows scatterplots of different oil price measures over time directly against ECAF. The relationship with the Brent moving average is steeper than the HECO-reported measures. This pattern indicates that HECO prices are typically higher than Brent, but much more so when oil prices are generally high than when they are low. When world oil prices rise, they tend to rise more in Hawai`i, and when world prices fall, they fall further in Hawai`i and converge toward the world price.
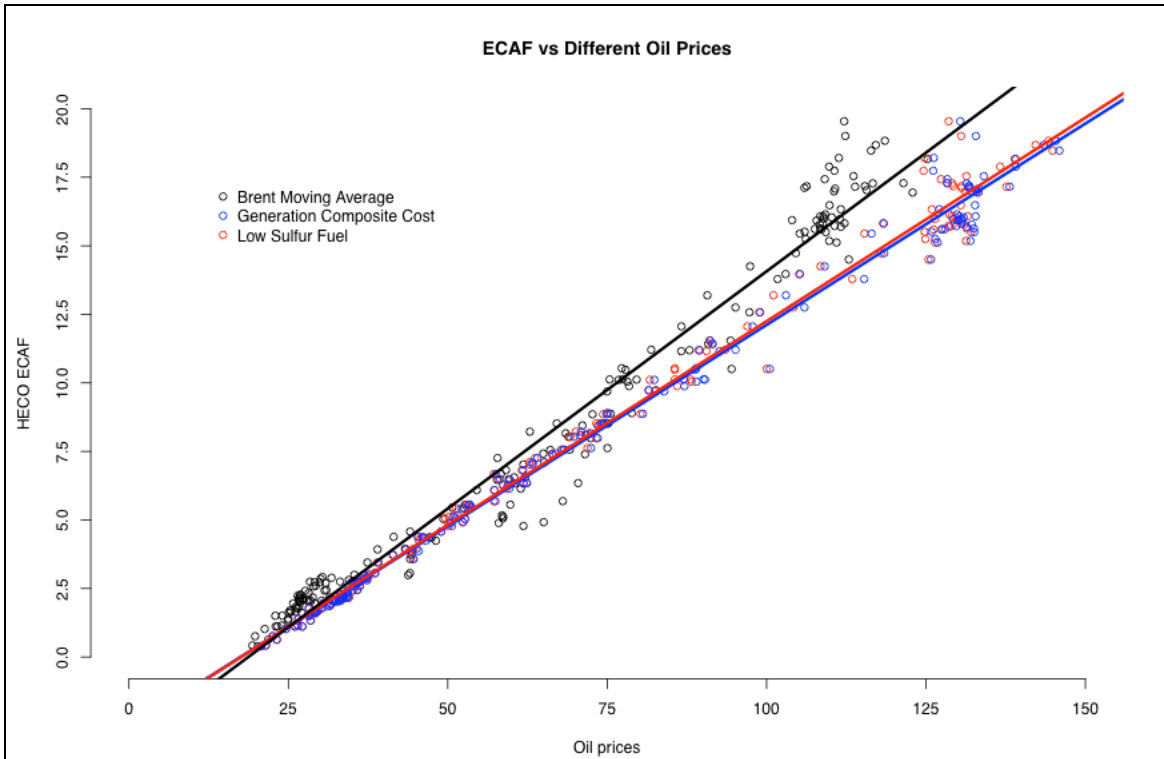

Figure 4. **Oil Prices Versus ECAF.** Different measures of fuel costs all predict the ECAF well. When oil prices are high, HECO's cost of oil tends to be even higher, especially in recent years, which helps to explain why prices have been so high.

While world Brent oil prices rose markedly over the last decade, the price Hawai`i pays for low-sulfur oil went up even further, an extra $20 to $30 per barrel between 2011 and 2014 (see Figure 3). This additional spike in oil prices began with the tsunami-induced Fukushima Daiichi nuclear disaster in Japan. After the disaster Japan's oil imports increased to make up for lost nuclear generation. And since Japan was drawing low-sulfur oil from the same south Asian sources as Hawai`i, prices rose more than the rest of the world. More recently, Japan has substituted toward natural gas and other fuels, reversing the post-Fukushima jump in oil demand.

World oil prices have taken an unexpected dive, falling from over $100 barrel in the summer of 2014 to around $50 in early 2015. At the same time, it

appears as though the gap between Hawai`i's price for low-sulfur oil and the world price, equal to about $30 in late 2014, has essentially vanished. It has taken a few months for this remarkable drop in oil prices to be fully reflected in lower electricity prices, given the long lag between world prices and HECO inventory prices. But the relief, finally showing up in Hawai`i electricity prices, is significant.

Most seem to expect oil prices to remain low for an extended period, but to eventually rise.[3] The price drop came about through a combination of weak demand (slower economic growth in Asia and Europe and rapidly improving energy efficiency), combined with rapid growth in oil extraction from hydraulic fracturing in the United States and from oil sands in Canada. Current prices sit below average costs for these extraction methods. Though it may take awhile, in the long run we should probably expect extraction to slow or demand to grow and prices to rise again, at least back to the extraction costs of these key sources. This kind of adjustment can take a long time due to a combination of large startup and shutdown costs involved with oil extraction operations combined with larger uncertainties about oil prices (Dixit, 1989).

Another factor weighing on oil prices is the potential for a nuclear agreement with Iran, which could remove sanctions, allow Iran to sell at world prices and markedly increase production. While events in the Middle East are uncertain, it is easy to imagine developments leading to either lower or higher prices. While prices remain low, recent weeks and months have shown great volatility amid speculation about events in the Middle East, demand growth in the wake of lower prices, and how much high-cost operations in the United States and Canada will scale back production. At this writing world prices have crept back up to around $58, but futures prices for delivery 8 years out (2023) remain are about $72. The best guess is that prices will rise only modestly over the next few years as Hawai`i rapidly transitions toward greater reliance on renewable energy.

Besides oil, there is one coal power plant on Oahu that produces electricity much less expensively. Coal power plants typically require a sufficiently large scale, and Oahu is the only island with that sufficient scale. In addition, coal is a lot more polluting, so adding another coal plant seems incompatible with Hawai`i's clean energy goals. Hawaiian Electric also buys electricity through a series of purchasing power agreements (PPAs). Prices paid on PPAs vary across contracts and sometimes on timing (peak or off-peak), and do not necessarily vary with the price of oil.

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[3] One prominent expert who seems to hold this opinion is James D. Hamilton, a Professor at the University of California at San Diego who is well known for his work linking oil prices to the macroeconomy. He also co-authors an influential blog (econbrowser), that often covers oil price developments. See, for example,
http://econbrowser.com/archives/2015/03/u-s-oil-production-still-surging
 and http://econbrowser.com/archives/2015/03/u-s-oil-supply-update

Hourly Loads and Incremental Costs

Retail energy prices only tell so much. The cost of producing electricity varies depending on the load and to some extent on load variability and power plant reliability, and thus the cost of reserve capacity in the event of power plant failure or a spike in demand. A little understanding about how the whole system works helps to clarify thinking about the challenges and opportunities surrounding renewables.

To gain some insight into changing demand profiles and to estimate actual costs of generation, we used two primary sources of data. First, we downloaded Form 714 data from the Federal Energy Regulatory Commission (FERC) that gives hourly load. The second data source is HECO Energy Cost Adjustment (ECAF) documents, submitted to the Public Utilities Commission each month, from which we obtained cost measures relating to different power plants in Oahu. This dataset contains information on different fuel expenses for generation, purchased power and distributed generation as well as their input mix.

The principal source of fuel is low-sulfur oil (LSFO) obtained from the two gasoline refineries, Exxon and Tesoro. Oil purchased by HECO is a byproduct from refining processes used to make gasoline and jet fuel. The byproduct is presumably less than the price of raw crude, otherwise HECO would buy the crude directly. The specific contracts between HECO and the refineries are not made public, but the ECAF reports total inventory cost to the Public Utilities Commission each month.

The document also reports purchase prices of energy from plants that also use low-sulfur fuel (Kalaeloa) and other sources that include wind (e.g. Kahuku) and distributed generation plants. Figure 5 shows these prices for the major plants in Oahu. The purchase price of the AES coal plant has been relatively constant around 3 to 4 cents/kWh. The price of purchased power from the low-sulfur Kalaeloa plant has been lower by around 2 cents/kWh than HECO's LSFO generation plants, except for the 2011-2015 periods where the gap was larger. The gap has recently closed again as oil prices have fallen. Historically, electricity generated from diesel peaking plants has been most expensive.
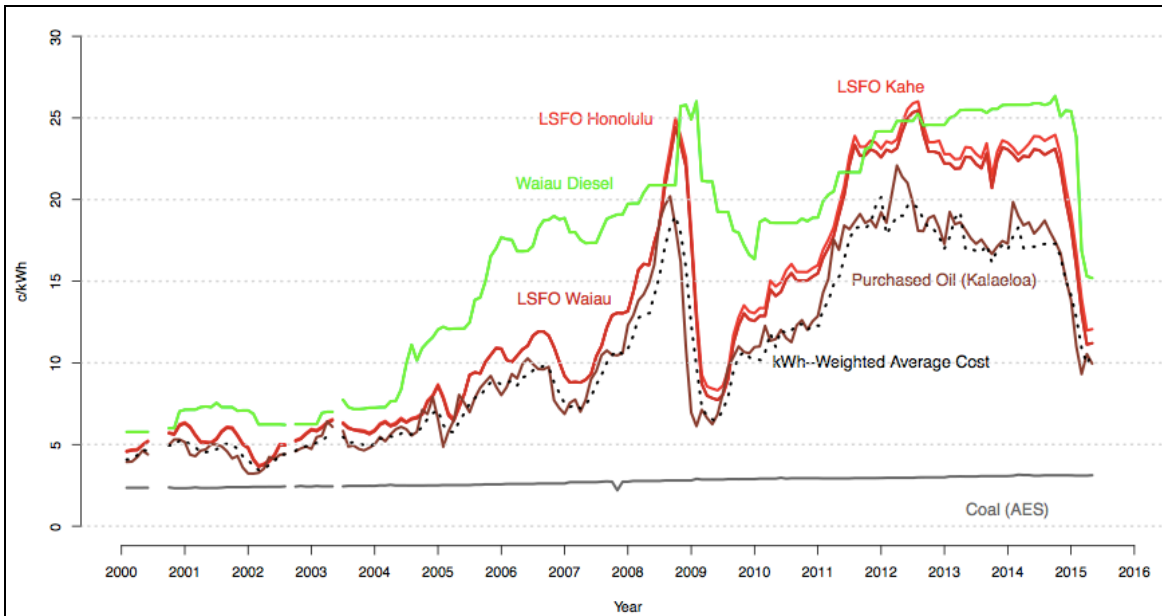
Figure 5. **Fuel prices from different sources.** The graph shows average, per kWh generation costs from the largest power plants in Oahu. Costs from most plants vary with the price of oil.

To an extent, costs vary by design. An essential tradeoff in system design pits capital costs against variable costs. Power plants can be made to burn fuel more efficiently, but at a considerable cost. To get the most out of a high-cost power plant, it helps to run the plant at full capacity most of the time. Conversely, low-capital-cost power plants with higher per-kWh incremental costs can still be economical if they aren't used very often. A system therefore tends to "stack" plants from low marginal cost base plants that operate nearly nonstop, with progressively higher marginal-cost plants that cycle with variable demand, and finally cheap peaking plants with high marginal costs that operate only during unusual peak loads (e.g, Waiau Diesel).

Another key aspect of cost and grid management involves maintaining reserve capacity in the event a power plant fails, electricity demand suddenly grows, or power from variable renewables suddenly falls off. Reserves can be met by relatively flexible, but expensive, load-following plants that can quickly ramp up and down depending on demand. The utility must keep enough reserve capacity to cover load from the largest power plant—the coal-fired AES plant—should it fail. Basically, this means the utility must keep expensive oil-fired power plants running at a minimum level much of the time, which acts to increase average generation costs even when the incremental cost is just 3 cents per kilowatt hour. Reserve, load-following plants are similarly critical for managing a grid with intermittent renewables. As the sun descends in the late afternoon, reducing solar generation just as demand grows towards its peak, load-following plants must quickly ramp up. Reserve costs tend to be larger in Hawai`i than other locations that can use cheap natural gas for this purpose and are connected to much larger grids with more and much larger power plants.

On Oahu, aside from the one coal-fired power plant, incremental costs are actually relatively uniform across the fleet of oil-fired power plants (incremental costs equal the slopes of cost curves in Figure 6). Exceptions include two plants at Kalaeloa, which are somewhat more efficient than the other oil-fired plants, but have a limited scale of operation, between around 70 and 95 MW each. The other two big exceptions are the very expensive diesel-fired power plants (W9 and W10 in the figure) which are much more expensive. These peaking plants are rarely used, but sometimes must be turned on at low levels for reserves during peak loads or when larger power plants have failed or have been shutdown for maintenance.
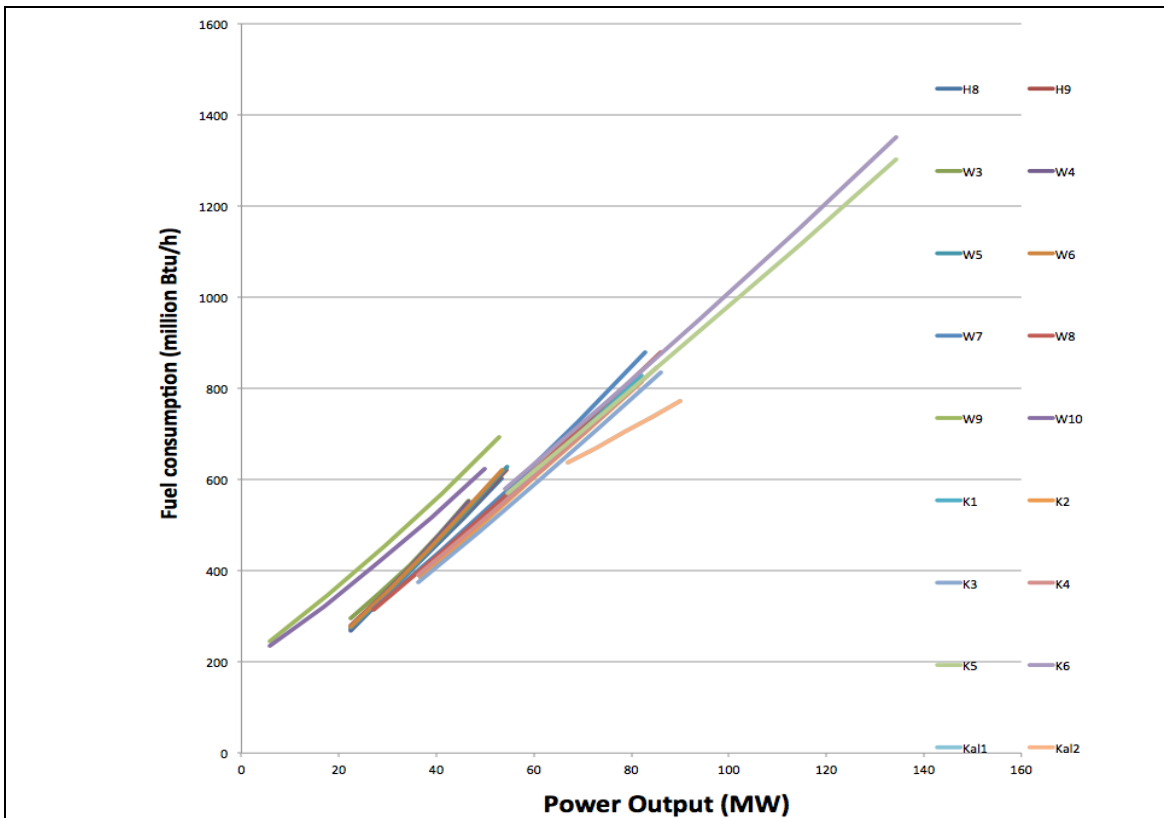

Figure 6. **Cost Curves for Oahu Oil-Fired Power Plants.** Each line in the graph represents a single electricity-generating unit. Each line plots fuel consumption on the vertical axis (one barrel of oil equals roughly 5.5 million Btu) against electricity power output. These cost curves were constructed by Matthias Fripp using data from a solar penetration report by GE Consulting.
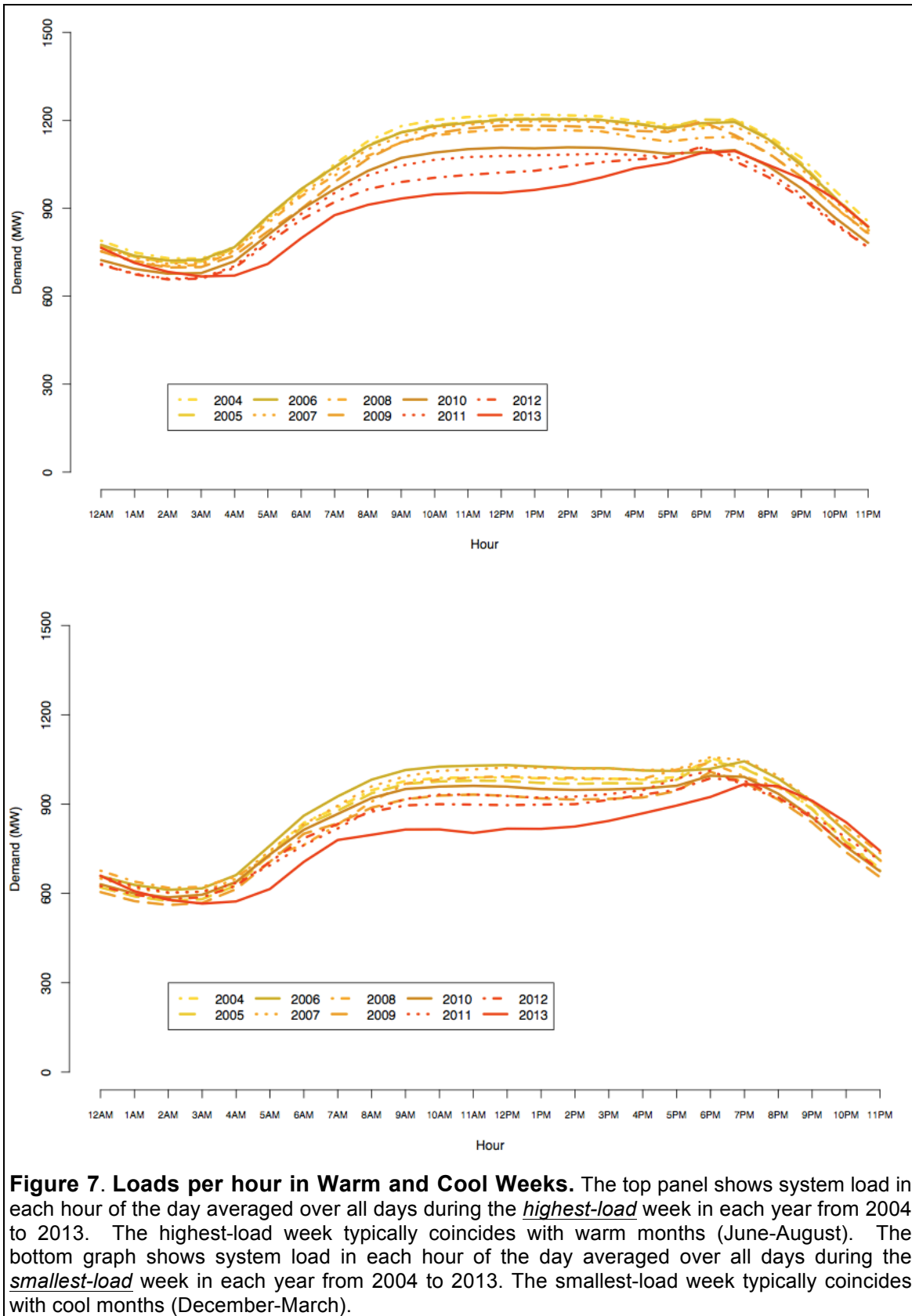
Figure 7. **Loads per hour in Warm and Cool Weeks.** The top panel shows system load in each hour of the day averaged over all days during the _highest-load_ week in each year from 2004 to 2013. The highest-load week typically coincides with warm months (June-August). The bottom graph shows system load in each hour of the day averaged over all days during the _smallest-load_ week in each year from 2004 to 2013. The smallest-load week typically coincides with cool months (December-March).

Because distributed solar provides the most energy midday when loads tend to be higher, the power can be relatively valuable as it displaces energy from HECO's relatively expensive LSFO plants. Figure 7 shows that as solar penetration has grown over the last few years, midday loads have fallen a bit relative to the evening peak. The data suggest solar penetration has therefore saved generation costs to the utility in greater proportion to the load displaced. While the year-to-year fluctuations in the afternoon to evening curves reflects changes in oil prices, it is clear that by 2013—when solar became more significant—midday loads fell relative to early evening.

Of course, as solar installations rise, the less valuable its energy becomes, as it further depresses the incremental cost of generation. If solar penetration grows large enough, and energy cannot be stored or load somehow shifted toward midday, some solar energy might be *curtailed*, a euphemism for throwing away energy. According to the Hawai`i Solar Integration Study by GE Energy Consulting, this kind of curtailment begins to occur in our current system when solar penetration reaches about 15%, or 2-3 times the current level, although the report did not consider storage or possible load shifting through demand response programs.

Curtailment can happen even when solar energy comprises significantly less than total demand, because some power plants cannot be cycled quickly and load-following plants must remain operating at a minimum level to supply reserves. A significant amount of curtailment of Maui's wind energy already occurs. In this environment a little bit of storage could go a long way toward reducing curtailment and improving efficiency. And if it were possible to shift demand toward the sunnier and/or windier times of the day, it would obviously make solar, wind and the whole system a lot more cost effective.

Curtailment seems like a remarkably inefficient way to cope with variable supply. Surely, if electricity were offered for free during these periods, many an entrepreneur would find a way to put the energy to good use, or perhaps find a creative way to store the energy. We expect this problem could be solved, and the general efficiency of the system greatly enhanced, if prices varied with incremental cost. Such pricing would allow anyone with an ability to shift load or store energy to take advantage. It would effectively decentralize the grid management problem, and generally act to minimize costs while facilitating greater use of renewable energy. We elaborate further on this point below when we discuss alternative policies.

Estimating Average Variable Cost by Fuel Expense

A simple way to estimate average variable costs (AVC) is to add up expenses for fuel and divide by kilowatt hours sold (Figure 8). This measure accounts for the electricity used by power plants and line loss, and other factors that cause net generation to be greater than electricity sold. It also accounts for "free" electricity from distributed solar from households that generate more than they consume. Figure 8 shows that the AVC ("Total Components" in the figure) has nearly quadrupled from 2000 to 2008 and more than doubled from 2009 to early 2015,

which were periods when oil prices have sharply increased. Note that there is a close relationship between AVC and the adjusted energy cost adjustment factor, with the difference presumably accounting for reserve-related costs. It is clear that most changes in average variable cost are driven by oil prices.
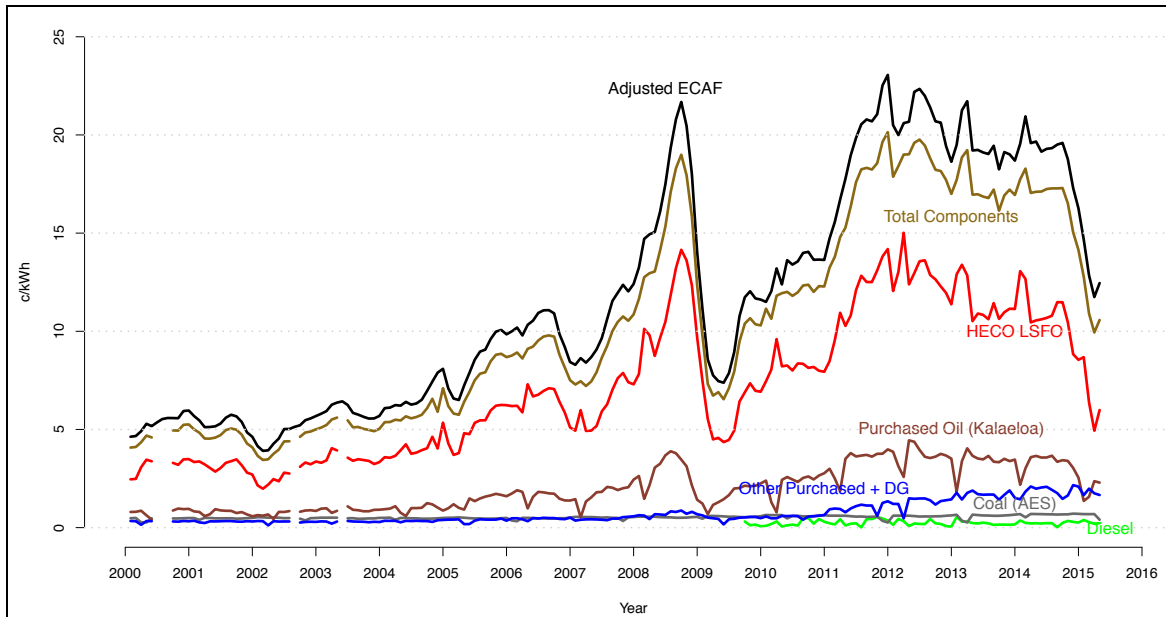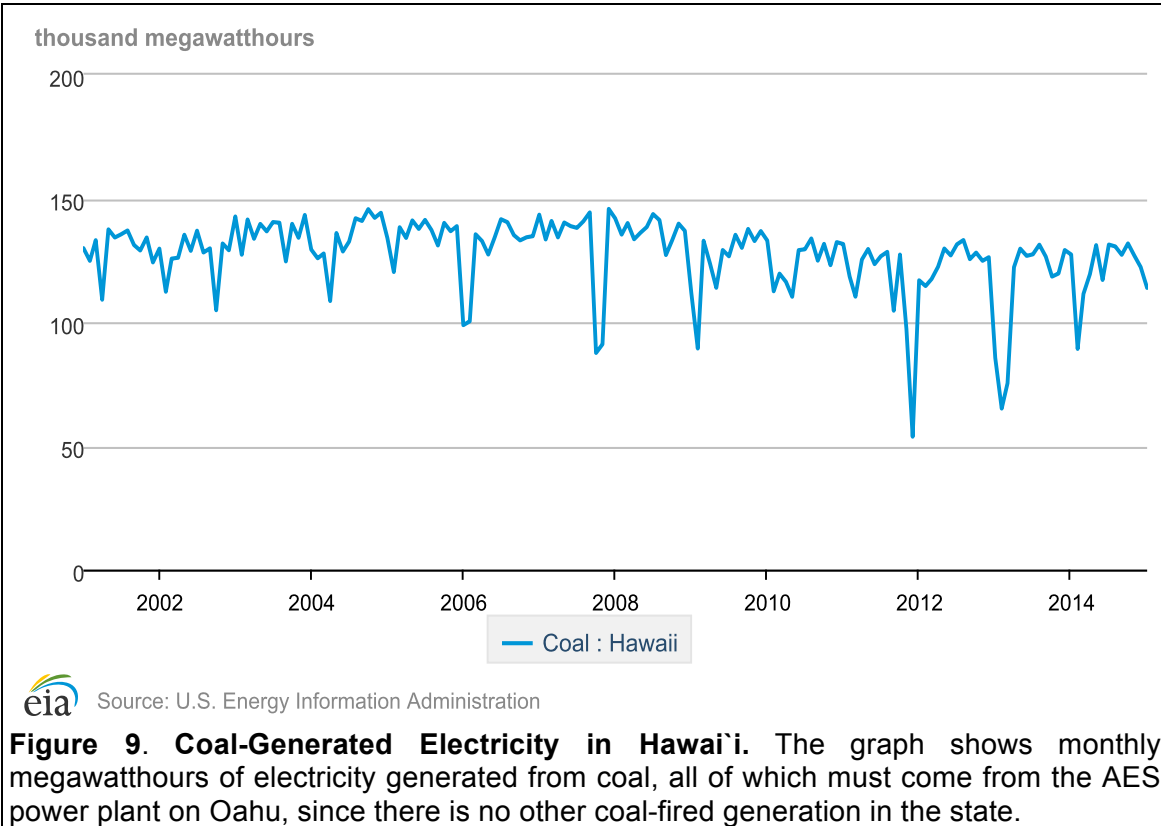

Figure 8. **Average Variable Cost by Source.** Each line shows the purchase or generation price of electricity multiplied by its share of the overall load. As an example, although electricity generated from diesel (green line in figure) is the most expensive among all major power plants (Figure 5), it has a very low share in generation and therefore does not figure significantly in average variable cost.

Although oil prices mainly drive AVC, generation costs may have risen due to more difficult grid management. Due to gains in efficiency and growth of distributed residential solar and wind (wind provides as much as 30 MW on Oahu), the utility's job of balancing supply with demand has become more difficult. As a result, the utility tends to keep more power plants running than the system really requires, sometimes to the point that relatively low-cost power plants (e.g. AES and Kalealoa) are underutilized. When low-cost power plants are operated below capacity, then it may be possible to lower cost by ramping up generation from these low-cost plants to substitute for some of the power generated from high-cost power plants. Also, power plants tend to operate less efficiently when running near their minimum capacity.

In Oahu, there is some evidence that the AES coal power plant has been recently underutilized. For instance, data from the Energy Information Administration (EIA) show that coal-generated electricity fell about 18 percent between 2008 and 2013 (Figure 9). If the grid could be managed in a way that fully utilized the AES power plant during all months of the year, the annual savings would amount to $30-50 million, or 1.5 – 2 cents per kWh averaged over

all electricity sold by the utility. There might be additional savings from operating fewer oil-fired power plants during low-load times. More cost-effective storage or other grid-stabilization tools, like variable pricing, might help to facilitate this kind of savings.

thousand megawatthours

Source: U.S. Energy Information Administration

Figure 9. **Coal-Generated Electricity in Hawai`i.** The graph shows monthly megawatthours of electricity generated from coal, all of which must come from the AES power plant on Oahu, since there is no other coal-fired generation in the state.

To estimate the rise in costs from grid management, we undertake an alternative method of estimating AVC for Oahu that assumes maximum efficiency, and then look to see how this measure has changed over time relative to actual reported generation costs. The details of this method are outlined in Appendix 1. Briefly, the method involves separately estimating the relationship of generation or purchase prices of the different power plants (AES, Kalaeloa, LSFO plants and diesel plants) to an appropriate Brent crude price measure as well as kWh sold by these plants.[4] Specifically, the regression takes the form

$$log(price) = brent + g(kWh\ sold) + error \qquad (1)$$

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[4] The Brent crude price measure is obtained by estimating equation (1) for different lag lengths and selecting the measure with the best fit.

We estimate this regression for each of the four major power sources. In this equation, log(*price*) is the natural log of the generation or purchase price, *brent* is a moving average of the Brent crude price over the best-fitting lag length and *g*() indicates a smooth function of kWh sold estimated using natural splines. We estimate this model using ECAF data from 2006 onwards. The fit is good, explaining about 90% of the variance in the price.

To build an overall cost curve, we further assume HECO meets demand by using the least-cost power first and progresses to more expensive sources as each source reaches its historical GWh maximum load (since 2006). Specifically, we assume that the first 146 GWh will be produced by AES, Kalaeloa produces the next 147 GWh, and LSFO plants will produce the next 454 GWh. If the demand is more that 747 GWh in a given month, then we assume diesel plants make up the rest.

Figure 10 shows our estimate of the simulated AVC along with the AVC obtained earlier in Figure 8 ("Total Components"), which is effectively HECO's reported AVC. The two measures of AVC are close together. Before mid-2009, the ECAF tended to be slightly below our simulated estimate, but since then there are periods where the ECAF is 1 to 2 cents/kWh higher than our simulated AVC. Some of the difference may be due to simple estimation error, since we don't have precise measure of oil or coal prices. But the difference may reflect a slight increase in costs due to rising grid-balancing costs.

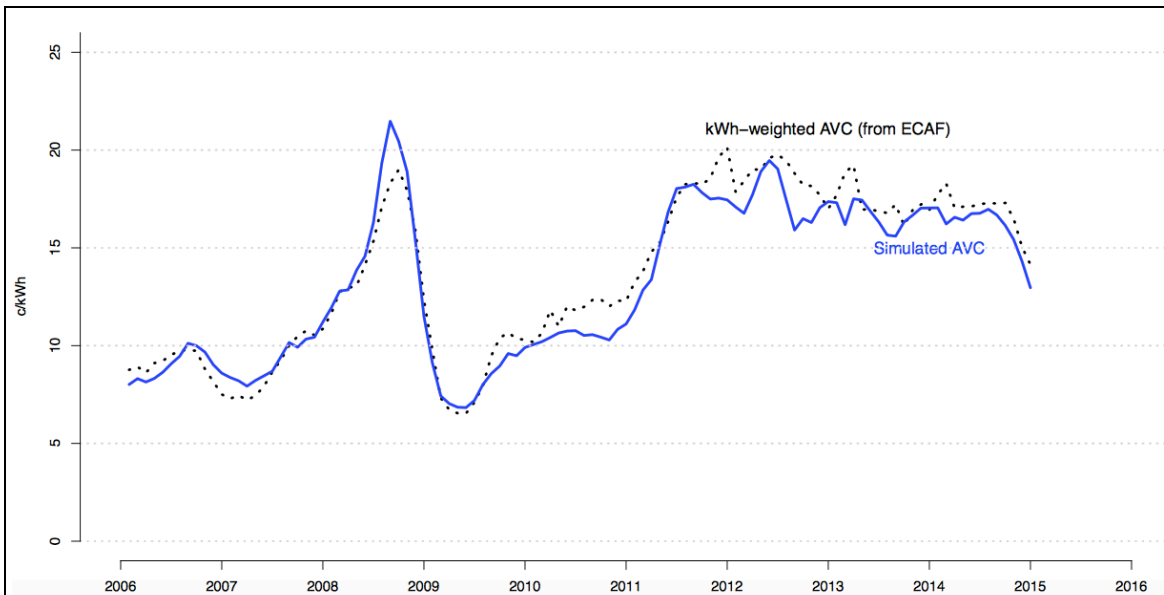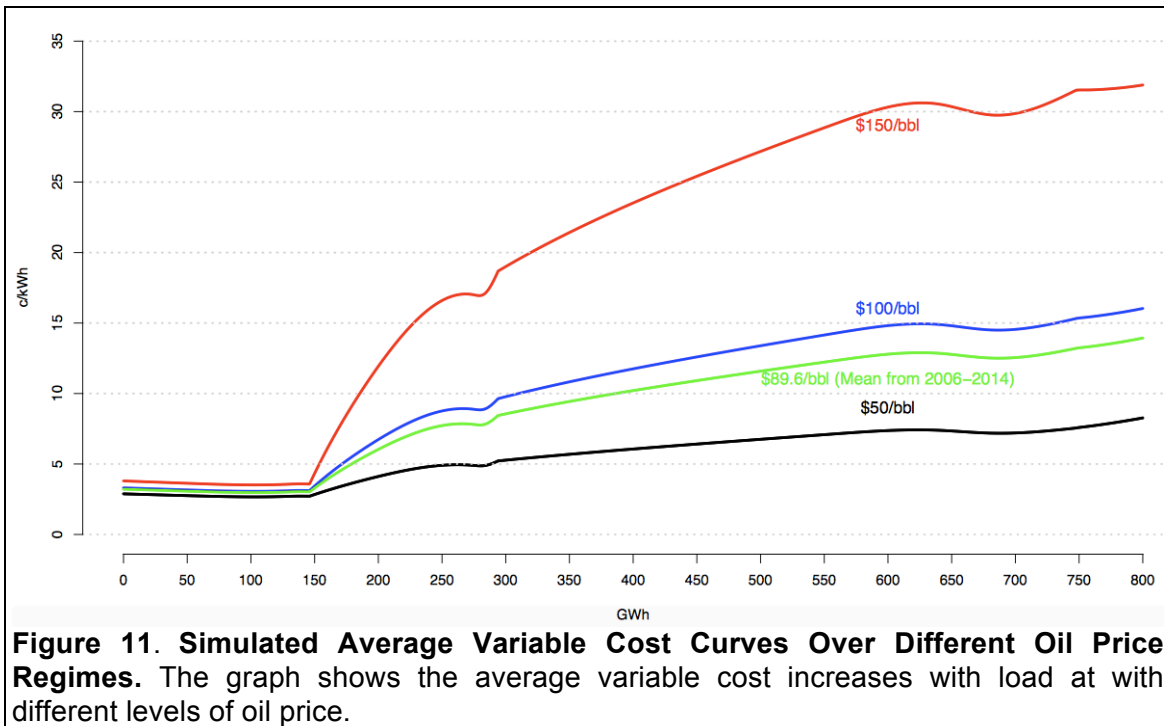**Figure 10**. **Simulated Average Variable Cost.** The graph shows the average variable cost assuming that HECO fully utilizes its low-cost power plants (Simulated AVC) and average variable cost obtained from weighting prices with kWh sold (see Figure 8) from 2006-2015.

As with the earlier AVC estimate, the simulated AVC shows marked increases from 2006 to 2008 and from 2009 to mid-2011, and a steep decline

with the recent fall in oil prices. To see how the cost curve shifts with oils prices, we constructed several average variable cost curves for different levels of oil prices and different load levels (Figure 11). When oil prices are low, around $50/bbl, the cost rises slightly with load since operating LSFO- and diesel-fired plants are not so expensive. However, during high oil price episodes such as those that occurred in 2008 and 2011, when the price of LSFO reached more than $125/bbl, the relationship between AVC and load became much steeper.

Figure 11. **Simulated Average Variable Cost Curves Over Different Oil Price Regimes.** The graph shows the average variable cost increases with load at with different levels of oil price.

Between 2006 and 2015, AVC increased roughly 4 cents per kilowatt-hour but electricity prices have increased by more than 10 cents per kilowatt-hour. Even taking reduced loads into account, these estimates imply much larger share of revenue being directed toward reserve capacity, fixed costs and HECO returns. We make these calculations and plot them in Figure 12. The calculation is simple: subtract estimated average variable cost from price and multiply by kilowatt hours sold, which gives total revenues toward fixed costs. The calculation indicates that revenue toward fixed costs and HECO returns were between $60 and $75 million dollars per month between 2006 and 2009 and have increased to around $100 million dollars per month in late 2014 to early 2015.
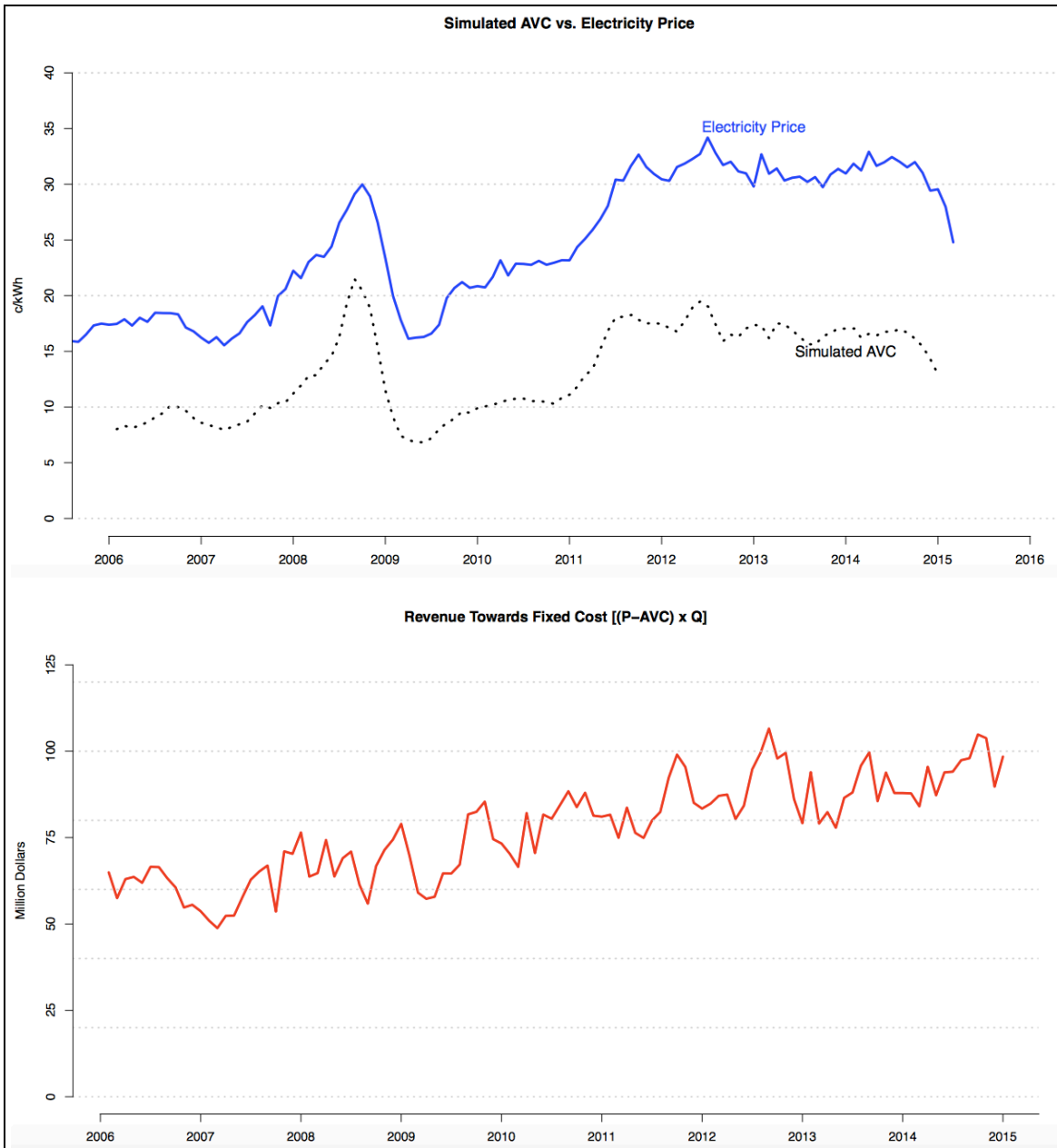
Figure 12. **Estimating Revenue Toward Fixed Costs.** The top graph shows average electricity price in blue and our estimated average variable cost in the dotted line. The difference gives an estimate for average fixed costs. The bottom graph shows average fixed cost multiplied by kilowatt hours sold each month. Fixed costs cover everything besides generation costs—capital, management, grid maintenance, billing and HECO returns on equity.

Increasing fixed cost in the face of declining loads brought about by increased efficiency and greater solar penetration can be readily explained by a few factors that may include:

(i)   Increasing cost of grid management. One concern is the underutilization of the AES coal power plant;

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(ii)   Our estimation technique does not account for reserves and might assume a larger capacity of coal generation than actually exists;

(iii)   Changes in reserve costs, which may have become more important as net generation has declined and renewables have grown to comprise a larger share of demand;

(iv)   The fact that fixed costs must be averaged over fewer kilowatt hours sold;

(v)   A revenue decoupling policy that allows the utility to raise prices to make up for demand lost to greater efficiency and distributed solar generation. Such adjustments, however, only apply between rate cases, and should not permanently increase fixed costs, but do raise the fixed cost per kilowatt hour sold per (iv).

(vi)   The fact that some households installing photovoltaic solar produce more electricity than they use, which means there is zero cost to the utility for some of the electricity sold.

Renewable Energy

Hawai`i is rich in renewable energy potential and politically committed, through the Hawai`i Clean Energy Initiative (http://www.Hawai`icleanenergyinitiative.org ), to sharply reduce reliance on fossil fuels.  Is this commitment a prudent one?  Given Hawai`i's small size, we can have little influence on global greenhouse gas emissions.   Local air pollution is mostly blown away by the trade winds. Honolulu's air quality is among the cleanest of all major cities in the nation. The problems we do have with air quality derive mainly from volcanic emissions on the Big Island of Hawai`i, which are beyond our control.

Still, there are pragmatic reasons to reduce fossil fuel consumption. We see at least three compelling justifications for our current course: (1) renewable energy is cost competitive; (2) renewable energy may present a broader economic opportunity for the state as a technology center; and (3) renewable energy could reduce vulnerability of the state's economy to oil price fluctuations. We flesh out each of these ideas below.

1. Renewable Energy is Cost Competitive

The cost of renewable energy has fallen tremendously in recent years. Electricity from wind can be obtained for less than 5 cents per kWh and solar for less than 7 cents per kWh (inclusive of Federal, but not state subsidies). These prices look remarkably inexpensive in Hawai`i. It's hard to believe we cannot reduce fossil fuel use while also saving money.

There are delicate tradeoffs between wind, solar and other energy sources. Wind is especially plentiful on Maui, Lana'i and Moloka'i, but these islands have small populations. Transferring wind energy from these islands to more populous Oahu would be costly, and also politically sensitive. At least so far, utility-scale installations for wind and solar on Oahu have contract prices that

are unusually expensive, both coming in around 15 cents per kWh and higher. The high prices are not because Hawai`i's wind blows less strong or because the sun shines less brightly; quite the opposite. Most attribute the relatively high price of renewables to land costs and the smaller-scale installations thus far. If land costs explain the difference, it implies a value to agricultural land that far exceeds observed prices. In the case of solar photovoltaic, the implied cost difference implies a land cost of over $300,000 per acre, which seems remarkably high for Oahu agricultural land.[5] So the case for renewable energy being more cost effective is not entirely clear-cut, in part because oil-based costs may have fallen considerably with oil prices, and partly because renewable prices here are comparatively high.

While costs of utility-scale solar and wind installations have been two to three times mainland costs, residential solar installations appear reasonably competitive with mainland costs. Before taking account of state or Federal subsidies, installed costs for residential solar are currently a bit below $4 per Watt of capacity, which pencils out to about 16 cents per kilowatt-hour at conventional interest rates (4.5-5%). Mainland priced for installed residential solar average $3.48 per Watt.[6] With federal subsidies but no state subsidies, this corresponds to a price of 12-13 cents per kilowatt-hour, which is notably less than the price of utility-scale solar or wind in Hawai`i. Add state subsidies to the mix, and the price falls as low as 7 cents per kilowatt-hour.[7] Given current prices, it is no surprise that demand for residential solar PV is so high. And given the high cost of utility-scale installations, residential installations appear significantly more cost effective than utility-scale installations. This situation stands in sharp contrast with the mainland, where utility-scale installations of solar are typically half the cost of residential installations. At the same time, state-level subsidies appear unnecessary given how much homeowners installing solar PV can save without them.

It is possible that current contracts for utility-scale renewable energy are less than competitive. After all, Hawai`i is a small place, and there may be only

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[5] This is a rough calculation by the author that goes as follows: On the mainland we typically see offers PV solar of 7 cents / kWh, with an installation costs of around $2mil / MW, numbers which are roughly consistent with basic present value calculations while including a federal tax credit plus a little extra for accelerated depreciation (see http://www.uhero.hawaii.edu/news/view/274). A MW of utility scale photovoltaic requires roughly 7 acres, according to NREL (http://www.nrel.gov/docs/fy13osti/56290.pdf). Assuming, conservatively, that land costs are zero on the mainland, this implies an additional cost in Hawai`i of about $2.3 mil for 7 acres, or over $300,000 per acre.

[6] Greentech Media. See: http://www.greentechmedia.com/articles/read/Fueled-by-Growth-in-Residential-Solar-US-Installs-1.3GW-of-PV-in-Q1-2015.
[7] These price estimates were made using the solar calculator at http://www.uhero.hawaii.edu/news/view/274 with the following assumptions: (a) a system size of 4kW that is always less than or equal to electricity use; (b) an installed cost per Watt of $3.83; (c) an interest rate of 4.8%; (d) a decay rate of 2% on panel efficiency; (e) annual maintenance costs of $100; and (f) no monthly connection fee. Under these assumptions, a price was selected that makes the internal rate of return as close the interest rate as possible.

so many suitable land parcels with willing owners. In time, increased competition and further technology improvements may push prices for renewables down further. And even without further price declines, it seems clear that renewable energy is, at a minimum, cost effective during mid-day when oil prices are sufficiently high.

2. Renewable Energy as an Economic Development Strategy

Because renewable energy—particularly wind and solar—is perhaps more economically viable in Hawai`i than in any other U.S. state, it could give Hawai`i a broader economic opportunity as a leader in renewable energy technology and expertise. The idea, as the introduction suggests, is to leverage Hawai`i as a laboratory for renewable energy, and use this natural comparative advantage to make the state a leading technology center.  Such a center might be particularly valuable in Hawai`i, a state that thirsts to broaden its economic base beyond tourism.

Slowly but surely, the world is coalescing around the reality that climate change is real, human caused, and that something needs to be done about it. Emerging economies have stifling and lethal pollution levels that could benefit tremendously from renewable energy despite climate change. And since costs of renewables have fallen so much, growth now looks inevitable, and solar and wind will almost surely comprise major components of the green revolution that will occur over decades to come.

History and a lot of accumulated evidence suggest there can be huge positive spillovers for regions first to invest in emerging technologies. For an excellent and accessible review of this evidence, see *The New Economic Geography of Jobs* by Enrico Moretti (2012). The benefit comes less from use of the technology itself. Indeed, earlier vintages of new technologies can quickly become obsolete, and it can often make sense to adopt new technology later than sooner. The benefit comes mainly from knowledge spillovers that occur when a critical amount of expertise amasses in a particular location, facilitating broader economic development with wide spillover effects. The poster child for this kind of development is Silicon Valley, but examples exist in cities throughout the world.

It appears as though seeds of this kind of interest in Hawai`i as a renewable energy innovation hub are already occurring.  NextEra's purchase of Hawaiian Electric Industries may be symbolic of this trend. Other examples include the Energy Excelerator, the Hawai`i Natural Energy Institute at the University of Hawai`i, heavy investments made by the military in energy efficiency and renewable energy, and experimental projects in smart metering being undertaking by the Japanese and others.

Idiosyncrasies of the different utilities and islands—Maui's comparatively rich wind resources, the Big Island geothermal, and the urbanized environment of O'ahu, all present an interesting mix of opportunities and challenges. Kaua'i is managed by a public cooperative; it will be interesting to see how the cooperative

fares relative to the privately-managed utilities on the other islands. While many of these idiosyncrasies may be unique to Hawai`i, it also seems likely that much of what we learn about creating and managing renewable energy here in Hawai`i will be useful to the rest of the world. That essential fact may imply great economic opportunity.

Perhaps the greatest technological opportunities have to do with finding ways to inexpensively shift loads and/or store electricity. The economic value of shifting demand and storing electricity is larger in Hawai`i than any other state, as indicated by the large variation incremental costs documented above. Variability in incremental cost is going to grow more extreme over the next few years as more solar and wind come online. And there many ways, big and small, to accomplish the job. Unfortunately, at present, there is little incentive for small firms to engage in this economic opportunity, because wholesale and retail prices are largely constant (some wholesalers have separate peak / off-peak rates), and a regulated monopoly maintains control. Introducing a new technology basically requires a contract with the utility, which is burdensome impractical for many kinds of potential technologies, which may be more suitable to households and individual businesses.

A different regulatory model, with variable hourly pricing for both buyers and sellers of electricity, perhaps with a regulated grid connection fee, would make it easier for entrepreneurs to test new technologies in the state. Anyone with a new idea for storing energy or shifting demand could profit by buying low and selling high. Illinois and Georgia have successfully implemented variable pricing, and several other states have implemented successful policy experiments, so we know variable pricing can work. But these states do not have costs nearly has high or as variable as Hawai`i. If Hawai`i had variable prices, the State would be the logical place to come to test new storage and load shifting technologies.

3. Renewable Energy as Insurance Against Oil Price Fluctuations

An influential paper by James Hamilton, written several decades ago, showed that oil price spikes often precede recessions.[8] Over time, our understanding of links between oil prices and the macroeconomy has evolved. More recent research suggests that effects of oil price shocks depend critically on the factors that drive them. Prices rising due to unrest or a war in the Middle East clearly has different implications that a spike resulting from unexpectedly fast growth in Asia (Killian, 2009). Nevertheless, there is clear evidence that variations in oil prices can be an important contributing factor in business cycles.

Moreover, it is also clear that Hawai`i's economy is relatively idiosyncratic, and much more reliant on imported oil than most economies. For one, we use

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[8] See Hamilton, J.D. "Oil and the Macroeconomy Since World War II." *Journal of Political Economy*, 91 (2): 228-48, 1983.

more oil in electricity generation than we burn driving our vehicles. We also depend implicitly on oil prices through the cost of jet fuel and tourist travel. All else the same, higher oil prices likely means fewer visitors and less tourism, a cornerstone to our economy. Our state's business cycle is surely more closely tied to the price oil than other states and countries.

There can be some difficulty and considerable debate in quantifying the value of reduced macroeconomic fluctuations. And there is relatively little existing research that considers how different states and regions may be more or less susceptible to these fluctuations. Still, the more recent literature (and recent acute experience) presents ample evidence that these fluctuations matter a lot.[9] By divesting or at least greatly diminishing our reliance on imported oil, renewable energy would likely reduce macroeconomic variability in Hawai`i, and this would have value. We would still be vulnerable to jet fuel prices and other factors affecting business cycles. So while it's not clear how large this benefit would be, it is surely real, and likely greater here than in most other states and nations.

Policy Implications

Energy economics and policy is a new gambit for us and we have a lot to learn. We therefore limit ourselves to a few policy implications that seem clear from basic economics and the data we have observed.

1. Regulation of the public utilities could benefit from more data availability.

In most parts of the country, detailed data is available from nearly all power plants. Hawai`i is an exception, in part because regulations under the Clean Air Act compel disclosure by most power plants do not apply to Hawai`i. However, the absence of federal regulations to compel disclosure does not prevent the local Public Utilities Commission from compelling disclosure of more detailed information.

What kind of data would be useful? A complete list would take time and perhaps some investigation. To start it would be useful to have information on the specific contract prices Hawaiian Electric pays for oil. We understand that oil used in power generation is mostly byproduct from the O'ahu's two gasoline and jet fuel refineries. It should be presumed that the price HECO pays is somewhat less than the price paid by Chevron and Tesoro refineries. It is in the public interest for these contract prices to be made transparent. Knowing something about the nature of the contracts would also shed more accurate light on actual costs, on the relative cost of oil versus alterative forms of generation, like natural

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[9] See the review by G. Barlevy, "The Costs of Business Cycles and the Benefits of Stabilization: A Survey." NBER Working Paper No. 10926 , November 2004. http://www.nber.org/papers/w10926.

gas and renewables. The specific contracts would also help to clarify the time lag between world crude prices and the energy cost adjustment factor. The available data do indicate that HECO's reported oil costs differ somewhat from those of Kalaeloa, a private LSFO generation plant. In the least, such information would be useful for forecasting future electricity prices and thereby aid planning by businesses and municipalities.

Second, it would also be useful to have detailed information on plant specific operations. On the mainland, minute-by-minute data on every power plant is available, making pollution and plant-level emissions completely transparent. Some of the evidence presented suggests HECO, the electric utility on Oahu, keeps a large number of its oil-burning power plants online even during low-demand periods, and thus does not fully utilize the lowest cost AES coal power plant. Since HECO is allowed to adjust prices to account for costs, it has little incentive to control costs on its own. While some cost information on each power plant has been made available in reports, it would help to have hourly reporting on utilization by each power plant. This would make hourly costs more transparent, and would expose any inefficiencies in system management. Since even more detailed data is available for most power plants in the country, surely it would be little imposition to compel the utility to make such information public.

Third, it would be useful for Hawaiian Electric to make its estimates of gross load, derived from sensors they have placed throughout the islands, publically available. Gross load includes electricity generated from distributed sources, especially residential photovoltaic, which depend on variable solar radiation. While crude estimates can be estimated from publicly available data, surely the electric utility's estimates would be more accurate.

Fourth, the Public Utility could compel disclosure of circuit and substation level net and gross loads, to make potential issues related to backfeed fully transparent to both the regulator and the public. For many years the utility has resisted expansion of residential solar, claiming that system was not designed to accept electricity flowing from neighborhoods back through substations and the rest of the grid. Installations were limited based on solar penetration relative to minimum daily loads. But since daytime loads tend to be much higher than minimum loads the degree of potential backfeed would be made more transparent if hourly data for each circuit were made publicly available. These data would show where actual backfeed has been greatest, and whether particular circuits with restricted installations were actually at risk.

2. Net metering agreements would benefit from variable pricing and a sell back option.

Residential rooftop solar remains an attractive opportunity for households and businesses, in part due to generous tax benefits. But even without these benefits, rooftop solar currently looks more cost effective than utility-scale alternatives, and most any other source of electricity except for coal.

The problem is that current net metering agreements may sharply limit the potential for using cost-effective rooftop solar for generation. At the same time, the current agreements may be discouraging conservation and energy efficiency. The essential problem is that households cannot sell excess generation back to the utility; they may only rollover excess generation from one month to another. At the end of the year, accumulated net excess generation is forfeited to the utility.

This net metering contract creates two perverse incentives. First, because photovoltaic solar, especially with subsidies, is well below conventional costs, households have an incentive to install more capacity than they will typically use, simply due to cost asymmetry. You lose more installing too little than in installing too much. And since households are more likely to install too much than too little, by the end of the year they may find themselves with a use-or-lose accumulated surplus of generation. And this surplus, in turn, gives households little incentive to upgrade to compact florescent or LED light bulbs, install more efficient Energy Star appliances, turn off the lights when they are not being used, or limit use of air conditioning. Free energy at the margin is anathema to energy efficiency.

And there's evidence that this sort of waste already occurs. Refer again to Figure 7. This time note how energy use declined uniformly between around 2006 through 2010, presumably due to rising prices and publicly-financed efforts to improve efficiency. Efforts by the military likely played a major role. Starting in 2011, solar installations accelerated, and the drop in net generation midday relative to the evening is clearly evident. Notice, however, that has solar penetration grew more substantial in 2012 and especially 2013, evening loads grew to new heights, reversing earlier declines from energy efficiency gains. It appears as though households installing solar are increasing their use of energy. It's not evident midday because gross load (which includes distributed solar generation) is not visible in net generation.

The second perversity is that rooftop solar may be one of the more cost effective means of generating electricity, and current net metering agreements artificially limit use of valuable rooftop space. If land costs are as large a constraint as reported, we ought to maximize use of comparatively cheap rooftop space.

There is a simple solution to both problems: simply allow households to sell surplus generation to the grid. Households would then retain an incentive to conserve energy, as greater conservation would lead to larger checks received from the utility each month.

The utility has been arguing for some time that net-metering agreements should have larger monthly fixed connection fees to pay for grid management and integration. This kind of connection fee to cover grid costs makes some sense. But it's not clear how this argument differs for households with and without rooftop solar—all could pay a connection fee to cover fixed costs and a lower price to cover generation costs. The real inefficiency comes from

household's inability to both buy and sell electricity to the grid at the incremental generation cost.

A closely related consideration is the fact that the sun only shines at certain times, and the marginal cost of generation varies greatly. Efficiency would dictate that households with solar would be compensated and charged according to the times when they provide energy to the grid and when they draw from it. But this issue, like the fixed payment for grid management, is not truly different for households with and without solar, which leads to the third policy suggestion.

3. Experiment with variable pricing.

The elementary criteria for economic efficiency is that price must equal marginal cost. Accordingly, economists have long argued in favor of variable electricity pricing. With variable pricing, consumers would be enticed to use more energy when it is less costly and to use less energy when it is more costly. When the marginal cost of electricity varies a lot, as it does in Hawai`i, the efficiency gains from variable pricing could be tremendous. Variability in marginal costs, and the benefits of variable pricing, are likely to become even more extreme as wind and solar generation grow. Maui is a poster child for variable pricing. Much of the wind generation on Maui is already curtailed. Surely many on Maui could be enticed to use free, presently curtailed electricity if it were instead priced at its true marginal cost.

There are practical challenges with implementing variable, marginal cost pricing. For one, we need smart meters that actually track each customer's electricity consumption from one hour to the next. Consumers also may be hard pressed to pay attention to each hour's system lambda. Finally, customers may be skeptical, and may be uncomfortable with variable pricing.

We believe these are surmountable obstacles. Recent experimental evidence in California (Jessoe and Rapson, 2014) shows considerable willingness by consumers to accept variable pricing and large responsiveness in electricity use during times of high prices. But this documented responsiveness surely scratches the surface of what's possible. In time, technologies could be developed such that water heaters, building cooling and heating systems, or water pumping, could anticipate and respond to prices automatically. If variable pricing can work in California, it can surely work in Hawai`i, because there are few, if any, places that have more to gain from it. Moreover, a few large users— the industrial class as reported by the Energy Information Administration— comprise a remarkably large share of electricity use. The cost of smart meters for large users is relatively trivial, and these users may have more capacity to shift loads to times with lower costs, easing grid management and reducing costs for everyone.

Another low-cost way to experiment with variable pricing would be through net metering agreements for households installing rooftop solar. As described

above, variable pricing—both buying and selling—would address current problems with net metering. And installing a smart meter at the time of solar installation would be nearly costless. These consumers may be more willing to try variable pricing scheme too, since they are likely to gain so much anyway for having comparatively inexpensive and subsidized solar. Variable pricing might even be proposed as an option for households installing solar, with lower and variable prices being offset by the ability to sell unlimited surplus generation back to the utility.

Perhaps the greatest challenge and opportunity for variable pricing involves development of complementary products, like smart thermostats, smart water heaters, smart household appliances, and smart building systems software that automatically monitor use and forecast prices and make adjustments in heating, cooling, lighting and water pumping, etc. This isn't science fiction. Engineers have been thinking about these ideas for a long time and many of them would be relatively easy to implement. But there's an inherent chicken or egg problem: which comes first, variable pricing or the technologies to cope with it? Until large-scale variable pricing exists, there is no incentive to develop the smart products. And until the machines exist that make living in a variable-pricing world a lot easier, there may be resistance to variable pricing itself.

Hawai`i may be just the place to break the starting point conundrum and kick off the innovation spiral. If we can't do it here, where the benefits to variable pricing are greatest, it's unlikely to happen anywhere. And in solving this conundrum, Hawai`i could open a much larger opportunity for economic development, because it would encourage all of the engineers and technologists with bright ideas about storing energy or shifting loads to come to Hawai`i to test their ideas. It's by no means clear that Hawai`i would become a substantial technology innovation hub. But the prospect seems plausible. Besides, the prospect is icing on the economic cake, for the savings from variable pricing would likely be substantial even if an innovation hub never takes hold.

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Appendix 1: Computing simulated average variable cost

Steps:

1. Get the average brent oil price lag structure for AES, Kalaeloa, HECO LSFO and Diesel by estimating:

Log(AES ECAF Price) ~ brent (different lags) + ns(AES kWh , df=3)

Log(Kalaeloa ECAF Price) ~ brent (different lags) + ns(Kalaeloa kWh, df=3)

Log(LSFO ECAF Price) ~ brent (different lags) + ns(LSFO kWh, df=3)

Log(Diesel ECAF Price) ~ brent (different lags) + ns(Diesel kWh, df=3)

And obtaining the estimate with the highest adjusted R-squared.

The average brent lag structure with the highest Adj. Rsq. are :

- AES = (-1646, -141). Adj. Rsq. = 0.87
- Kalaeloa = (-49, -1). Adj. Rsq. = 0.95
- LSFO = (-134, -9). Adj. Rsq. = 0.96
- Diesel = (-383, -32). Adj. Rsq. = 0.93

2. Get the historical maximum GWh generated for each of the components:

    - AES: 146 GWh
    - Kalaeloa: 147 GWh
    - HECO LSFO: 454 GWh
    - Diesel: 14.12 GWh

3. To get the simulated AVC, compute the following:

    - If total GWh generated in a month is less than 748 GWh, compute

$$AVC = \frac{\left(\left(AESAVC_{pred}^{max} * 146 \right) + \left(KalaAVC_{pred}^{max} * 147 \right) + \left(LSFOAVC_{pred}^{max} * (GWh_{total} - 293) \right) \right)}{GWh_{total}}$$

    - If total GWh generated in a month is 748 GWh or more, compute

$$AVC = \frac{\left(\left(AESAVC_{pred}^{max} * 146 \right) + \left(KalaAVC_{pred}^{max} * 147 \right) + \left(LSFOAVC_{pred}^{max} * 454 \right) + \left(DiesAVC_{pred}^{max} * (GWh_{total} - 747) \right) \right)}{GWh_{total}}$$

where

AVC_{pred}^{max} is the predicted value of AVC for the components at the historical maximum