Meeting All Electricity Needs via PVs on Available Roof Area

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Abstract: Can Hawaii County Become Energy Self-Sufficient?
As Hawaii strives for renewable and sustainable electricity generation, this analysis found that potentially over 150% of our consumption may be generated via solar-PV on residential and commercial roof tops.

Executive Summary: We can read in the news about the many new large solar-PV (PhotoVoltaic) and wind farms, but comments are scarce about whether we can continue to grow and support these types of renewable and sustainable energy sources to achieve self-sufficiency, without hurting prudent land-use planning and stewardship. There is no question that with just 0.057% of Hawaii County land area dedicated to solar PV panels, all its electricity and transportation energy needs could be met. More densely populated areas such as the US mainland and Europe would need percentages of over 1 and 2, respectively. That led to the question about what fraction of presently used electricity the County could generate by using the generally idle but available space on residential and commercial roofs?

We found an answer to this question by a 3-step exercise: 1) Estimating the available roof area, which was logically taken as the first floor area, 2) Determining a conservative PV kWh/year yield per sq.ft. of solar panel and 3) Comparing the obtained total kWh annual energy generation potential with actual consumption data.

Specifically: 1. The County can potentially generate 156% of all its electricity needs via solar PV (photovoltaic) panels, i.e. 1.56 x 1120 GWh/year = 1748 GWh/year, if we use the available and suitable roof space of all residential, commercial and industrial buildings (94 million ft^2, of which 70.6 million ft^2 are residential), without requiring new land for such panels. This is **628 GWh** more than needed in 2005 and not much less today. I will detail below the data used, and assumptions made, as well as comment on how to meet the needs of all stakeholders – residents, businesses and electricity providers. (A list of used Abbreviations is provided below).

2. All these PVs would cost $10.0 or **$6.4 billion** to produce 1748 or 1120 GWh/year, respectively, at today's small PV system prices of 7.5$/W)peak), which includes all fees and taxes. Each average home roof of 1076 ft^2[1] would be fitted with a 14.3 kW(peak) PV system, at a present cost of $107 k before rebates*. But with the expected decrease in solar-PV costs, the rise in fossil fuel cost, and the small share of the residential portion of the 1120 GWh/year of only 38%[2], some creative and profitable financing could surely be worked out.

Presently, the above PV cost is close to that of 20 to 25 years of HELCO's fossil fuel and labor to generate the same amount of electricity, as evidenced by comparing the value of each kWh of electricity from roof-PVs over their warranty period of 8760 hours/year x 25 years, with the average value of electricity obtained from HELCO, as per its 2007 revenue of $350 million from the sale of 1260 million kWh[12]. The cost of capital and PV maintenance were assumed to be small and ignored for this comparison:

$$\text{Cost of roof-PV kWh} = 7.5\ \$/W(p) / (0.15\ W(avg)/W(p)) \times 1/8760/25/(\text{life hrs}) = 0.228\ \$/kWh \quad (1)$$

$$\text{Cost of fuel-generated kWh} = (350\ M\$/y) / (1260\ GWh/y) = 0.278\ \$/kWh \quad (2)$$

So, the people of Hawaii County should ask whether their quality of life is further enhanced with importing fuel or solar-PV panels to generate electricity. The answer has to do with the difference in local jobs, tax revenue and net import values. Also the added cost of energy storage and stand-by generation (see item 4 below) needs to be studied as part of the roof-PV scenario. Suffice it to say at this point that less than half of the above installed roof-PV cost is for imported materials once every 25 years, vs. importing probably over 70% of the kWh value every year. This quantifies the imported content of (kWh) energy for PV vs. fuel-based as less than 2% vs. more than 70%, respectively. Let us also compare the labor content: Over 0.228 x 0.50 = 0.114 $/kWh for PVs vs. less than 0.278 x 0.3 = 0.083

$/kWh (this incl. labor for generators), or 37% more local labor content in roof-PV energy at this time. This may seem surprising but welcome news to the people of Hawaii, and is consistent with the distributed nature of the roof-PV source of energy.
Therefore, it may indeed be worth a look at the total scenario, including stand-by, storage, incentives and capital costs in a follow-on study, involving all stake holders: the public, businesses, Hawaii County and HELCO. To illustrate that point one may now ask the rhetorical question a renewable-energy professor asked his students at the start of his lecture: **"Who would be using cell phones today if each user had to invest 20-25 years worth of phone use at the start of service, to compensate cell phone companies for their investment?"**
* The cost to commercial buildings would be higher, in proportion to the roof area of each establishment.

3. Because only ~70% of Hawaii County electricity is generated with fossil fuels, only that amount needs to be replaced by renewables to achieve self-sufficiency. The renewable energy we chose for purposes of this study is solar-PV. That means that the 30% or **336 GWh/y** of existing renewables (mostly from geo and wind energy) do not need to be replaced. Rather, that amount of new roof-PV energy can be redirected and added to the above excess of 628 GWh/y. This adds up to a total of **964 GWh**, to more than fully energize the whole fleet of some 160,000 light-duty vehicles registered in Hawaii County in 2005[2], after their potential but total conversion to electric vehicles or PHEVs. They would consume **679 GWh/y**, as derived and detailed in the Discussion. Even more idle real estate is available for solar-PV sources in spaces such as over parking lots[9], aqueducts in Arizona[9], and highways.

4. Energy storage and stand-by generators are needed when PVs generate a high fraction of grid electricity, in order to achieve the level of supply reliability, which electric utilities have consistently provided. HELCO has been studying pumped storage hydro (PSH)[2]. ESA has updated their comparative storage cost data[13]. PSH ranks as the one of lowest cost – 0.1 to 1 cent per delivered kWh per cycle; battery costs range from 3 to 100 cents/kWh per cycle[13]. However, even a retail, sealed, golf-cart lead-acid battery of 50 $/kWh, with 75% efficiency and a life of 1500 cycles (for depth of discharges of 80%) translates to a cycle cost on only 50/0.75/1500/0.8 = 5.4 cents/kWh, so that even distributed storage options may be worth considering.
Careful consideration should be given to the amount of storage (kWh) for each kW of installed PV generation ability, since it is dependent on weather statistics, the available amount of weather-independent stand-by generating power (kW), the number of similar PV systems on the same electrical ("smart") network and the desired electricity delivery reliability. The good news is that the larger the storage system, the fewer deep discharge cycles would occur in a given time, so that its service life, e.g. in the case of a battery, would increase and the cost per withdrawn kWh would tend to compensate for its initial investment.
By way of example, a PV system would be able to deliver a steady output (day and night) of 15% of its peak power, if:

- Each day provides an average amount of sun energy. and
- Each installed PV kW(peak) is tied to a battery size of 1 kW x 24 h x 0.15 x 0.83 = 3 kWh, whereby the 0.83 is an empirically determined factor.

Because cloud cover and energy demand vs. time of day are different each day, the above example only represents a first iteration at quantifying the needed amount of storage. Any excess storage capacity adds life to the battery and provides a more reliable delivery despite variations in the daily generation and demand profiles.

Important advantages of using roof-PVs for power generation and EV transportation, besides using available roof space, achieving energy security and sustainability, and eliminating gaseous emissions, are the ultimate cost savings to consumers[16]. Therefore, we also see business possibilities in the form of energy performance contracts and roof area rentals as attractive opportunities for Hawaii: With payback periods in the 5 to 9 year range[16,19] and PV warranties of 25 years (inverter MTBFs over 300 years), conservatively, the returns would be over 7%/year, spread over 25 years (Profit/cost = ((25-9)/9)/25 = 0.071), assuming a 4% cost of capital.

Discussion: As mentioned above, three main steps led to the above conclusions: 1) Estimating the available roof area, which was conservatively taken as the first floor area, 2) Determining a conservative PV kWh/year yield per sq.ft. of solar panel and 3) Comparing the obtained total kWh annual generation with actual consumption data. These three steps are laid out in the Data & Assumptions section. The results are as follows: The annual GWh we could potentially generate with roof-top PV is exciting: Distributed but available roof space in Hawaii County could generate a total of 18.6 kWh/(ft^2.y) x 94.0 Mft^2 = 1,748 GWh/year, i.e. 628 GWh or 56.1% more than the 1,120 GWh used in 2005[2].

This encouraging result is dampened only by:

1) The uncertainty of the available average roof space of 1076 ft^2 per housing unit[2], which was estimated by using as average floor space of 1200 ft^2 by ref.[6] and still others as 1700 ft^2[4]. But a floor- to roof-space ratio of 0.7[4], brings the average roof space back to 1190 ft^2. The most recent value is from S. Sitko, with 2009 records of 71,329 residences (combination of individual condo units and single family dwellings) with an average of 1277 ft^2 on the first floor[3], or a credibly 29% higher than the 2005 base values[2] used in this study. Actual roof space may be even 15% larger in Hawaii because lanais often are counted separately from the living space, and because an average roof slope of 20 degrees would add another 6.4%, relative to the floor area, without counting the ~15% roof overhang, amounting to a total roof space larger by some 40% than any of the above roof areas. However, no data were found for shading or orientation effects, so that we retained the conservative value of 1076 ft^2 for this exercise
2) The sizable investment for (but not necessarily by) the average household, with its roof area of 1076 ft^2, needed to install the over 65,000 PV systems. Each would have a peak generating capacity of 15.2 kW_{peak} and presently cost of 7.5 $\$/W_{peak}$ x 15.2 kW = $114k, and after subtracting presently available rebates: $34.2k Federal and $5k State, for an adjusted total of $74.8k for the avg. residence.
3) The disappointingly small roof space of all condos and commercial and industrial buildings, which was kindly generated by Stan Sitko[3] and based on the Hawaii County taxation database, and
4) The need to invest in distributed and bulk (i.e. utility-size) energy storage, as discussed in ref.[7] in the form of pumped hydro, batteries (bulk for utilities and distributed for homes, as well as PHEVs), and hydrogen

Whether the total 964 GWh excess would be enough to power all of Big Island's light-duty vehicles after their potential conversion from gasoline or diesel to PHEVs is a question worth looking into, since an affirmative answer would eliminate over 90 million gal (46% of total or over $220 million) of annual fuel imports[2]. To find the answer, we need to determine the average mileage of the future mix (passenger, SUV and truck) of electric vehicles (EVs). Based on:

1. Recently released data of the "Cash for clunkers program,"[10], listing gas mileage increases from 15.8 to 24.9 miles/gal, averaged over cars, SUVs and trucks, we shall use 20 miles/gal as the present US and Hawaii average and an overall energy efficiency of 17%[14].
2. The ability of existing, low-rolling resistance, hybrid cars to achieve 40-50 miles/gas[11], w/o electricity input, but with regenerative braking, we shall use 40 miles/gal as an average achievable hybrid mileage and an overall energy efficiency of 34%[14].
3. Overall energy efficiency of electric vehicles (EVs) of 80 %, incl. battery charge and discharge losses
4. Obtaining the average mileage of EVs, M, by multiplying the gas mileage (20 or 40) by the efficiency ratio (80/17 or 80/34) and by the energy conversion from gasoline-Btus to kWh:
   M = 20 miles/(gal gasoline) x (80/17) / (115,000x1053 joules/gal) x (3600000 joules/kWh) =
   = 2.8 miles/kWh,
   which is consistent with data for the BMW Mini-E (4.3 mi/kWh), BYD e6 (5.2) and Tesla (4.7) on the high end, and the Chrysler Jeep EV (1.48) and the much acclaimed but limited edition of the Toyota SUV RAV-4EV (2.17) on the low end.

The electrical energy to “fuel” all of Hawaii County future EVs (after conversion from gasoline and diesel) would then be 95,000,000 gal x (17/80) x (115,000x1053 joules/gal) / (3.6×10^{12} joules/GWh) = 679 GWh.

This means we still have 964 – 697 = 267GWh left over to address other needs such as synthesis of aviation fuel, which may be the object of a future study. The main point of the present write-up is that we have enough potential roof PV power and energy to eliminate all liquid fuel for generation and transportation except for the 14% aviation fuel imports to the Big Island. If we were to sell the 267 GWh excess electricity at 0.30 $/kWh, we could buy the needed 27.6 million gal aviation fuel at 3 $/gal, but not synthesize it, because its energy equivalent is a staggering 929 GWh.

Significantly, if roof PVs were widely implemented, future growth in population, housing and demand for transportation fuel may be covered by a proportional growth in roof-PV electricity generation.

Data and Assumptions:

1. Roof area:

1st-Floor Homes	71,500,000 ft^2 or	6.64 km^2 [1]
1st-Floor Commercial	20,437,477 ft^2	1.90 km^2 [3]
1st-Floor Condos	2,017,439 ft^2	0.19 km^2 [3]
1st-Floor Excluded Structures	982,677 ft^2	0.09 km^2 [3]
Total	94,028,573 ft^2	8.74 km^2

2. Solar energy conversion rate in kW_{peak}/ft^2 and $kWh/(year.ft^2)$

Solar input (insolation) to upper atmosphere: 1.959 $cal/min/cm^2$ = 1366 W_{peak}/m^2

SAA at equator at sea-level, normal incidence, no clouds, after atm. attenuation 1000 W_{peak}/m^2

SAA but averaged to allow for day/night and sun inclination (25% of max insolation) 250 W_{avg}/m^2

SAA after also allowing for clouds, remain 3.6 h/d, 15% or 1314 h/y or 150 W_{avg}/m^2

SAA after 16 % efficient PV conversion (HI-avg.) to DC electricity 2.23 W_{avg}/ft^2 or 24 W_{avg}/m^2

SAA after micro-inverters of ~95% efficiency[5] convert DC to AC electricity 2.12 W_{avg}/ft^2

Bottom line: Expect annual energy yield of 2.12 W_{avg}/ft^2 x 8760 h/y = 18.6 $kWh/(year.ft^2)$

Sanity check: My 2.1 kW_{peak} PV system uses 12 panels of 60”x30” = 150 ft^2, with the individual micro-inverters to produce 2.1/(12x60x30/144)x1314 = 18.4 $kWh/(year.ft^2)$

3. We can now calculate the total potential solar-PV electricity generation: 18.6 kWh/(year.ft2) x 94.0 Mft^2 = 1,748 GWh/year, i.e. 628 GWh or 56.1% more than the 1,120 GWh used in 2005[2]. Note that the used 94.0 Mft^2 represent the conservative ~40% lower roof space than the actual one, and thus makes up for limitations due to orientation and shading.

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Abbreviations

ft^2	square feet = 0.0929 m^2
GW	gigawatt = 1,000,000,000 watts
GWh	gigawatt hours = 1,000,000,000 watt hours
h	hour
km^2	square kilometer = $1/1.609^2$ square miles
kW	kilowatts or 1,000 watts
kWh	kilowatt hour = 1,000 watt hours = 3,600,000 joules = 3419 Btu (British thermal units) = 860,421 calories
m^2	square meter = 1/0.0929 ft^2
MW	megawatts = 1,000,000 watts
MTBF	Mean Time Between Failures
PHS	Pumped Hydro Storage
SAA	same as above
W_{peak}	peak watts, i.e. power level generated only under peak solar incidence, when the incident sun rays form a θ = 90° angle with the solar panel surface. Power generation decreases even faster than sin(θ) because of additionally increased atmospheric attenuation, as we know from experience of observing the sun near sunset
W_{avg}	average watts are only 15 to 20% of peak watts, after allowing for the suns daily input variability

References

[1] US Census cited in ref[2], p.59: There are 6.5 km^2 of roof area on the Big Island. And in the footnote: "There are 65,605 housing units on the island (US Census) and for the purpose of this estimate it is assumed that each unit has 100 m^2 (1076 ft^2) of roof area.

[2] J. Johnson, D. Leistra, J. Opton-Himmel, & M. Smith, "Hawaii County Baseline Energy Analysis" sponsored by The Kohala Center, 10 May (2006), http://www.co.hawaii.hi.us/rd/hawaii_county_baseline_energ.pdf

[3] Stanley A. Sitko, Real Property Tax Department, County of Hawaii, Private Comm., Sep.(2009)

[4] Appendix I – GPRA06 Solar Energy Technologies Program Documentation http://www1.eere.energy.gov/ba/pba/pdfs/gpra_fy06_appendix_i.pdf

[5] Enphase Microinverter M190. Technical Data … weighted efficiency: 95.0%

[6] Department of Business, Economic Development & Tourism "Data Collection and Analysis of the Heat Mitigating, Passive Design Strategies at the Waianae Model Demonstration House" Submitted by Honolulu Chapter American Institute of Architects Committee on the Environment, September 2002, as per ref.[7]

[7] Michael Davies et al (Yale School of Forestry and Environmental Studies), "Analysis and Recommendations for the Hawaii County Energy Sustainability Plan," sponsored by Hawaii County and The Kohala Center, 3 October 2007

[8] County of Hawaii at http://www.co.hawaii.hi.us/general_plan_rev/revision/Land Use - Introduction.doc . The total area of the island of Hawaii is ~ 2.5 million acres; or 4,023 square miles of land and 4.4 square miles of inland water.

[9] Power for the Planet, Inc. website at http://www.p4penergy.com/projects.html

[10] "Clunker pickups traded for new pickups," West Hawaii Today, 5 Nov.'09, p. A1. The average vehicle exchange increased the gas mileage from 15.8 to 24.9 miles/gal

[11] Data from http://www.edmunds.com/reviews/list/top10/145167/article.html: list of top10 2009-2010 best mileage cars (EPA city / hwy): Prius hybrid – 50/49; Honda Civic hybrid – 40/45; ... ; Ford Fusion hybrid 41/36

[12] Hawaiian Electr.Industries at http://www.wikinvest.com/stock/Hawaiian_Electric_Industries_(HE) HELCO had electricity sales of 1259 GWh (270 MW and 53.2% avg. Load) in 2007 of ~ $350 million averaging 0.278 $/kWh and net income of (not given). Total generating capacity of 270 MW.

[13] Energy Storage Association(ESA) website http://www.electricitystorage.org/site/technologies/

[14] The values of 17 and 34% IC vehicle energy efficiency are drawn by the author from many studies. A recent paper in Scientific American[15] cites 17 and 20% for average vehicles[15].
[15] M.Z.Jacobson and M.A.Deluchi (Stanford U. and UC Davis), "A Path to Sustainable Energy by 2030," Sc. American, 301 #5, 58 (2009, Nov.)
[16] U.Bonne, "Contributions to Sustainable Energy Independence," presentation to Rotary Club – Kona, HI, 31 March & 9 June 2009; and U.Bonne, "Helpful Hints for Homeowners with New Photovoltaic Systems," http://energyfuturehawaii.org/learn-more.html 10/6 /2009
[17] Ken Silverstein (EnergyBiz Insider), "Coal's Evolution," October 26, 2009 http://www.energycentral.com/articles/energybizinsider/ebi_detail.cfm?id=764
[18] Letters received by EnergyBiz Insider regarding ref.[17], posted at http://www.michigangreen.org/article-print-666.html
[19] U.Bonne, "Study of a Newly Installed Home Solar PV System: Actual and Calculated Outputs, " 7 Dec. 2009, rev. 20 Jan. 2010 http://www.energyfuturehawaii.org/learn-more/7-renewable-energy-a-energy-efficiency/119-study-of-a-newly-installed-home-solar-pv-system-actual-and-calculated-outputs.html or http://minnefuels.pbworks.com/Home-Solar-PV-Performance-Data