Generation of electricity and synthetic fuel from renewable energy

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The Problem -- Regarding the planned expansion of Puna Geothermal power by 8 MW, one wonders how this may fit into an overall Hawaii County power and energy strategy, given that both geothermal and wind energy deliveries to the grid are less than what they can produce, which results in significant curtailments of their output. Why not curtail fossil-fuel generators first, before curtailing wind & geo sources, especially when we see crude oil and gasoline prices rise much faster than the CPI? Or similarly, why not also generate synthetic fuel from renewable energy, CO2 and water for greater energy security, price stability and independence?

Discussion -- The short answer is that the total installed generation capability, on the Big Island, as well as in the US and in other countries, is typically used to an average of 40-50% of the total or nominally possible level (US is ~ 43% as is HELCO; Japan and Germany are closer to 50%). This has to do with being able to schedule maintenance, overcome unplanned outages, and have enough reserve to meet peak demand loads, while maintaining the expected and contracted level of stability of grid voltage and frequency.

Curtailment of some generators is thus part of normal business, and does not mean that we do not need wind, geothermal, solar or stand-by fossil generators. Indeed, if we add the desire to minimize cost and maximize profit, finding the ideal solution poses quite a challenge. Without in any way implying to be an expert, I think that most of us agree that we need:

- Non-oil-based supply of electricity, which can match the minute-by-minute-, hourly-, daily- and seasonally-variable demand over time
- Non-oil-based supply of road- marine- and jet-transportation fuels, which can match the variable demand and production-rate over the seasons
- Draw such supplies from a variety of distributed (not all "eggs in one central basket" or location) and technology sources such as geo, wind, sun (PV, SCP, Water Heaters), ocean (waves and thermal gradient (OTEC)) and bio-mass
- Have enough energy-generation reserves consistent with prudent resource management to cope with outages and peak loads.
- Have enough stored electricity and/or fuel (for generators), to cope with above-mentioned variability of demand and supply
- An optimal mix of the above to achieve the desired reliability at a minimum energy cost to customers, while meeting the allowed profit margin to HELCO and its shareholders.

Table 1. Comparison of clean energy sources to output ~100 MW(avg) or 27.2 MGGE/y

	2 Source --	Capex/ Output $/W(peak)	4 Cap.Fact %	5 O&M % capex/y	PeakOut or InputGen kW	7 Capex M$	8 O&M+F M$/mo	9 Price** $/kWh	10 Price** $/GGE	Capex/ Ouput $/(GGE/y)
1	Fossil Gen.	2	45	(2) 42.8***	222222	444.44	15.852	**0.2670**	8.599	16.3
2	**Geo**	6	90	5.0	111111	666.67	2.778	**0.1128**	3.633	24.5
3	**Wind**	1.38	50	1.3	200000	276.00	0.299	**0.0350**	1.127	10.1
4	**PV**	3	17	0.2	588235	1764.71	0.221	**0.2010**	6.473	64.9
5	**Wave**	4	50	3.0	200000	800.00	2.000	**0.1170**	3.768	29.4
6	**OTEC**	30	90	3.0	111111	3333.33	8.333	**0.4880**	15.716	122.5
7	**Batteries**	1.0	62.5	8.5	160000	100.00	0.708	**0.0261**	0.841	3.7
8	**CO2-Synth.Fuel S***	9.3	20	1.64	500000	926.00	1.268	0.1210	**3.897**	34.0
9	**CO2-Syn.F.Plant**	2.36	40	31.7	250000	236.00	6.240	0.1115	**3.591**	8.7
10	**Algae-Bio.F.Plant**	4.59	33.3	(3) 5.3	300000 B	459.04	2.028	0.0792	**2.551**	16.9
11	**Wood-Bio.F.Plt.-A**	4.59	31.5	(3) 9.1	317460 B	459.04	3.476	0.1048	**3.375**	16.9
12	**Wood-Bio.F.Plt.-K**	3.16	39.0	(3) 10.1	256410 B	315.59	2.669	0.0720	**2.319**	11.6

* Complete plant system, including wind-farm. Weighted avg. O&M between WTs & plant. B = biomass feed in kW

** Before taxes and distribution costs; 10 %/y 25-year levelized ROI, after including 30% gov't. for capex. Equity-financed. No excalation of electricity or fuel above CPI.

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*** 2% w/o fuel or biomass. Fuel cost assumed ~2.00 $/gal for HELCO

Fuel Syn \ TL-11-Car-Options & Plant Benchm

Let us expand a bit on the "minimum energy cost" aspect, and the electricity cost estimates presented in Table 1. There are only two cost components for the envisioned non-fossil-oil-based generators, because the source energy is free (if we count biomass farming and harvesting as part of O&M, i.e. Operation and Maintenance costs) and if we ignore taxes and distribution costs for now:

1. Amortization of capital expense (capex) and
2. O&M costs, including labor & parts for maintenance, and insurance (opex)

The level of 100 MW, or its energy equivalent of 27.2 million gallons of gasoline equivalent (MGGE) per year, were selected to represent a significant contribution to Hawaii's economy[4], with energy costs and economies of scale consistent with such levels[1]

As shown in the $/kWh column, wind may represent the lowest cost of available electricity, even if battery costs are included, as long as appropriate land with wind is available. If not, other choices and their estimated kWh costs are also shown and may be compared to estimated inputs of generator costs ($/W(peak) and $/W(average)), and O&M costs in terms of % of capital costs expended annually. They were obtained with the freely available Calculator on the website of Friends of NELHA, http://www.energyfuturehawaii.org/solarCalc.php with Calculator instructions at www.EnergyFutureHawaii.org to be accessed by pressing the "Return to NELHA" button at bottom left. The columns 6-8 are needed as inputs to the calculator.

The first and last six data rows beg for an explanation for why they belong in Table 1. They were included because they may serve as reference points, especially the first row "Fossil Fuel," representing what we have today with oil-fired generators. The row for "Batteries" was included, because batteries may be needed to match loads with any of the weather-dependent sources of energy; their $/W entries were chosen to fall between high-quality lead-acid and Li-batteries; we assumed a "round-trip" charge-discharge" efficiency of only 80%. The high 8.5%/y O&M represents the cost to allow replacement after 13 years; the resulting 0.0261 $/kWh would be added to the kWh-cost of the associated generator.

Finally, "Synthetic Fuels" (Rows 8 and 9 in Table 1) were included to represent the synthesis of clean fuels such as H2, NH3 (ammonia), methanol, ethanol, DME (a diesel substitute) and gasoline/diesel/jet fuels, which could be made from electricity, water and CO2 from air or other sources (stack gases, waste-gas from Fischer-Tropsch-processed biomass, etc). CO2 would of course not be needed to make H2 or NH3. The capex for Row 8 includes the cost of the (wind-farm, PV or geo) electricity generation. The output price (after securing a 25-year levelized ROI of 10 %/y, but before taxes and distribution) of 0.121 $/kWh or 3.90 $/GGE (based on lower heating value (LHV) of 110,000 Btu/GGE) was a welcome result, and mainly reflects the estimated 40 % overall process efficiency x 50% wind-farm capacity factor (both contribute to the value in Column # 3). If fossil fuels continue to rise at ~ 3 %/y above CPI, by the time a synthetic fuels plant can be started up in ~ 7 years, their relative price would have risen another 23 %, and thus helping to make the synthetic fuels even more competitive. The economics for the same plant, but w/o the wind-farm was shown in Row 9. The obtained fuel product price is 8.5 % lower (and more trustworthy) than the one in Row 8, due to simplifying assumptions made when calculating economics for the complete system of Row 8. The reason the O&M costs are so much higher in Row 9 is due to the included electricity price, which the stand-alone plant would pay to the wind-farm.

In Rows 10-12 we included the result of analyzing several bio-fuel plants. Data available from news releases were augmented with reasonable estimates on plant costs and scaled to output 27.2 MGGE/y; overall plant conversion efficiencies were derived from published input biomass tonnage and GGE outputs, by assuming a LHV of biomass of 8500 Btu/lb*. As expected, bio-fuels from algae (Row 10) resulted in lower-cost fuel than from CO2 synthesis. Row 11 represents a wood-to-fuels plant, based on "cooking" biomass with microwave technology. Row 12 represents a more conventional plant, consisting of cellulosic biomass gasification-to-syngas-and-FT route to fuels, resulting in 0.072 $/kWh or 2.32 $/GGE – before taxes or distribution, which may add ~20-30 % to a retail price of 3.014 $/GGE

* and a biomass cost of 50 $/ton (charged to O&M), except for algae (20 $/ton) because its "waste" biomass can be resold, after extracting/pressing out the oil.

All of the above data were derived assuming no fuel market price or CPI escalation. However, if fuel prices were to escalate at a constant 3 %/y above the CPI over the 25-year life of the plant, the relative whole-sale fuel price before taxes at the time of plant start-up (Row 12) would drop to ~1.60 $/GGE, while still realizing a levelized ROI of 10 %/year. If the CPI and fuel cost were both to increase at the same rate of 3 %/y (causing an increase of O&M as well), the above price would be back up to 2.00 $/GGE

Complementing the electricity and fuel supply side is the demand side. Table 1 would compel us to install as many WTs as possible and use them to synthesize transportation fuels, if the appropriate land is available (floating WTs are being tested off the coast of Portugal and elsewhere). But before we embark into making too much of such synthetic or biofuels, Table 2 is an attempt at comparing the merit of alternate approaches to use clean energy, via a simple example of car mile-range achievable with a clean energy input of 100 MWh (3100 gal), using a few different approaches: CV (conventional IC engine vehicle), EV (electric vehicle) and FCV (fuel-cell vehicle). Table 2 data address the question of: Which path will provide the most road miles. That result should weigh heavily on us, when we must choose an energy strategy for Hawaii, if we follow guidelines for long-term energy sustainability, independence and security:

Table 2. Comparing alternate ways to spend 100 MWh of new energy for road transport miles

- Convert the 100 MWh to synthetic fuel (NH_3, methanol, gasoline) & get enough fuel to fill up CVs to drive = 30-60,000 MWh * 1 mile /kWh (equiv. to 32.2 MPG effic'y.) >> **30-60,000 miles**
- Make synthetic H_2 worth 70 MWh >> fill up FCVs = 70,000 kWh * 2 mile /kWh (equiv. to 64.4 MPG "efficiency") >> **140,000 miles**
- Charge today's EVs = 100,000 kWh * 4 miles/kWh (incl. 0.8 charge/discharge & motor efficiency) >> **400,000 miles**
- Charge super-light EVs = 100,000 kWh * 60 miles/kWh (as per Purdue's 2011 Shell EcoMarathon car) >> **6,000,000 miles**
- Electricity 100 MWh >> charge electr.storage (hydro/compressed air/battery) = 100 MWh * 60-80% efficiency) = **60-80 MWh** avail. for energy security. We can now feed those stored MWh to either of the above options

Clearly, Table 2 would incentivize us towards PHEVs and EVs, as fast as technology catches up to meet market demands for affordability and miles-range per battery charge, especially by taking weight out of the cars. However, there is a further criterion to consider: Reduction in user's vehicle life-cycle cost and reduction of imports, as Table 3 (see ref.[5] for access to an xls version) will try to illustrate.

Table 3. Life-cycle ownership cost comparison: Conv. vs. renew. fuel vehicles, 2020-2025*

2020 Fossil Gasoline = **5.9** $/gal | **2020** Synthetic Gasoline **3.80** $/gal

Fossil Electricity, Commercial Rate = **0.44** $/kWh | Renewable Electricity **0.20** $/kWh

Inputs | **Main Outputs**

	Conventional Fuel Vehicles				Renewable Fuel Vehicles					Imports
	Car Cost		Fuel Import	Total Cost	Car Cost		Fuel C.	Total Cost	Fuel Import	Reduction
	$/car	$/y/car	$/y/car	$/y/car	$/car	$/y/car	$/y/car	$/y/car	$/y/car	$/y/car
Fossil IC Vehicle	25,000	1,250	2,091	3,341						
EVs	45,000	2,250	1,216	3,466	45,000	2,250	548	2,798	274	**942**
H2FCVs	50,000	2,500	1,081	3,581	50,000	2,500	694	3,194	347	**734**
NH3 ICV					35,000	1,750	1,719	3,469	860	**732**
Methanol ICV					30,000	1,500	1,719	3,219	860	**982**
Synthetic ICV					25,000	1,250	1,342	2,592	671	**1,420**

***Assumptions:** ICV in MPG: 31 EV mi/kWh: 4.0 miles/y 10,950 Vehicle life in years: 20

The Table 3 comparison is set for the years 2020-2025, by which time a large part of the possible replacements of conventional ICVs to PHEVs and EVs may have materialized, and renewable fuel processing plants may have started up. Inputs are entered in the yellow fields.

Car user life-cycle costs are shown in the two left blue fields. The savings for switching to renewable fuels would be their difference. We assume that by 2020, locally made and renewable gasoline and electricity will cost less than their fossil-based and imported counterparts. The life-cycle cost reduction of import-dollars per year and per car is listed in the blue field at the far right. These values include allowance for renewable plant construction and maintenance with local labor. The non-zero values in the renewable, locally-produced Fuel Import column represent the fuel cost component caused by the estimated 50% renewable fuel plant capital cost of imported parts; the installation and maintenance would be done with the other 50%.

Note that a renewable synthetic-fuel car user may realize a lower life-cycle "User Cost" than an EV user. Even the envisioned reductions in electricity and energy prices by 2020 may not yet overcome the contribution of the higher capital car cost, unless the synthetic fuel price increases above the electricity rate by over a factor of 4.37/0.20= 21.9 ($/gal)/($/kWh). On the other hand, if vehicle service-life is shorter than the assumed 20 years (the EVs and FCVs may need more frequent battery or FC replacement), the life-cycle cost advantage of renewable fuel ICVs would be even more pronounced than shown in Table 3.

Conclusions -- In view of the above, it seems that a responsible conclusion we must draw and consider, as we forge a long-term energy (electricity and fuel) security and independence strategy, is that we should not only minimize the use of fossil fuel generators, but add as much clean and renewable electricity generation and synthetic fuel production capacity from wind, geo or solar energy as possible, and make it available preferentially, to:

1. Directly operate electrical equipment during daytime availability of solar PV, geothermal and wind electricity as much as possible, so as to avoid incurring the 80-90% round-trip energy loss for storage in batteries
2. Utilities and rate payers should make use of smart-grid signals (e.g. grid voltage level) to indicate grid-load, so that rate payer equipment can effectively adjust demand and benefit from low-cost, off-peak electricity supply to operate equipment, including PHEV and EV chargers
3. Support the installation and operation of plants to produce synthetic fuels from water, carbon dioxide and electricity, because both ICV vehicle user/owner life cycle and imports costs are likely to be lower than for EVs or FCVs, as illustrated by Table 3.
4. Design the synthetic fuel processing plants so that they can ramp production up and down to follow the availability and use of excess or "reserve" renewable electricity, rather than waste the wind, solar and/or geothermal energy during off-peak periods, as we are doing today

All of the above contribute to reducing fossil energy use and import costs as described in Table 3.

This has implications on how much synthetic fuel to produce. For Hawaii County, two to three 20 MGGE/y (synthetic or bio-) fuel plants should take care of Hawaii County's foreseeable jet fuel needs***. For Hawaii County to replace 50% of today's ~140 MGGE/y of fuel for CVs, the added electricity generator investment would then be equivalent of (50/100)*140/4 = 17.5 MGGE/y, i.e. 1/4th of the fuel needed for CVs due to EVs 4x higher energy efficiency than CVs, or as little as 17.5e6 GGE/y*110000 Btu/GGE *1054 J/Btu/(3.6e6 J/kWh) /(8760 h/y) = **64 MW(average)** in the next ~10-15 years. This time fits well with the needed ~8-10-year time to study, get permits, design, install and start-up the 20 MGGE/y plants, after which they would produce for 25-30 years. The produced fuels would be certified for use as aviation fuel, and for gasoline or diesel fuel for road engines.

*** Similarly, 150-200 MGGE/y may about meet the jet fuel needs for the State of Hawaii. On the long run, we assume that we may only have to replace half of the total amount of fossil fuels used today of ~750 MGGE/y because of the adoption of EVs and PHEVs may eliminate the need for the other half..

Replacing the remaining 70 MGGE/y imported fossil fuel to Hawaii County with locally-produced synthetic fuel may require **300-500 MW(average)** electrical power for the producer plants, depending on their overall 40-70 % conversion efficiency. Clearly, the capital investment in clean, renewable electricity generation to put EVs on the road is much lower (64 MW) than for ICVs, which additionally may need ~700 M$ to install the 70 MGGE/y synthetic-fuel producer plants. Both of these M$ numbers (and associated amortization and maintenance) strongly determine the exact price of synthetic fuels.

For a fascinating documentary of the development, struggles, costs and implementation of a synthetic gasoline production industry by BASF in Germany between the 1920s – 1940s (also adapted later by Sassol in S.Africa) from coal, which now would be replaced by CO_2, H_2O and electricity as feedstock, read ref.[6].

Questions -- With such a strategy, one might do well to be prepared to answer questions like these:

1. How can one expect to find customers willing to drive EVs with only ~100 miles with one charge? A.: Over the next 10-20 years, that 100-mile range is likely to expand to 300 or 400 miles, as battery technology advances, battery costs drop and (most importantly) also car weight drops, thanks to the use of lighter composites. Think of the 2500 MPGs (60-80 miles/kWh) achieved by cars in the 2011 Shell EcoMarathon[2]; we would only need 5-10 kWh batteries (not 40 kWh as in the Tesla) to achieve a 350-mile range.

2. Why bother with synthetic H_2 via electrolysis, if we could simply capture the gas coming out of our land-fills, which is now just wasted and flared? A.: The amount we could draw from land-fills would only be like a drop in a big bucket. On top of that, it may also cost more to purify and make H_2 from it than starting with clean water.

3. Is it realistic to assume that EVs and PHEVs will increase market share in Hawaii, in view of their high cost, small range, long-time to re-charge and our high (~0.40 $/kWh) electricity cost? A.: As mentioned above and demonstrated with the cars in the 2011 Shell EcoMarathon[2] and the huge MPG savings with lighter cars[3], we expect that while the cost of EVs comes down, their miles/kWh will increase due to weight reduction and the charging time will also come down due to improved (higher charge-&-discharge efficiency) battery technology. Boat mileage might also improve as more light-weight materials are used.

4. Regarding the high cost of electricity (0.40 $/kWh is the energy cost equivalent of 12.88 $/gal gasoline), at what point is it more economical to drive an EV vs. an ICV? A.: By comparing an ICV of 20% fuel efficiency with an EV of 80% "electricity-fuel" efficiency, the gasoline/electricity price ratio in units of ($/gal) / ($/kWh) needs to be greater than 12.88/0.4*4 = 8.05 to favor EV fuel economy, e.g. if the gas pump price is 4 $/gal, the effective electricity price should be less than 4 / 8 = 0.50 $/kWh (as is true today in Hawaii) to result in an EV mileage cost in $/mile that is lower than that of an ICV, for about equal size cars.

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References

[1] Capital costs, C, of generation and fuel plants typically scale as power functions: $C \sim Co(C/Co)^n$, where $0.6 \leq n \leq 0.7$

[2] "Results of the 2011 Shell EcoMarathon international car race in Houston,TX," Friends of NELHA website, http://energyfuturehawaii.org/

[3] Amory B. Lovins (Rocky Mountain Inst., CO), "Prifitable Solutions for Climate, Oil and Proliferation," AMBIO 39 236 (2010), DOI 10 1007/s13280-010-0031-6, www.springerlink.com/content/0u401176160q6196/fulltext.pdf "The primacy of lightweighting emerges from a typical car's physics. About 87% of the fuel energy never reaches the wheels; it is lost in the engine, idling, driveline, and accessories. Of the 13% that reaches the wheels, just over half is irreversibly lost heating the tires, the road, and the air that the car pushes aside. **Only the last 6% accelerates the car and then heats the brakes**. Yet, only about 1/20th of the mass being accelerated is the weight of the driver

[4] Jeremiah Johnson, Dan Leistra, Jules Opton-Himme and Mason Smith (Yale Univ.), "Hawaii Cty. Baseline Energy Analysis," Sponsored by the Kohala Center, Kamuela, Hawaii, 10 May 2006, rev. 19 Feb. 2007

[5] Access Table 3 at http://minnefuels.pbworks.com/w/file/fetch/41234610/TL-11-Car-Ownership-Cost.xls

[6] Thomas Hager, "The Alchemy of Air" paperback, Three Rivers Press, NY (2008)

Acronyms

Btu British thermal unit. 1 Btu = 1054.37 joules = 0.2929 Wh = 0.0002929 kWh
CapEx Capital Expenditure, e.g. to install a generation plant

CO2	Molecular formula for carbon dioxide
CPI	Consumer Price Index
CV	Conventional (IC-engine) Vehicle
DME	Dimethylether, CH3-O-CH3, and oxygenated diesel fuel of no or low soot emissions
EV	Electric Vehicle
FCV	Fuel-Cell Vehicle
FT	Fischer-Tropsch reactor process to convert syngas (CO+H2) to fuels
GGE	Gallons of Gasoline Equiv., of its energy content or heating value (LHV~110,000 Btu/gal)
h	Hour
H2	Molecular formula for hydrogen
HELCO	Hawaii Electric Light Company
IC	Internal Combustion
ICV	Internal Combustion Vehicle
k	Kilo, i.e. thousand
LHV	Lower Heating Value, ignoring the heating value contribution of water condensation
M	Mega, i.e. million, e.g. 1 M$ = 1 million dollars or MGGE = 1 million GGE
MPG	Miles Per Gallon
OTEC	Ocean Thermal Energy Conversion (generator)
PHEV	Plug-in Hybrid Electric Vehicle
PV	Photo-Voltaic (generator)
ROI	Return On Investment in %/year, either levelized or averaged over the life of the equipment; or the total ROI in % of the total investment, or compounded ROI in %/y over that period . Example: A levelized ROI of 10 %/y over 25 years would be equivalent to a total ROI of 250 % after those 25 years, or a ~5 %/y compounded ROI (same as a compounding savings account)
SCP	Solar Concentrating Panel
W	Watt, a unit for power. 1 MW = 1 million watts
Wh	Watt-hour, a unit for energy. 1 MWh = 1 million watt-hours
WT	Wind Turbine