Program Record (Offices of Solar Energy Technologies & Fuel Cell Technologies)	
Record #: 14003	**Date:** February 27, 2014
Title: Levelized Costs of Electricity from CHP and PV	
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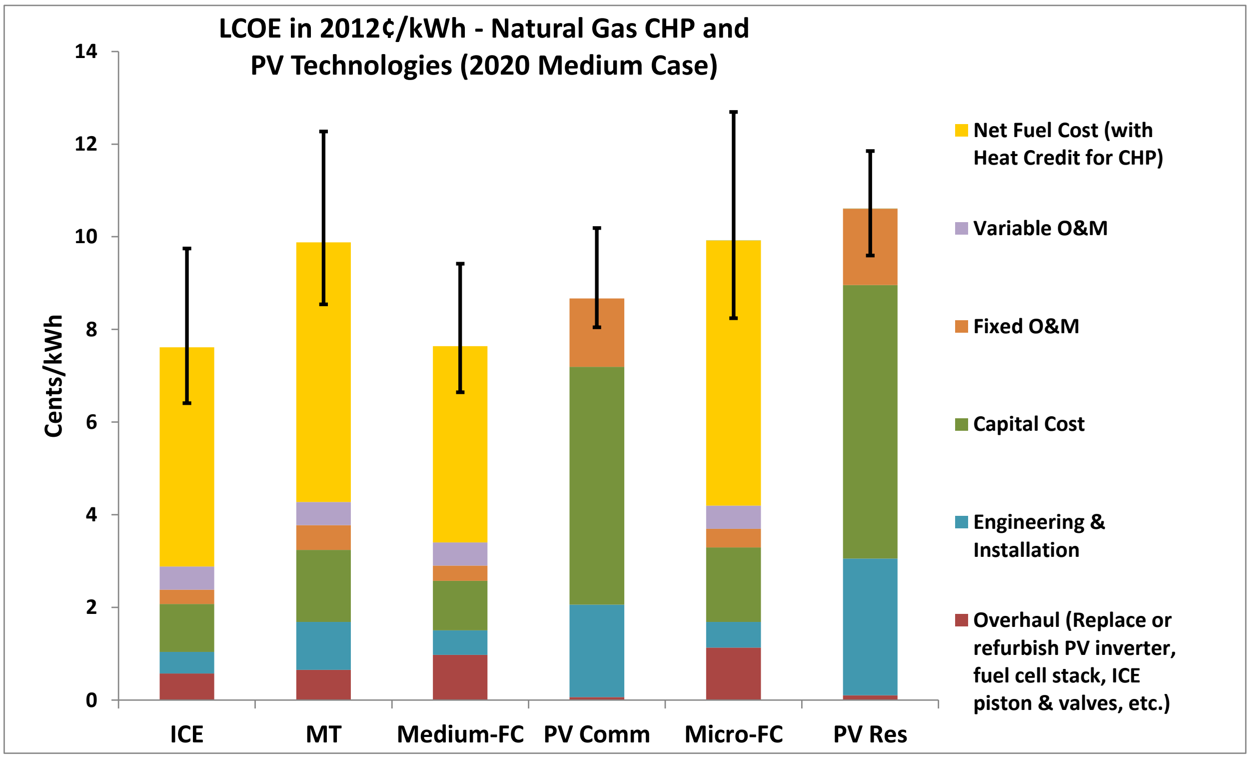
Approved by: Minh Le Sunita Satyapal	**Date:** March 14, 2014

Item:

The levelized costs of electricity (LCOE) associated with combined heat and power (CHP) technologies and solar photovoltaic (PV) technologies were compared. This record documents the assumptions and results of analyses conducted to estimate the LCOE. The results are summarized graphically in the following figure.

LCOE in 2012 Cents/kWh (Technology in 2020, No Incentive Assumed)



Low/high: sensitivity to uncertainties associated with capacity factor, fuel prices, and heat utilization (heat recovery applies only to CHP systems)

Note:
Sunshot targets were published as total installed costs. Engineering & installation costs were derived by estimating the allocation of Sunshot installed cost target between capital and engineering & installation, based on breakdown for installation, permitting, profit, etc. from an assessment of German PV systems in Barbose 2013.

Data, Assumptions, References

- Results are based on a projected state of the technologies in 2020, assuming that cost and efficiency targets are met for commercial PV (PV Comm), medium-scale CHP fuel cells on natural gas (Medium-FC), residential PV (PV Res), and micro-scale CHP fuel cells on natural gas (Micro-FC). Costs and efficiencies for two other commercial-size systems - internal combustion engine (ICE) and micro-turbine (MT) CHP (both using natural gas) - are from a California study (Itron/PG&E 2011) that made use of information for existing ICE and MT systems from an Environmental Protection Agency document (Environmental Protection Agency 2008) and projected the costs of these systems through

2020. Each system's life was assumed to be 30 years. Other major assumptions are listed in Table 1 and additional information on the references for Table 1 is provided after the table.

Table 1. Major Assumptions[1]

	ICE	MT	Medium-FC	PV Comm	Micro-FC	PV Res
Size, kWe	500	200	500	495	7.0	6.8
Capital Cost/kWe	1,400	1,700	1,000	982	1,300	1,109
Engineering & Installation, $/kWe	450	1,000	500	382	450	554
Capacity Factor (CF)[2]	0.81 (0.78 - 0.84)	0.81 (0.78 - 0.84)	0.81 (0.78 - 0.84)	0.17 (0.15 - 0.19)	0.81 (0.78 - 0.84)	0.19 (0.17 - 0.21)
Elec. Efficiency (HHV)	35.5%	32.5%	45.1%	N/A	40.6%	N/A
Elec. Efficiency (LHV)	39.3%	36.0%	50.0%	N/A	45.0%	N/A
Combined Effic. (HHV)	78.5%	70.4%	81.2%	N/A	81.2%	N/A
Fraction of Recoverable Heat Used[3]	0.80 (0.65 - 0.95)	0.80 (0.65 - 0.95)	0.80 (0.65 - 0.95)	N/A	0.80 (0.65 - 0.95)	N/A
Waste Heat Utilization, kBtus/kWh	3.4 (2.7 - 4.0)	3.3 (2.6 - 3.9)	2.3 (1.9 - 2.8)	N/A	3.1 (2.6 - 3.7)	N/A
Pre-Inverter Efficiency	N/A	N/A	N/A	0.93	N/A	0.93
Inverter Efficiency	N/A	N/A	N/A	0.98	N/A	0.97
Annual Degradation	0.5%	0.5%	1.2%	1.0%	3.1%	1.0%
Years to 1st, 2nd, 3rd Overhaul	5, 10, 15	5.5, 12, 18	9, 18, 28	20, >30, >30	7, 14, 21	20, >30, >30
Sum of Life-time Overhauls (Inverter, FC stack, ICE piston & valves, etc.) $/kWe	560	635	920	12	922	20
Other O&M, ¢/kWh	0.81 (0.80 - 0.82)	1.03 (1.02 - 1.06)	0.83 (0.82 - 0.84)	1.47 (1.37 - 1.73)	0.90 (0.89 - 0.92)	1.65 (1.49 – 1.84)
Fuel Price, $/Mbtu	8.3 (7.3 - 10.5)	8.3 (7.3 - 10.5)	8.3 (7.3 - 10.5)	N/A	10.6 (8.9 - 13.7)	N/A

The 540-kW DC output rating of the commercial PV systems (7.5-kW DC output rating of the residential PV systems) was converted to AC output rating, taking into account the product of the Pre-Inverter Efficiency and Inverter Efficiency factors[4], resulting in approximately 495 kW AC (6.8 kW AC for residential PV), nearly the same as the rated 500 kW AC of Medium-FC (7.0 kW AC of Micro-FC). Fuel cell manufacturers frequently cite their products' efficiency after taking into account inverter efficiency loss. Therefore the table shows this rated efficiency of the fuel cell system and does not need to show inverter specifications.

Installed cost, efficiency and durability targets are from EERE's Office of Solar Energy Technologies, Table 4-1 of DOE's Sunshot Vision Study (Department of Energy (Sunshot)), and the Fuel Cell Technologies Office's records on micro and medium-scale fuel cell CHP (DOE FCT 2012a, http://www.hydrogen.energy.gov/pdfs/11016_micro_chp_target.pdf, and DOE FCT 2012b, http://www.hydrogen.energy.gov/pdfs/11014_medium_scale_chp_target.pdf). DG systems' performance was assumed to be restored following each major overhaul (except for PV systems – only inverters are

[1] The model used is NREL's Fuel Cell Power Model, at http://www.hydrogen.energy.gov/fc_power_analysis.html

[2] In the table, when three values are listed for a parameter (e.g., capacity factor), the average value is shown above the less optimistic and more optimistic values (these two numbers, indicating a range, are shown between parentheses).

[3] At times, the technically recoverable heat from the CHP system is wasted, e.g., when seasonal demand for heat is low. For example, when this value is 0.80, it is assumed that 20% of the available heat is not recovered due to a lack of demand at the time it is produced.

[4] Pre-inverter losses include losses in wiring, connections, etc. Pre-inverter and inverter efficiencies are 93.5% x 98% for PV Comm and 93.5% x 97% for PV Res.

assumed to be replaced for PV). The Sunshot cost targets shown are in $/kW AC output and therefore are higher than the original Sunshot targets ($/kW DC output).

For ICE, the electrical efficiency from the previously cited references (EPA 2008 and Itron/PG&E) was assumed to increase modestly from approximately 34% HHV to 35.5% HHV in 2020 because this technology is already mature. The MT electrical efficiency was assumed to improve from approximately 25% HHV, the current value in those references, to 32.5% HHV by 2020.

Fixed costs for CHP and commercial PV systems include property tax and insurance, assumed at 1.5% of the system's installed cost (Fthenakis 2009, Northwest Power and Conservation Council 2010).

Natural gas (NG) is the assumed fuel for CHP. Utilities set residential rates based on wholesale costs (to the utilities), distribution charges, other charges, and local and state taxes. Therefore rates can vary widely across the U.S., as illustrated with two examples in Table 2. Table 2 shows December 2013 prices at the Henry Hub and 2 utilities' residential rates to illustrate this point.

Table 2. Two Examples of Natural Gas Prices Charged to Residential Customers

	Consumers Energy Per Thous CF	**PG&E** Per Thous CF
Henry Hub Price (EIA December 2013)[5]	$4.24	$4.24
Wholesale Cost (from Utilities - December 2013)	$4.63	$5.30
Distribution Charge (Rate Sheets)	$2.60	$5.29
Customer Charge (Rate Sheets: $10-$11.50 per month, 2-person household)	$0.90	$0.00
Local & State Taxes (approximation)	$1.00	$1.00
Total Residential Rate per Thousand Cubic Feet or MBtu	**$9.13**	**$11.59**

Sources: EIA http://www.eia.gov/dnav/ng/hist/rngwhhdm.htm, Consumers Energy Co. http://www.consumersenergy.com/content.aspx?id=1254, Pacific Gas & Electric (PG&E) http://www.pge.com/tariffs/GRF.SHTML#RESGAS

EIA tracks annual residential, commercial and industrial prices for each U.S. region. Using EIA's 2013 data, the average residential rate was approximately $10.60 per Mbtu, with the lowest price at $8.90 in the Mountain Region and highest price at $13.70 in New England (these low, medium and high values were used in this study's analysis of the micro-scale fuel cell system), and the corresponding commercial rate was approximately $8.30, $7.30 and $10.50, respectively (these were used to analyze commercial-scale systems). Table 3 shows the assumed natural gas prices for this analysis.

Table 3. Natural Gas Prices ($/Mbtu) in 2013 – EIA Regional Data for 2013

	Commercial	**Residential**
Low	$7.30	$8.90
Medium	$8.30	$10.60
High	$10.50	$13.70

For NG ICE, a reference value of 43,000 hours between major overhaul activities was assumed for 2020 in this analysis, based on the 30,000-72,000 hour range in EPA 2008. For MT, the interval between major overhaul was 40,000 hours in the recent past (EPA 2008). Since MT is a newer technology, this was

[5] Located in Erath, LA, the Henry Hub is a pipeline interchange and the delivery point for the natural gas futures contracts associated with the New York Mercantile Exchange (benchmark for U.S. natural gas wholesale prices).

increased to 50,000 hours in 2020. Overhaul expenses in the literature are typically lumped with other O&M and shown per kWh, based on service contracts. For medium-scale fuel cell systems in 2020, stack replacement was assumed at $930 per kW, based on improvement over estimates of $1,500 per kW for early technology (Chevron Energy Solutions 2004, Mohegan Tribe 2007). Degradation rates for ICE and MT were assumed to improve to 0.5% per year by 2020 from the current 1% per year value in Itron 2011. This analysis breaks out the major overhaul items (reciprocating engine, core turbine components, fuel cell stack) because these expenses are incurred at future intervals (corresponding to the assumed life of PV inverters or fuel cell stacks).[6]

Table 4 shows a summary of financial assumptions.

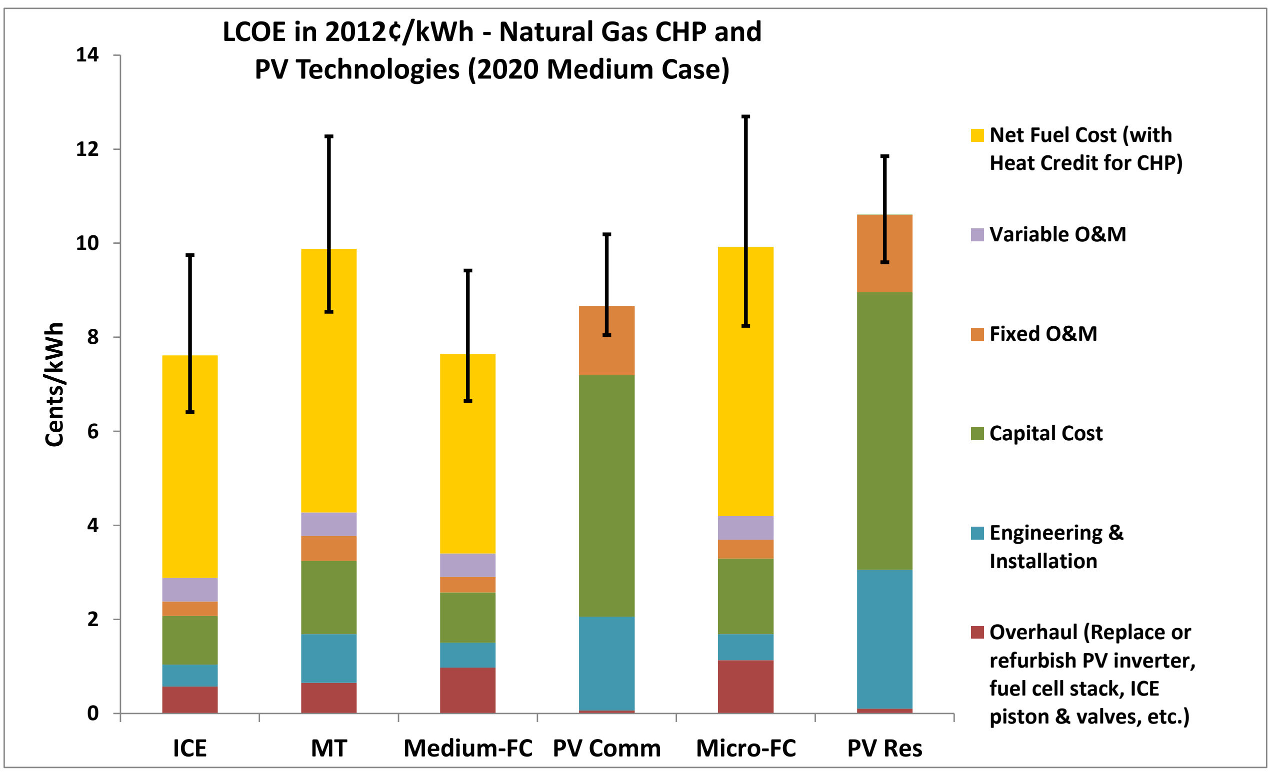
Table 4. Financial Assumptions

	Commercial	Residential
Debt Percentage	60%	100%
Debt Rate	7%	7%
Debt Term (years)	12	12
Economic Life (years)	30	30
Cost of Equity	6%	Not Applic.
Depreciation Term (years)	5	Not Applic.
Percent CHP Depreciated	100%	Not Applic.
Tax Rate	39%	Not Applic.
Discount Rate	5%	7%

Results

The results (2012 cents) are summarized in Figure 1 and Table 5.

Figure 1. **LCOE in 2012 Cents/kWh (Technology in 2020, No Incentive Assumed)**



6 The assumed costs of overhaul for ICE and MT and replacement of fuel cell stacks, when converted to discounted $/kWh, and added to fixed and variable O&M costs, resulted in total O&M costs compatible with the range of 1.2 – 2.2 ¢/kWh found in EPA 2008 and Itron/PG&E.

Table 5. Levelized Cost of Electricity (Medium Optimism, No Incentive Assumed) – 2012 Cents/kWh

	ICE	MT	Medium-FC	PV Comm	Micro-FC	PV Res
Capital Cost	1.03	1.55	1.07	5.13	1.60	5.90
Engineering & Installation	0.46	1.03	0.53	2.00	0.56	2.95
Fixed O&M	0.31	0.53	0.33	1.47	0.40	1.65
Variable O&M	0.50	0.50	0.50	0.00	0.50	0.00
Net Fuel Cost (with Heat Credit for CHP)	4.73	5.61	4.23	0.00	5.72	0.00
Overhauls Total (Replace or refurbish PV inverter, fuel cell stack, ICE piston & valves, etc.)	0.58	0.65	0.98	0.06	1.13	0.10
LCOE, 2012 ¢/kWh	**7.61**	**9.88**	**7.64**	**8.67**	**9.92**	**10.60**

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