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Geospatial Combined Heat and Power (CHP) Opportunity Mapping Smart Power Electronics Potential for Smart Grid Integration

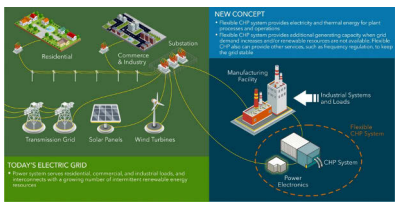
NREL/PO-6A20-74059

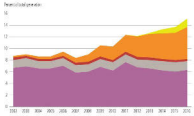
2019 PROGRAM PEER REVIEW
U.S. DEPARTMENT OF ENERGY
ADVANCED MANUFACTURING OFFICE

CHP IGATE-E Methodology

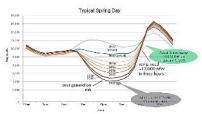
Flexible CHP Systems: Concept Basics

- Concept would improve grid reliability and resiliency, along with providing economic benefits to manufacturing facilities
- Technology advancements are needed to bring the concept to fruition
- Non-dispatchable renewables (particularly wind and solar) are increasing rapidly on the U.S. grid.
- The rapid increase of renewables exacerbates the load changes at peak demand periods requiring additional fast-reacting grid resources.





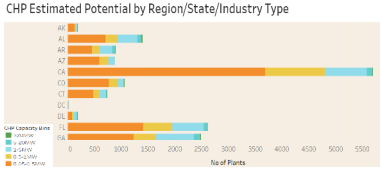
Renewable generation as a percentage of total U.S. Electricity generation



California's "Duck Curve"

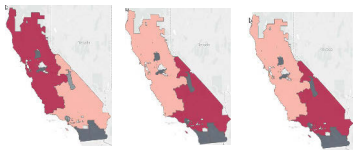
IGATE-E CHP Example: CA CHP Potential Industrial sites

CHP Estimated Potential by Region/State/Industry Type



Potential Impact of flexible CHP on California's Grid

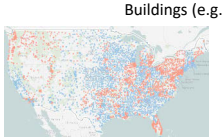
- IGATE-E provided information on manufacturing sites in California
- Study assumed three scenarios for CHP support of the grid
  - Baseline: Existing 3,385 MW CHP capacity
  - Traditional CHP: In addition to baseline CHP capacity, 4,081 MW of CHP installed (3,722 MW Baseload and 358 MW Surplus)
  - Advanced CHP: In addition to baseline CHP capacity, 5,046 MW of CHP installed (3,722 MW Baseload and 1,324 MW Surplus)
  - Combined CHP: In addition to baseline CHP capacity, 4,722 MW of CHP installed (3,722 MW Baseload and 1,000 MW Surplus)

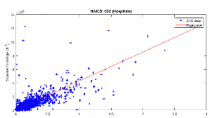


Heat maps : California Utility regions

Sites identified using IGATE-E to identify those as being cost-effective using traditional CHP technology

IGATE-E Methodology Expanded to Commercial Buildings (e.g., Hospitals)



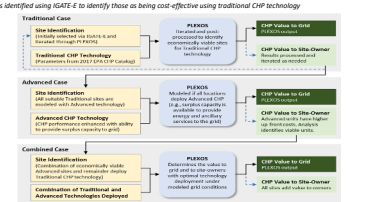


- Regressions of energy per sq.ft. versus No. of employees are developed using data from the American Hospital Association (AHA) database (private)
- Energy consumption is estimated for each location based on energy intensity estimates from the 2012 Commercial Buildings Energy Consumption Survey (CBECS)
- Load factors and thermal to electric ratios are estimated by climate zone based on EnergyPlus building energy modeling (using the DOE Commercial Prototype Building models)
- Finally, CHP potential is evaluated at the facility-level using the methodology developed by the CHP Technical Assistance Partnerships (CHP TAPs)

High-Level Modeling for the CHP Deployment Scenarios

Case	Description
Base Scenario	CA grid if no additional CHP is added
Traditional	Grid modeled if all locations where Traditional CHP is cost-effective deploy Traditional CHP • Traditional units are constrained to operate no more than 500 hours per year
Advanced	Grid modeled if all locations where Traditional CHP is cost-effective deploy Advanced CHP • The Advanced CHP units come with additional up-front capital costs • The scenario determines the value each site-owner would obtain from deploying Advanced CHP units and the associated return on investment. • The results from the Advanced case point to an economically viable set of Advanced CHP deployments that could be modeled with Traditional CHP units at the remaining sites • Advanced CHP units may become more economically viable with increased research and development to lower costs, or the addition of capacity payments in CA markets
Combined	Grid modeled if economically viable Advanced CHP units are deployed and the remaining suitable sites deploy Traditional CHP

**Sites identified using IGATE-E to identify those as being cost-effective using traditional CHP technology*



Value to the Grid: 8 Different Utility Regions Modeled in CA

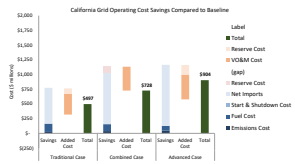
Revenue (thousands)			
Case	Energy	Ancillary Service	Total
Traditional	$1,182	$12,820	$14,002
5+ MW (HR 6040)	$1,059	$9,336	$10,394
1-5 MW (HR 6080)	$121	$3,175	$3,296
Under 1 MW (HR 6815)	$2	$309	$312
Advanced	$759,303	$7,748	$767,051
5+ MW (HR 4900)	$759,144	$3,707	$762,851
2-5 MW (HR 6540)	$122	$2,006	$2,128
Under 2 MW (HR 6800)	$37	$2,035	$2,073
Combined	$763,828	$16,934	$780,762
5+ MW (Advanced - HR4900)	$763,737	$14,805	$778,543
5+ MW (Traditional-Recip HR 6040)	$4	$0	$4
1-5 MW (Traditional-Recip HR 6080)	$83	$1,922	$2,006
Under 1 MW (Traditional-Recip HR 6815)	$3	$206	$209
0-2 MW (Traditional-Microturbine)	n/a	n/a	n/a

Region	PLEXOS Code	Name
IID	IID	Imperial Irrigation District
TIDC	TIDC	Turlock Irrigation District
SMUD	BANC	Sacramento Municipal Utility District
SCE	CISC	Southern California Edison
SDGE	CISD	San Diego Gas and Electric
LDWP	LDWP	Los Angeles Department of Water and Power
PG&E_BAY	CIPB	Pacific Gas & Electric - Bay
PG&E_VLY	CIPV	Pacific Gas & Electric – Valley

High-grid-stress hours by region

Region	Base
PG&E Bay	22
PG&E Valley	22
SCE	11
SDG&E	10
BANC	23
IID	10
LDWP	4
TIDC	23
Total	125

Grid Stress hours reduced to zero for all three cases that were modeled



CHP Capacity by Scenarios

Scenario and CHP unit size grouping	Baseload		Surplus		Total
	Heat Rate	Capacity	Heat Rate	Capacity	Capacity
Base		**1,855**		**1,530**	**3,385**
Traditional		**3,722**		**358**	**4,081**
5+ MW	5,300	1,655	6,040	165	1,820
1-5 MW	5,150	1,787	6,080	172	1,959
Under 1 MW	5,400	281	6,815	21	302
Advanced		**3,722**		**1,324**	**5,046**
5+ MW	5,610	1,655	4,900	808	2,463
2-5 MW	5,130	1,032	6,540	258	1,290
Under 2 MW	5,680	1,035	6,800	259	1,294
Combined		**3,722**		**1,000**	**4,722**
5+ MW (Advanced - HR4920)	5,610	1,642	4,900	799	2,441
5+ MW (Traditional-Recip)	5,500	13	6,040	1	14
1-5 MW (Traditional-Recip)	5,150	1,787	6,080	179	1,965
Under 1 MW (Traditional-Recip)	5,400	209	6,815	21	230
0-2 MW (Traditional-Microturbine)	6,940	72	n/a	0	72

Impact of Flexible CHP Concept on the Grid: Modeling of the California Market

(Updated analysis nearly complete)

Objective: Estimate value of added flexible CHP at California **industrial and institutional sites** due to increased revenue from grid services and lower CHP costs.

Three scenarios modeled: Added flexible CHP systems on the CA grid in 2024:

Baseline: 33% renewables on grid, 3,385 MW existing CHP for site loads

Traditional CHP: Serves site loads + 10% capacity for grid services <500 hr/yr

Advanced CHP: Serves site loads + large flexible capacity for grid services

Combined Scenario: Selects most profitable option (between traditional and advanced) at each site

Key findings:

Reduced Grid Operating Costs: All scenarios reduce grid operations by $1 Billion or more.

Increased Generation Capacity: Alleviates need for new centralized power plants.

Lowers Site Energy Costs and Provides Additional Revenue Stream: Sites average additional revenue of receive $40,000 - $780,000 / MW surplus capacity

Reduction in Grid Stress: Eliminates hours when reserves may not be met or transmission ratings exceeded

OAK RIDGE National Laboratory

CHP System Cost & Grid Interconnection

Overview of U.S CHP Market

As of December 2017, CHP had an installed capacity in the U.S. of approximately 81.3 GWe (DOE EERE 2017) , which represents nearly 8% of the total U.S. generation capacity (Global CCS Institute 2018).

The top 10 states make up 73% of the all the installed CHP sites across the United States

The average new CHP installed capacity from 2008 – 2017 was approximately 741-MWe/yr, and the number of sites installing CHP was around 177/yr.

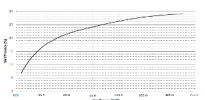
CHP installed capacity distribution across the country (DOE EERE 2017)

CHP Prime Movers

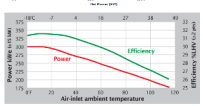
CHP Prime Mover	Technology	Fuel Source	Available Sizes	Cost of Technology ($/kW)
Gas Turbine	Direct combustion with air, and expansion of hot gas through the turbine	Natural Gas	500 kW to 300 MW	$1,200 -$3,300
Microturbine	*Same principle as gas turbines much smaller version in size up to 60,000 revolutions per minute (RPM)*	Natural gas, gasoline, diesel, kerosene, naphtha, alcohol, propane, methane, and digester gas	30 kW to 250 kW with multiple unit packages up to 1,000 kW	$2,500 -$4,300
Reciprocating Engine	Fuel is mixed with air, compressed and expanded, through the movement of multiple pistons	Oil, diesel, natural gas, and petrol	1 kW to 10 MW in DG applications High speed (1,200 RPM) ≤4MW <80 MW for Low speed (60-275 RPM)	$1,500 - $2,900
Steam Turbine	Very hot steam is passed through a steam turbine to extract energy out of the hot steam as the temperature and pressure of the fluid is decreased through the stages	Coal fired boilers, natural gas HRSGs or oil to water heater exchangers, concentrating solar power (CSP)	50 kW to several hundred MWs	$670 – $1,100
Fuel Cells	Works by the chemical reaction of combining hydrogen and oxygen to form electricity and water produce DC power in an electro-mechanical process and then to AC via an inverter	Alkaline, phosphoric acid, molten carbonate, direct methanol, solid oxide, and proton exchange membrane	5 kW to 2 MW	$5,000 - $6,500

Modular Microturbines for CHP Plants

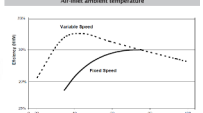
Capstone C200S
- Capacity: 200kW
- Heat Recovery: 1 MMBtu/hr
- Single controller controls all units.
- Scaling to 1MW



FlexEnergy MT/GT250
- Capacity: 250kW
- Heat Recovery: 1 MMBtu/h
- Nominal Heat Rate
- HHV: 12,645 Btu/kWh (13.3 MJ/kWh)
- LHV: 11,380 Btu/kWh (12.0 MJ/kWh)
- Electrical Efficiency: 30%



TecoGen InVerde INV100 e+
- 100kW
- *Water-Cooled Permanent Magnet Generator*
- *Customized Power Electronics with Patented Topology for Variable Speed and Standby Operation*



DER Capable Microturbine Package Cost

Microturbine	Capstone C30*	Capstone C200 *	Capstone 200s**	FlexEnergy MT250**	FlexEnergy MT330*	TecoGen InVerde INV100 e+**
Gen Set Package	$53,100	$359,300	$402,200	$441,200	$566,400	$165,000
Heat Recovery	$13,500	$0	$70,000	included	included	included
Fuel Gas Compression	$8,700	$42,600	$0	$0	$0	$0
Total Equipment ($)	**$75,300**	**$401,900**	**$472,000**	**$441,200**	**$566,400**	**$165,000**
Unit Cost ($/kW)	**$2,689**	**$2,010**	**$2,360**	**$1,765**	**$1,716**	**$1,650**
Controller Cost	N/A	N/A	$50,000	N/A	N/A	N/A
Installation Cost	$45,100	$196,600	$167,500	$167,500	$167,500	$65,000
Total Installed Cost ($)	**$120,400**	**$598,500**	**$689,500**	**$608,700**	**$733,900**	**$230,000**
Total Unit Cost ($)	**$4,300**	**$2,993**	**$3,448**	**$2,435**	**$2,224**	**$2,300**

**EPA, 2017*
***NREL, 2018 (personal interview, and web search)*

Grid Inertia & Power Electronics

An increasing penetration level of Distributed Generation (DG) units can therefore result in larger frequency deviations.

Inertial response of DG units to the grid, needs to be controlled by power electronic converters (PECs).

PECs have an output filter to reduce the harmonic distortion by increasing capacitance.

However, power electronic converter circuits also have a tendency to generate harmonics in the supply system as well as in the load circuit.

Summary of Grid Integration Equipment Cost

The successful integration of any CHP system into the Area EPS on a dispatchable basis depends on what is installed in the interconnection system.

Estimated cost ranges of the interconnection equipment for different system size.

Potential costs that could be added for the interconnection of a CHP system to a local grid or EPS operated by a California utility like Pacific Gas and electric (PG&E) or Southern California Edison (SCE).

1	Transfer Switch =	$1,000 -	$14,000
2	Paralleling Switchgear =	$13,000 -	$25,000
3	Dispatch, Communication & Control =	$15,000 -	$80,000
4	DER Controls =	$5,000 -	$26,000
5	Power Conversion =	$40,000 -	$170,000
6	Metering & Monitoring =	$5,000 -	$19,000
UP*	Wiring and Cables =	$15,000 -	$60,000
	TOTAL =	$94,000 -	$ 394,000
7	CHP Unit (Microturbine /Steam Turbine)		

Equipment Description	Cost ($) SCE 2018	Cost ($) PG&E 2018
12/16,000V 480 V transformer	$35k – $173k	$35k – $173k
Overhead to Underground (UG)	$30k – $40k	$30k - $40k
Overhead (OH) Service	$16k + $120/ft	$16k + $120/ft
Underground to Underground	$15k – $36k	$15,000 – $36,000
Metering	$5k – $108k	$5k – $108k
Telemetry	$56k – $140k	$130k – $200k
System Equipment	$12.5k – $274k	$12.5k – $300k

CHP Plant Case Studies: 2,000-kW vs 200-kW

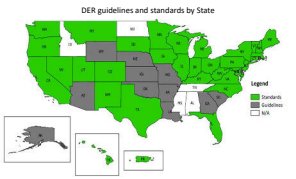
2,000 kW CHP System		
Equipment Cost ($/kW)	**$/kW**	**$**
Generator Set Package	$369	$738,000
Heat Recovery	$495	$990,000
Exhaust Gas Treatment	$401	$802,000
Total Equipment Cost ($/kW)	**$1,265**	**$2,530,000**
Labor/Materials	$310	$620,000
Project Management and Construction	$200	$400,000
Engineering and Fees	$126	$252,000
Project Contingency	$68	$136,000
Project Financing	$63	$126,000
System Cost w/o Interconnection ($/kW)	**$2,032**	**$4,064,000**
Interconnection Equipment	$70	$140,000
Distribution Upgrades	$400	$800,000
Total System Cost w/ Interconnection ($/kW)	**$2,502**	**$5,004,000**

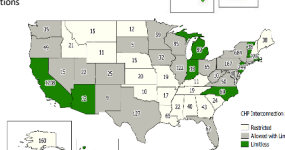
200 kW CHP System		
Equipment Cost ($/kW)	**$/kW**	**$**
Generator Set Package	$1,400	$280,000
Heat Recovery	$250	$50,000
Exhaust Gas Treatment	$0	$0
Total Equipment Cost ($/kW)	**$1,650**	**$330,000**
Labor/Materials	$500	$100,000
Project Management and Construction	$125	$25,000
Engineering and Fees	$250	$50,000
Project Contingency	$95	$19,000
Project Financing	$30	$6,000
System Cost w/o Interconnection ($/kW)	**$2,650**	**$530,000**
Interconnection Equipment	$550	$110,000
Distribution Upgrades	$720	$144,000
Total System Cost w/ Interconnection ($/kW)	**$3,920**	**$784,000**

- The results of case 1 (2,000-kW) and case 2 (200-kW) showed that; the unit cost of 2,000-kW system ***(2,502 $/kW)*** is smaller than the unit of 200-kw system ***(3,920 $/kW)*** *on the grid side*.
- However, the unit cost of interconnection is more expensive ***(1,270 $/kW)*** for a small system when compared to a bigger system ***(470 $/kW)*** a big system.

Codes, Standards & Guidelines

- The interconnection of CHP to the area EPS transmission and distribution system is regulated by codes and standards, which sets requirements for CHP interconnection equipment manufacture, installation and operation.
- 32 states plus the District of Columbia have interconnection standards and 13 states provide guidelines for some or all distributed generation interconnections





CHP interconnection capacity restrictions overlain by number CHP sites in the U.S

- **Institute of Electrical and Electronical Engineers (IEEE)**
  - ***IEEE 1547:*** *Establishes criteria and requirements for interconnection of DER with EPS and associated interfaces*
- **Underwriter Laboratories (UL)**
  - ***UL 1741:*** *Cover inverters, converters, charge controllers, and interconnection system equipment (ISE) intended for the use in stand-alone (not grid connected) or utility-interactive (grid connected) power systems*
- **American National Standards Institute (ANSI)**
  - ***ANSI C84.1 :*** *Establishes nominal voltage ratings and operating tolerances for 60 Hz electric power systems above 100 volts*
- **National Fire Protection Association (NFPA)**
  - ***NFPA 70:*** *Covers the installation of electrical conductors, equipment, and raceways; signaling and communications conductors, equipment, and raceways; and optical fiber cables and raceways*

References

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