



Potential Impact of Flexible CHP on the Future Electric Grid in California

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Analysis Background

Hypothesis

- Advanced CHP technologies can efficiently and cost-effectively provide flexibility the grid needs.

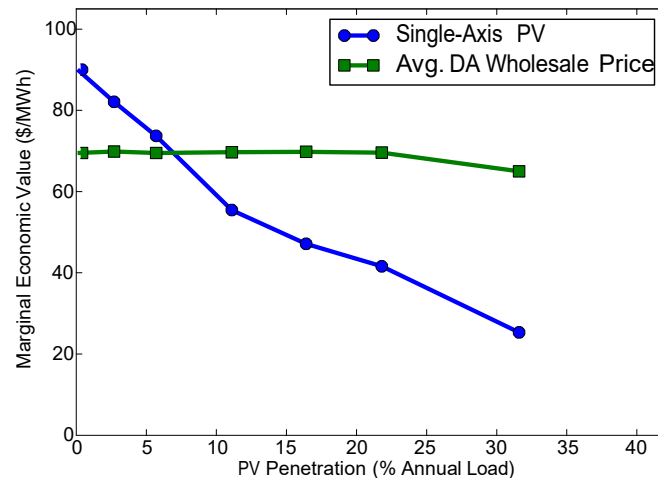
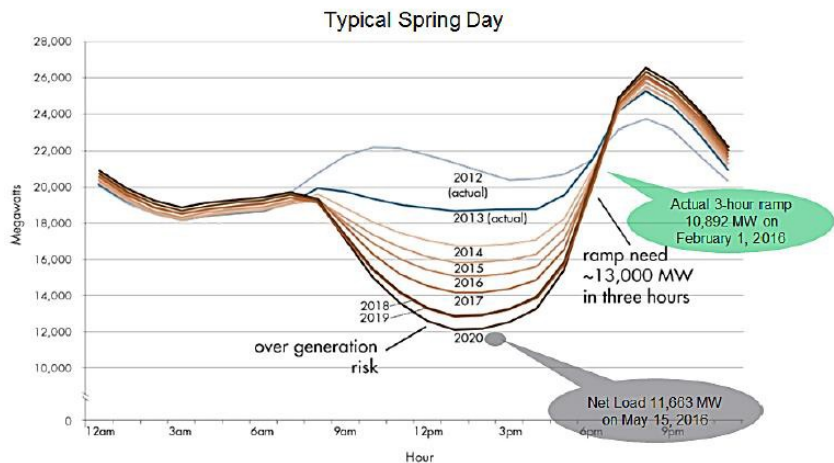
Objective

- Cost-benefit analysis to quantify opportunity and guide R&D decisions.
- Compare the cost of operating the grid in California without and with advanced CHP.

Motivation for Grid

As renewable penetration increases, overgeneration and transients become larger concerns.

The economic value of renewable electricity generation decreases significantly with increasing penetration. Causes risk of RE deployment being limited.



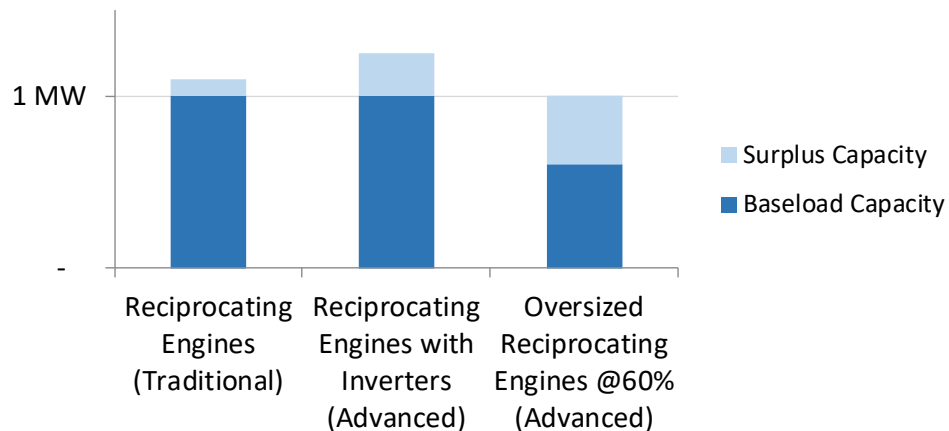
Compensated Services

Compensated by Most Electricity Markets	Not Compensated by Most Electricity Markets	
<p>Bulk power capacity and energy services</p> <ul style="list-style-type: none">• Energy• Generating capacity <p>Ancillary services</p> <ul style="list-style-type: none">• Frequency control• Spinning reserves• Non-spinning reserves• Supplemental reserves• Voltage support• Black start service	<p>Indirect system benefits</p> <ul style="list-style-type: none">• Reduced overall system electricity production cost• Reduced curtailments of variable generation• Reduced cycling and ramping of conventional generating units• Reduced system emissions (depending on plant mix)	<p>Power system stability services</p> <ul style="list-style-type: none">• Inertial response• Governor response <p>Transmission benefits</p> <ul style="list-style-type: none">• Transmission congestion relief• Transmission investments deferral <p>Non-energy benefits</p> <ul style="list-style-type: none">• Portfolio diversification• Local economic development and job creation• Security of fuel supply• Generation resilience

Flexible CHP Configurations Analyzed

Configuration	Grid Support
Traditional: Primarily Serve On-site Electrical Loads and are not ramped to support the grid	
CHP sized to baseload but allowed to operate at 10% overcapacity to provide grid services	Limited to 10% of capacity for 500 hours per year
Advanced: Serve site loads and use surplus capacity to provide a range of services to the grid	
CHP sized between baseload and peak load	More active, limited to 25% and 500 hours per year
CHP sized above peak load	Provides up to 40% of the its capacity reserved for grid support, without constraints

Operation at 1 MW for Traditional and Advanced CHP Units

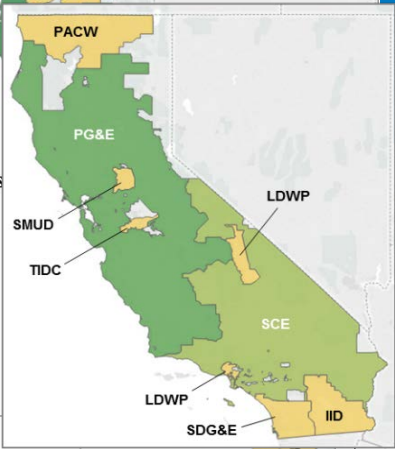


Analysis Scenarios

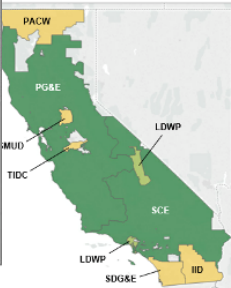
Scenario	Description
Reference	CA grid if no additional CHP is added
Traditional	<p>Grid modeled for all locations where Traditional CHP is economically viable to deploy Traditional CHP</p> <ul style="list-style-type: none">• Traditional units are constrained to operate no more than 500 hours per year
Advanced	<p>Grid modeled such that, in all locations where Traditional CHP is economically viable, Advanced CHP is deployed</p> <ul style="list-style-type: none">• The Advanced CHP units have higher up-front capital costs than the traditional units• 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 such that economically viable Advanced CHP units are deployed, and the remaining suitable sites deploy Traditional CHP

Potential CHP Sites

Reference Scenario



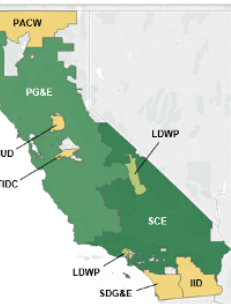
Traditional Scenario



Advanced Scenario



Combined Scenario



Region	Reference capacity (MW)	Model sites	Traditional max capacity (MW)	Advanced max capacity (MW)	Combined max capacity (MW)
IID	—	6	17	25	24
TIDC	—	12	36	46	42
PACW	—	12	25	34	25
SMUD	70	102	354	418	393
SCE	1,053	641	2,987	3,442	3,292
SDG&E	47	119	365	429	404
LDWP	562	72	840	909	891
PG&E_BAY	449	241	1,064	1,205	1,152
PG&E_VLY	1,203	204	1,778	1,924	1,883
Total	3,385	1,409	7,466	8,432	8,108

- Many opportunities across the California Independent System Operator (CA-ISO) territory
- Potential increase of up to 150% over projected installations
- SCE Balancing Authority has the greatest potential

Maximum capacity = (Reference+Baseload+surplus) (MW)
 Region names as follows: Imperial Irrigation District (IID); Turlock Irrigation District (TIDC); PacificCorp West (PACW); Sacramento Municipal Utility District (SMUD); Southern California Edison (SCE); San Diego Gas and Electric (SDG&E); Los Angeles Department of Water and Power (LDWP); Pacific Gas & Electric-Bay (PG&E_BAY); Pacific Gas & Electric-Valley (PG&E_VLY)

Energy and Ancillary Service Revenues to CHP Owner

Case	Revenue (\$ thousands)			Hours operating at surplus	Surplus capacity (MW)	Revenue (\$ thousands per MW surplus)
	Energy	Ancillary Service	Total			
Traditional	\$1,182	\$12,820	\$14,002	3,418	358	\$39
5+ MW (T6040)	\$1,059	\$9,336	\$10,394	2,964	165	\$63
1-5 MW (T6080)	\$121	\$3,175	\$3,296	333	172	\$19
Under 1 MW (T6815)	\$2	\$309	\$312	121	21	\$15
Advanced	\$759,303	\$13,212	\$772,515	45,696	1,324	\$583
5+ MW (A4900)	\$759,144	\$8972	\$768,116	45,269	808	\$951
2-5 MW (A6540)	\$122	\$2077	\$2,199	205	258	\$9
Under 2 MW (A6800)	\$37	\$2,163	\$2,200	222	262	\$9
Combined	\$763,828	\$16,934	\$780,762	45,180	1,000	\$781
5+ MW (A4900)	\$763,737	\$14,805	\$778,543	44,689	799	\$974
5+ MW (T6040)	\$4	\$0	\$4	135	1	\$3
1-5 MW (T6080)	\$83	\$1,922	\$2,006	232	179	\$11
Under 1 MW (T6815)	\$3	\$206	\$209	124	21	\$10
0-2 MW (MT)	n/a	n/a	n/a	n/a	n/a	n/a

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1-5 MW (T6080)	\$121	\$3,175	\$3,296	333	172	\$19
Under 1 MW (T6815)	\$2	\$200	\$212	121	21	\$15
Advanced	\$75				1,324	\$583
5+ MW (A4900)	\$7				808	\$951
2-5 MW (A6540)					258	\$9
Under 2 MW (A6800)	\$37	\$2,163	\$2,200	222	262	\$9
Combined	\$763,828	\$16,934	\$780,762	45,180	1,000	\$781
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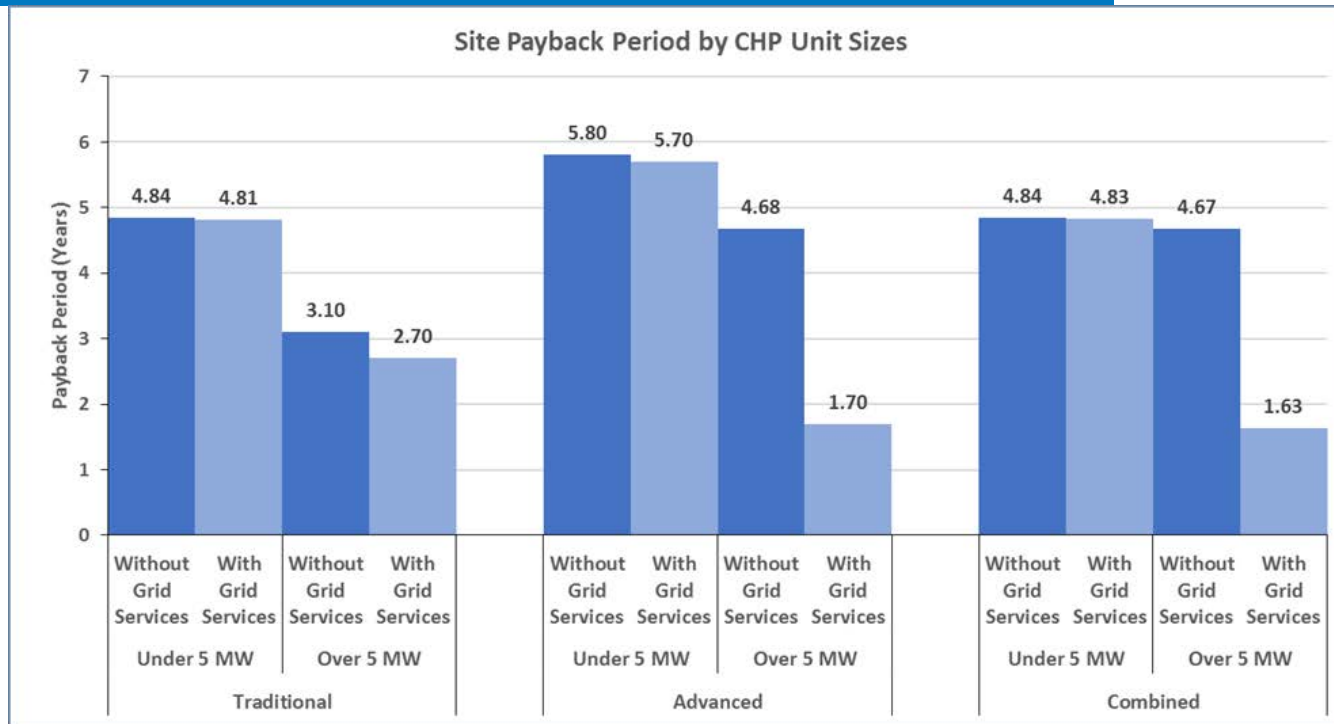
The greatest opportunities are for larger (5+ MW systems)

Potential Value of Capacity to CHP Owners

Capacity payments could increase the site's income by 20% - 100% if rules and regulations allow for that payment

Scenario	Capacity Payment (\$20/kW-year) \$ thousands	Capacity Payment (\$100/kW-year) \$ thousands
Traditional	\$149,320	\$746,600
Advanced	\$168,640	\$843,200
Combined	\$162,160	\$810,800

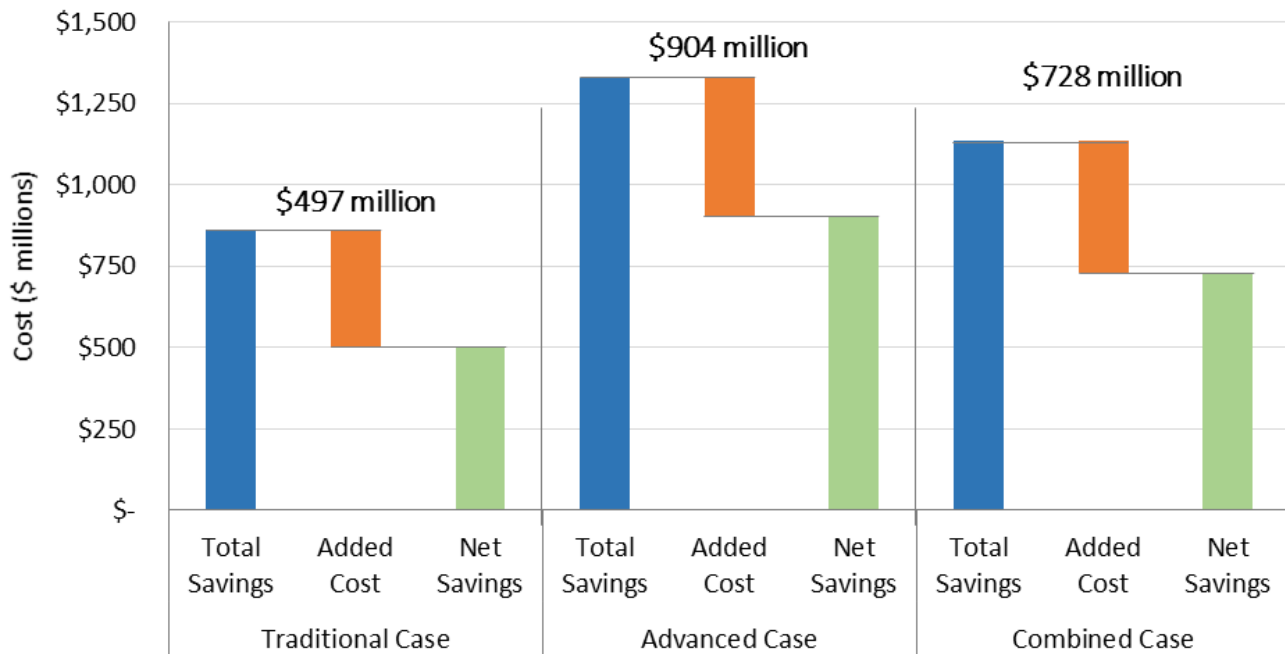
Impact of Grid Revenue on CHP Owners



The ability to participate in grid services markets enables advanced technologies especially for larger systems

Impacts on Cost to Operate the Grid

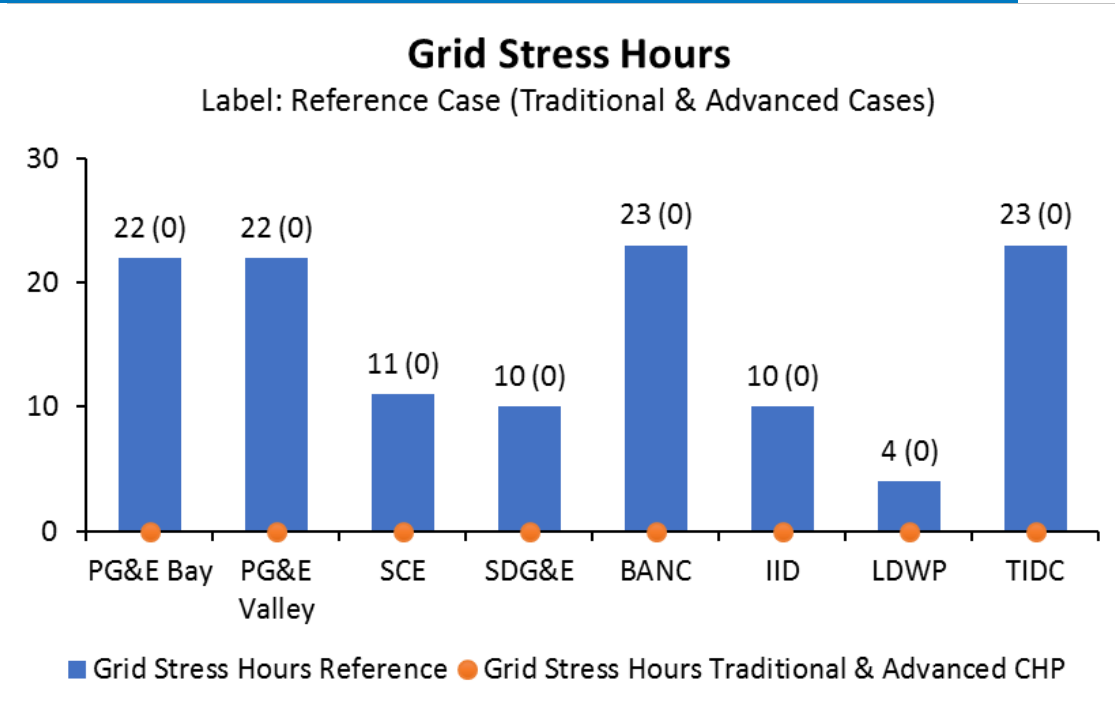
California Grid Operating Net Savings Compared to Baseline



CA Grid Costs	Ref. Case (\$ million)
Emissions	\$1,970
Fuel	\$8,174
Start & Shutdown	\$160
VO&M	\$342
Reserve	\$298
Net Imports	\$2,403
Total Cost	\$13,347

Grid operating costs can be reduced by over \$700 million (5% of total cost)

Impacts on Grid Stress



Advanced CHP in California can eliminate hours with grid stress

Conclusions

Advanced CHP can

- More than double capacity with a 6 year payback period
- Save site owners up to \$760 million
- Reduce CA-ISOs operating cost by over \$700 million
- Eliminate hours of grid stress in CA-ISO

Thank you

www.nrel.gov

NREL/PR-6A20-80943

Desai, Jal, Ruth, Mark, Lemar, Paul, Bhandari, Mahabir S., Storey, John, Srivastava, Kiran, Rogers, Jonathan, and Schwartz, Harrison. “Modeling the Impact of Flexible CHP on the Future Electric Grid In California.” United States: N. p., 2020. Web. doi:10.2172/1649545. <https://www.osti.gov/biblio/1649545-modeling-impact-flexible-chp-future-electric-grid-california> and <https://info.ornl.gov/sites/publications/Files/Pub129588.pdf>

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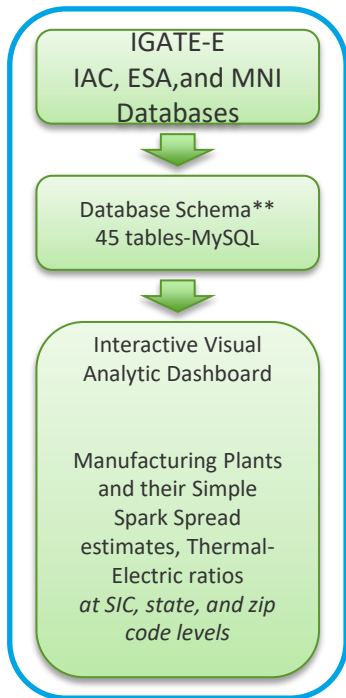


Supporting Slides

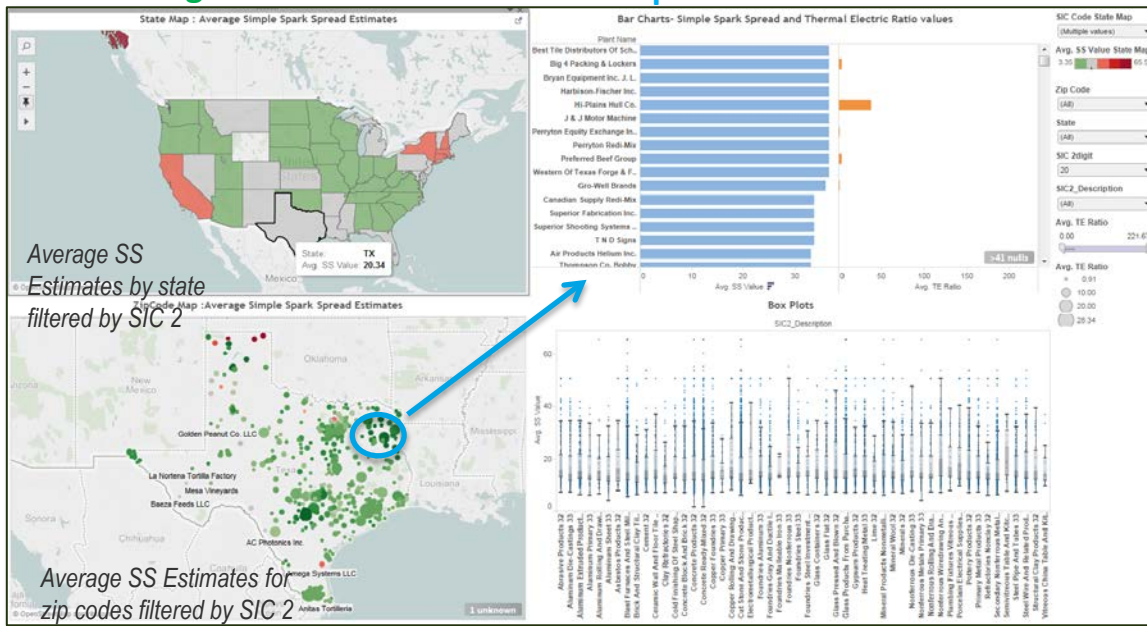
Performance Requirements

Market	Requirements to participate
Energy	Provide energy to the grid based on day-ahead unit commitment per economic dispatch signals
Generating Capacity	Generate on-demand at any time during the year
Frequency Control	Follow Automatic Generation Control Signal (4 second frequency) – Load-frequency control rate sufficient
Spinning Reserves	Ability to respond within 10 minutes to address contingency events
Non-Spinning Reserves	Ability to respond within w0 minutes to address contingency and flexibility events

IGATE-E: National, Web-based CHP Potential Analysis



State or Regional-level Overview Plant Specific TE* ratios and SS* estimates



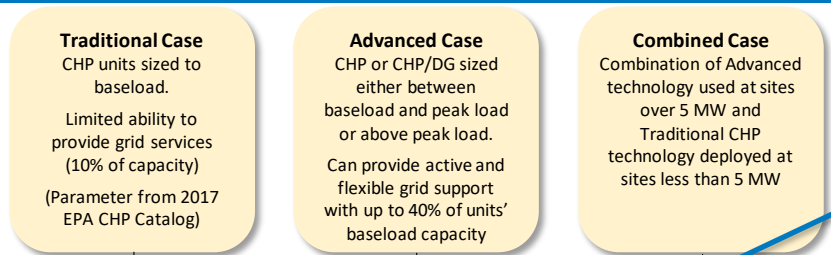
State, County, and Zip Code-level Filter/Zoom Capability

TE and SS Box Plots & Outliers by Industry Sub-sector

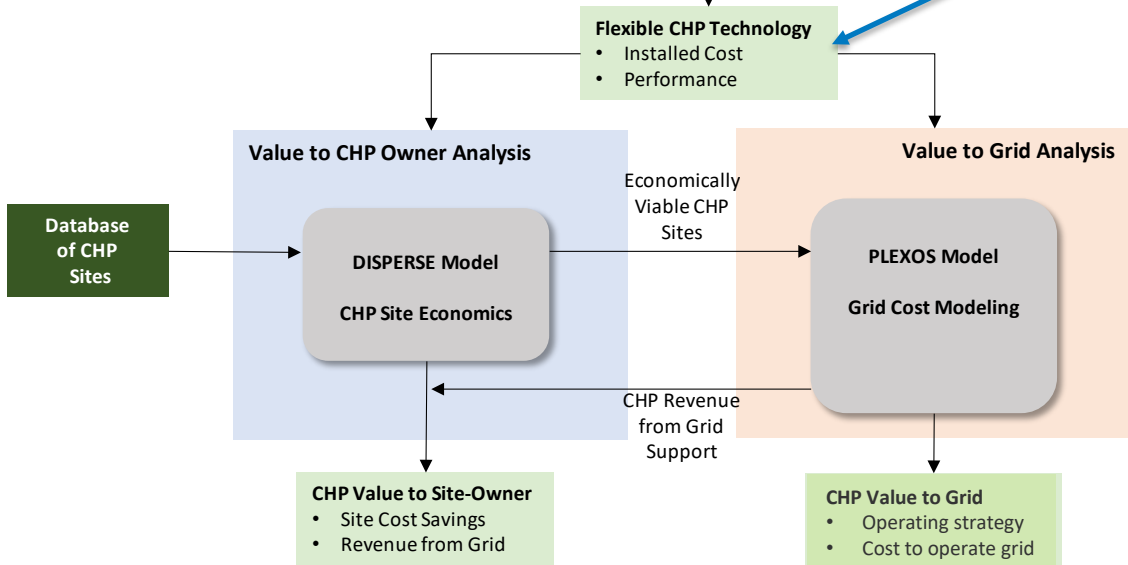
*TE – Thermal to Electric ratio and SS – Simple spark spread, as defined in the CHP Resource Guide by Midwest CHP TAP.

**A database schema of a database system is its structure described in a formal language supported by the database management system (DBMS) and refers to the organization of data as a blueprint of how a database is constructed (Source – Wiki).

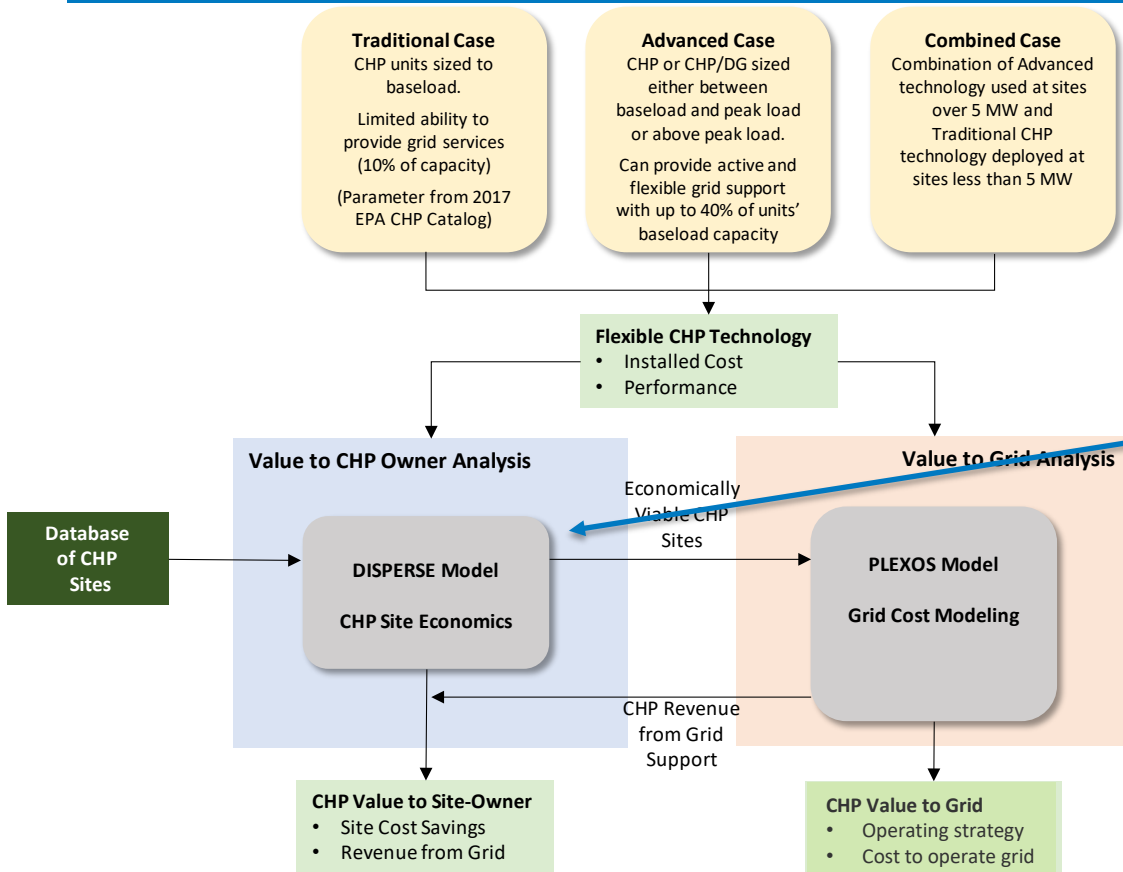
Analysis Methodology



1. Estimate potential improvements to CHP technologies,

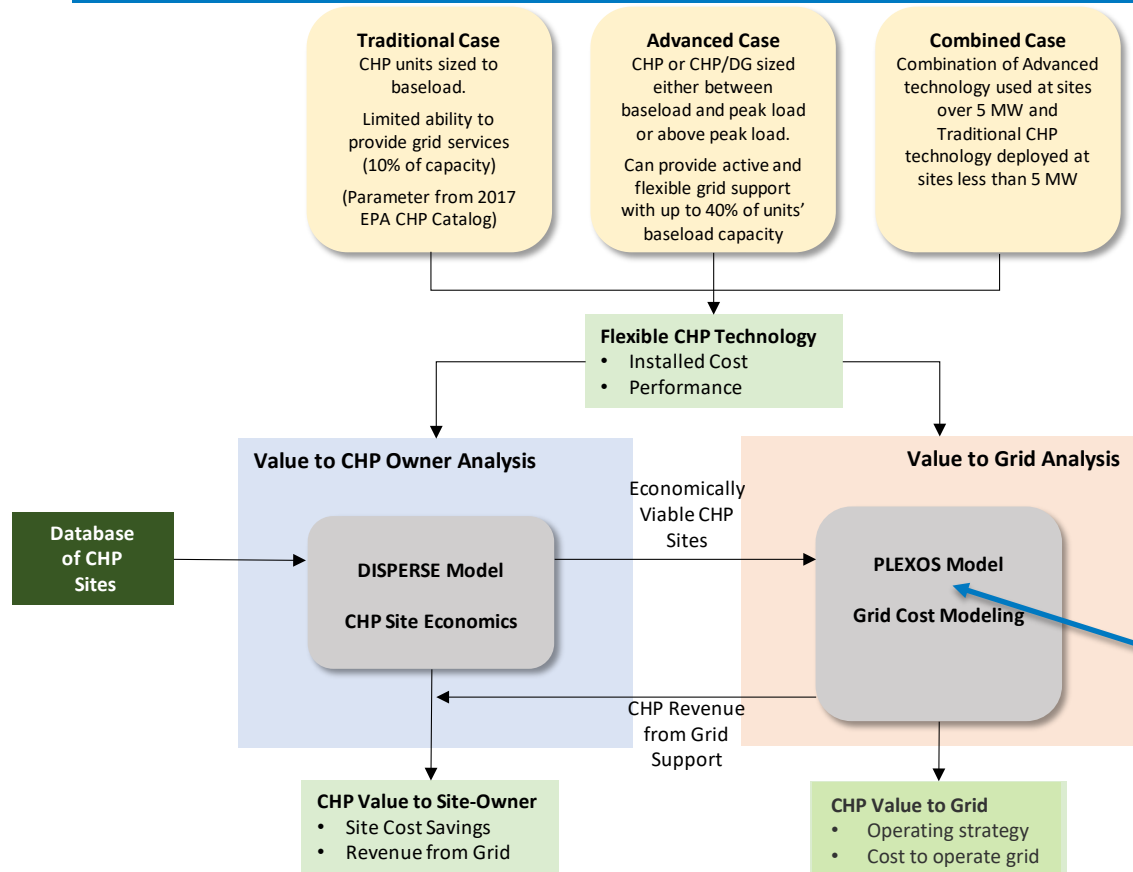


Analysis Methodology



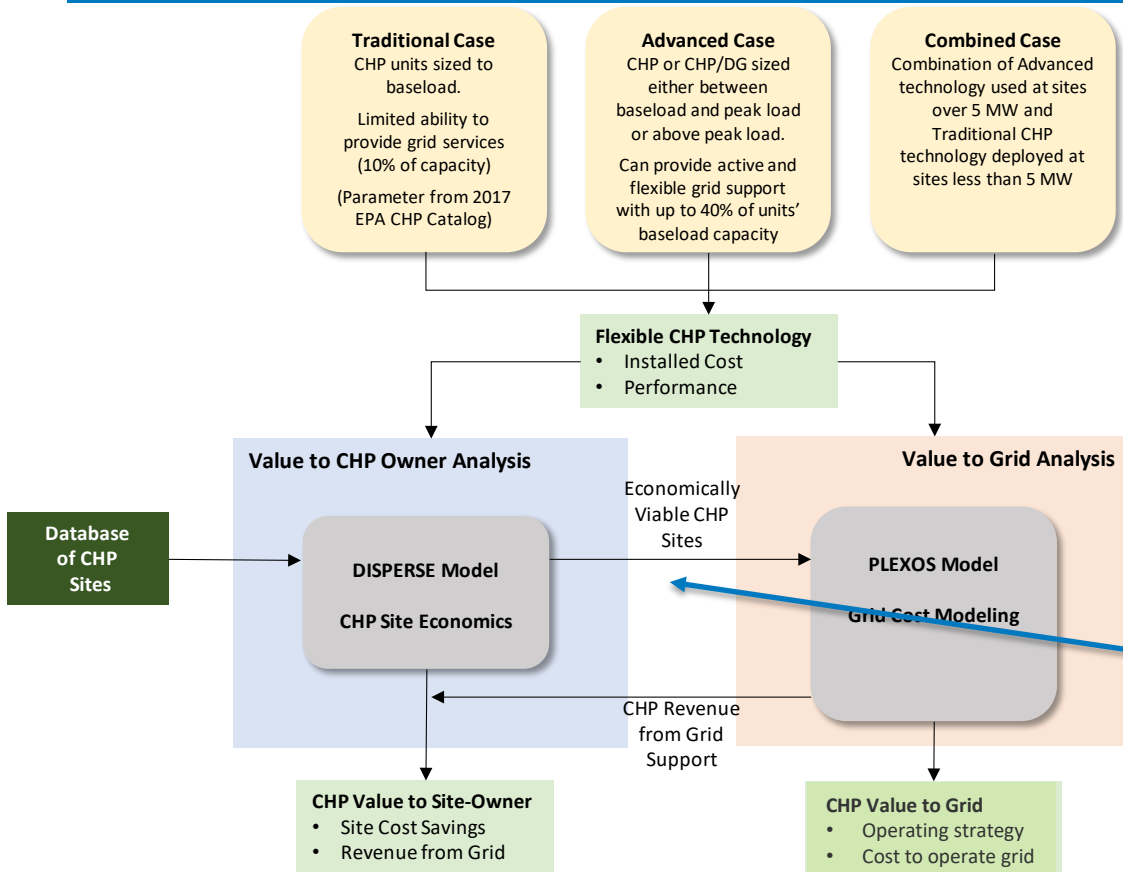
1. Estimate potential improvements to CHP technologies,
2. Identify locations where those technologies reduce owner costs,

Analysis Methodology



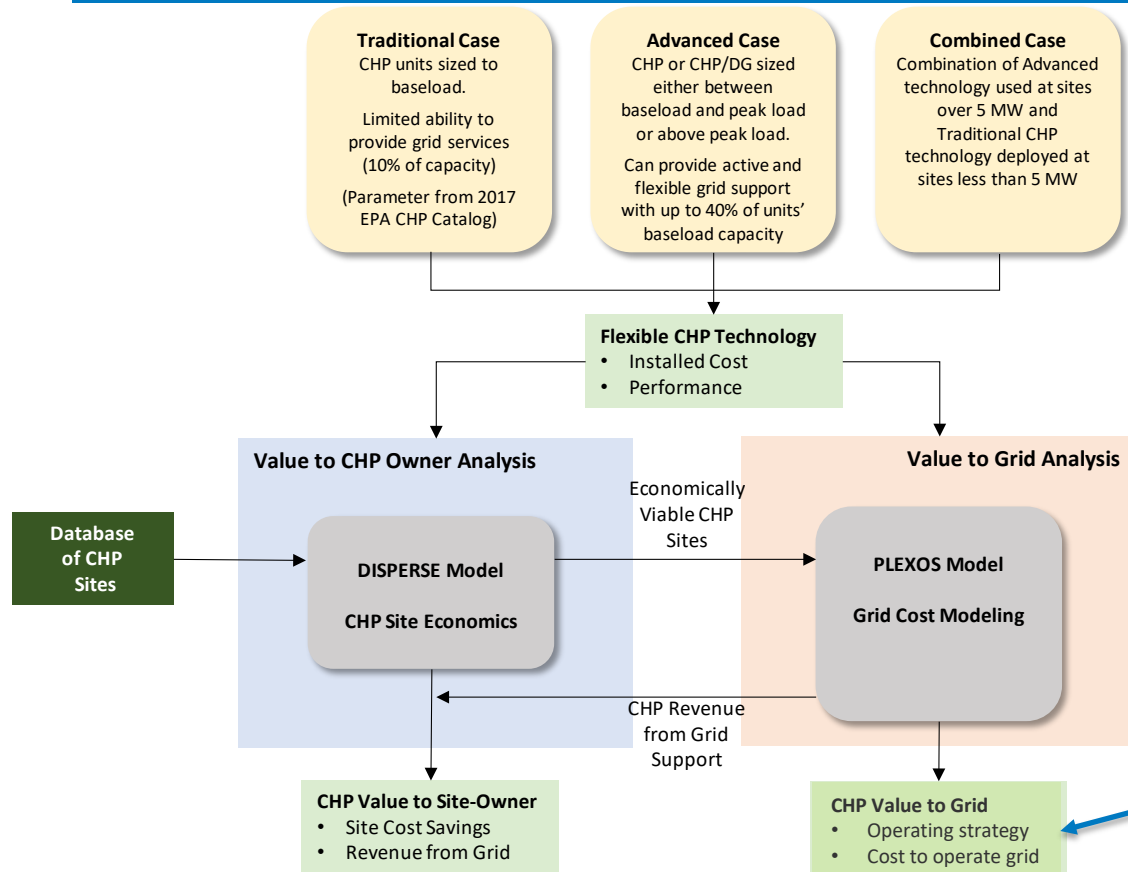
1. Estimate potential improvements to CHP technologies,
2. Identify locations where those technologies reduce owner costs,
3. Run electricity system production cost model without adding the technologies,

Analysis Methodology



1. Estimate potential improvements to CHP technologies,
2. Identify locations where those technologies reduce owner costs,
3. Run electricity system production cost model without adding the technologies,
4. Add the technologies to production cost model and run it again,

Analysis Methodology



1. Estimate potential improvements to CHP technologies,
2. Identify locations where those technologies reduce owner costs,
3. Run electricity system production cost model without adding the technologies,
4. Add the technologies to production cost model and run it again,
5. Compare results

Energy and Ancillary Service Revenues to CHP Owner

Case	Revenue (\$ thousands)			Hours operating at surplus	Surplus capacity (MW)	Revenue (\$ thousands per MW surplus)
	Energy	Ancillary Service	Total			
Traditional	\$1,182	\$12,820	\$14,002	3,418	358	\$39
Advanced	\$759,303	\$13,212	\$772,515	45,696	1,324	\$583
Combined	\$763,828	\$16,934	\$780,762	45,180	1,000	\$781

Advanced CHP technology can increase the revenue to site owners by \$760M. Focusing that advanced technology increases benefits.

Traditional CHP Cost and Performance Details

Size Range	0.1-0.8 MW	0.8-2.0 MW	2-5 MW			5-10 MW		10-20 MW		20+ MW	
Technology	Recip + Inverter	Recip + Inverter	Recip + Inverter	Recip	CT	Recip	CT	Recip	CT	Recip	CT
Operation of CHP Unit											
Installed Cost (\$/kW) of CHP Unit	\$3,075	\$2,566	\$2,274	\$1,949	\$3,051	\$1,548	\$2,184	\$1,436	\$1,597	\$1,324	\$1,382
Nominal Electric Power (kW)	633	1,141	3,325	3,325	4,600	9,341	7,965	18,682	21,745	28,023	43,069
Net Electric Power (kW)	633	1,141	3,325	3,325	4,324	9,341	7,487	18,682	20,440	28,023	40,485
Thermal Output (MBTU/kWh)	4.5	3.9	3.2	3.2	5.5	2.8	4.6	2.8	3.6	2.8	3.1
Heat Rate (BTU/kWh HHV)	9,890	9,074	8,342	8,342	13,648	8,342	11,685	8,207	10,308	8,207	9,611
Net Heat Rate (BTU/kWh HHV)	5,403	5,166	5,127	5,127	8,170	5,495	7,127	5,359	6,749	5,359	6,505
Variable O&M (cents/kWh)	2.5	2.3	1.9	1.9	1.4	1.6	1.3	1.0	1.0	1.0	1.0
Variable O&M (\$/MWh)	25.0	22.6	19.1	19.1	14.1	16.0	13.0	9.7	9.7	9.7	9.7
Incremental Installed Cost (\$/kW) for Overload Capacity	\$0	\$0	NA	\$0	NA	\$0	NA	\$0	NA	\$0	NA
Total Capacity (kW)	696	1,255	NA	3,658	NA	10,275	NA	20,550	NA	30,825	NA
Overload Capacity (kW)	63	114	NA	333	NA	934	NA	1,868	NA	2,802	NA
Net Heat Rate (BTU/kWh HHV) of Overload Capacity	6,815	6,087	NA	6,072	NA	6,039	NA	6,039	NA	6,039	NA
Operating Limitation (Hrs/yr)	500	500	NA	500	NA	500	NA	500	NA	500	NA

Notes: Based on DOE Tech Characterizations, costs escalated to 2024. Some improvements to part load efficiency of advanced recip units assumed.

Variable cost based on \$8.1/MMBTU forecasted natural gas price to industrial users

Steam generation for STIGCHP at \$45/kW (Jacobs Consultancy, Control Technologies Review, Cogeneration Units, Prepared For Clean Air Strategic Alliance, February 2010)

Advanced CHP Cost and Performance Details

Size Range	0.1-0.8 MW	0.8-2.0 MW	2-5 MW			5-10 MW				10-20 MW				20+ MW				
Technology	Recip + Inverter	Recip + Inverter	Recip + Inverter	Recip @ 60%	CT with STIG	Recip @ 60%	Recip	CT with STIG	CT with STIG	CT with STIG	Recip @ 75%	Recip	CT with STIG	CT with STIG	Recip @ 75%	Recip	CT with STIG	CT with STIG
Operation of CHP Unit																		
Installed Cost (\$/kW) without Surplus Capability	\$3,075	\$2,566	\$1,949	\$2,566	\$3,051	\$1,548	\$1,548	\$2,184	\$2,229	\$1,453	\$1,548	\$1,642	\$1,597	\$1,358	\$1,548	\$1,427	\$1,382	
Installed Cost (\$/kW) of CHP Unit with Surplus Capability	\$3,400	\$2,891	\$2,274	\$3,304	\$3,288	\$2,625	NA	\$2,421	\$2,466	\$1,938	NA	\$1,879	\$1,834	\$1,811	NA	\$1,663	\$1,618	
Nominal Electric Power (kW)	633	1,141	3,325	1,611	4,600	5,511	9,341	7,965	7,965	14,012	18,682	21,745	21,745	21,017	28,023	43,069	43,069	
Net Electric Power (kW)	633	1,141	3,325	1,611	4,324	5,511	9,341	7,487	7,487	14,012	18,682	20,440	20,440	21,017	28,023	40,485	40,485	
Thermal Output (MBTU/kWh)	4.5	3.9	3.2	3.9	5.5	3.3	2.8	4.6	4.6	3.1	2.8	3.6	3.6	3.1	2.8	3.1	3.1	
Heat Rate (BTU/kWh HHV)	9,890	9,074	8,342	9,712	13,648	8,861	8,143	11,685	11,685	8,617	8,143	10,308	10,308	8,617	8,143	9,611	9,611	
Net Heat Rate (BTU/kWh HHV)	5,403	5,166	5,127	5,778	8,170	5,592	5,296	7,127	7,127	5,494	5,296	6,749	6,749	5,494	5,296	6,505	6,505	
Variable O&M (cents/kWh)	2.5	2.3	1.9	1.7	1.4	1.0	1.0	1.3	1.3	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	
Operation at Surplus Capacity																		
Incremental Installed Cost (\$/kW) for Surplus Capacity	\$1,200	\$1,200	\$1,200	\$1,061	\$390	\$1,453	NA	\$390	\$435	\$1,168	NA	\$618	\$573	\$1,073	NA	\$618	\$573	
Total Capacity (kW)	791	1,426	4,156	2,731	7,117	9,341	NA	12,323	12,323	18,682	NA	29,429	29,429	28,023	NA	58,290	58,290	
Surplus Capacity (kW)	158	285	831	1,120	2,793	3,830	NA	4,358	4,836	4,671	NA	8,989	7,684	7,006	NA	15,221	15,221	
Net Heat Rate (BTU/kWh HHV)	6,661	6,897	6,540	4,986	4,045	4,800	NA	3,463	7,383	4,820	NA	7,921	3,138	4,820	NA	7,874	3,699	
Operating Limitation (Hrs/yr)	500	500	500	6,000	500	6,000	NA	500	500	6,000	NA	500	500	6,000	NA	500	500	

Notes: Based on DOE Tech Characterizations, costs escalated to 2024. Some improvements to part load efficiency of advanced recip units assumed.

Variable cost based on \$8.1/MMBTU forecasted natural gas price to industrial users

Steam generation for STIGCHP at \$45/kWh (Jacobs Consultancy, Control Technologies Review, Cogeneration Units, Prepared For Clean Air Strategic Alliance, February 2010)

Ways Flexible CHP can Support the Grid

Goal	How Flexible CHP Supports the Goal
Grid Reliability	Installations can improve power quality, provide ancillary services, and relieve grid congestion
Customer Resilience	Systems can allow critical loads to continue operation during grid outages and provide dispatchable power for microgrids
Energy Efficiency	Uses less fuel and is more efficient, which saves energy compared to conventional, separate electricity generation and heat production
DER Integration	Can help utilities integrate new renewable distributed energy resource (DER) deployments and balance variable loads
Locational Value	Can be deployed at strategic locations on the system where it is needed most thus relieving grid congestion
Affordability	Can often meet system needs more cost effectively than investments in traditional assets, thus lowering costs for ratepayers across the utility system
Emissions Reductions	Efficient CHP systems have lower emissions than conventional grid resources, and can be used to meet emissions reduction targets (ex: states w/ GHG goals)

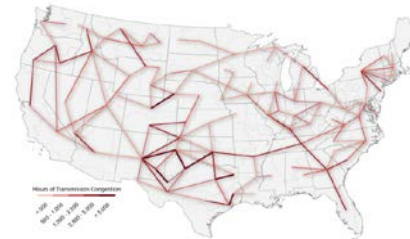
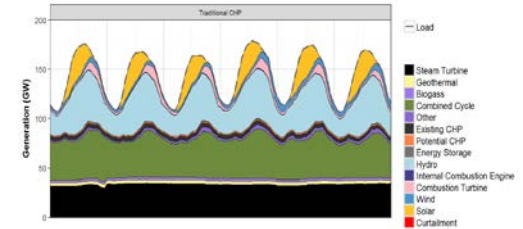
PLEXOS production cost model

- Simulate operation of electric power system
- Hourly or sub-hourly chronological
- Commits and dispatches generating units based on:
 - Electricity demand
 - Operating parameters of generators
 - Transmission grid parameters
- Used for system generation and transmission planning
 - Increasingly used for real-time operation



Locational prices,
production cost

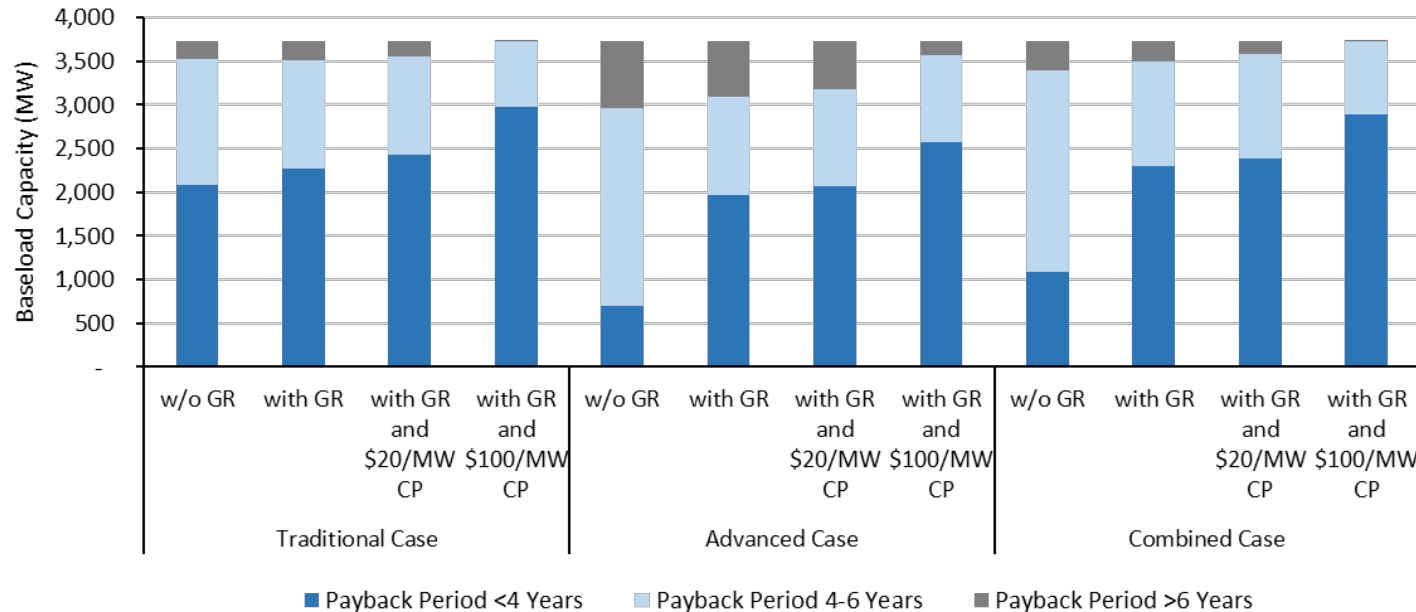
Dispatch
information,
fuel usage



Transmission
congestion

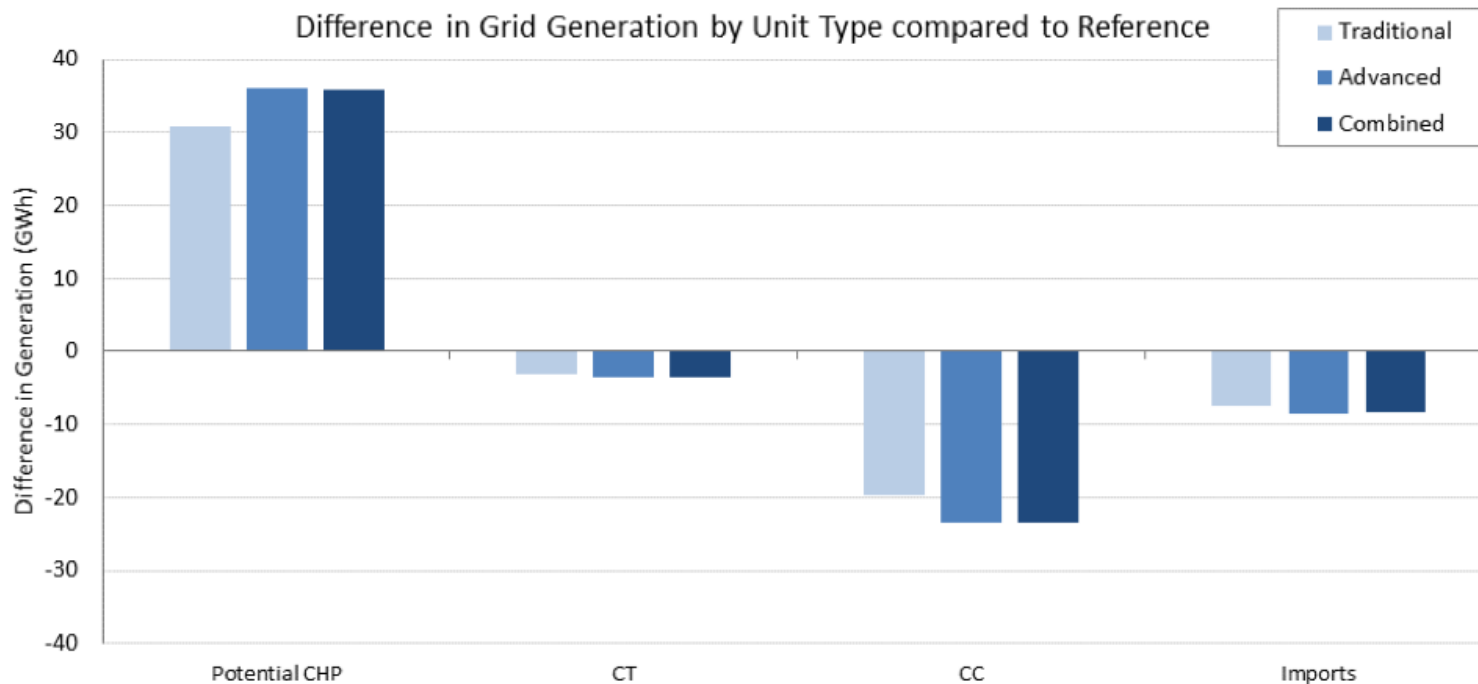
Impact of Grid Revenue on Population of CHP Owners

Payback Period of Baseload Capacity (3,722 MW) grouped by Modeling Case and Revenue Streams



If both grid services and capacity payments are available, payback periods are <6 years at almost all primary sites

Impacts on Grid Operation Profiles



Advanced CHP in California offsets combined cycle units, combustion turbines, and imports