Evaluating the Greenhouse Gas Performance of Combined Heat and Power Systems: A Summary for Californian Policymakers

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Abstract: *Combined Heat and Power (CHP) is the sequential production of electricity and thermal energy from the same fuel source. Historically, CHP has been perceived as an efficient technology and is promoted in California as a preferred electric generation resource. However, as California continues towards an ever-cleaner energy future, there is a need to revisit and understand under which circumstances CHP will actually reduce greenhouse gas (GHG) emissions. Conventional fossil-fueled CHP reduces GHG emissions if the CHP facility produces fewer emissions than the separate heat and power (SHP) sources (e.g., steam produced using a boiler and power purchased from the electric grid) to produce and deliver an equivalent amount of electricity and heat. If deployed and operated in an inefficient way, conventional CHP, unlike renewable generation, has the potential to increase GHG emissions. Moreover, as more renewable power is added to the grid, GHG benefits from fossil-fuel CHP systems are expected to decline.*

We analyze the GHG emissions reduction potential of example conventional CHP systems over a variety of CHP system technologies (micro-turbine, gas turbine, fuel cell, and reciprocating engines) and sizes incorporating representative design efficiencies. We construct two simple scenarios to capture optimistic and pessimistic system operation parameters such as hours of operation, heat rate degradation over time and total thermal utilization. We also assess a range of possible SHP sources benchmark emissions (e.g. avoided grid and avoided boiler emissions) to measure the effectiveness of CHP systems in reducing GHG emissions relative to SHP. The results of our analysis are designed to inform energy regulators and stakeholders regarding the sensitivities around GHG emissions reduction potential of CHP systems in California.

1. Introduction

CHP systems generate electricity and useful thermal energy sequentially from the same fuel source.[2] In contrast, SHP systems generate electricity and thermal energy separately (see Figure 1). Historically, CHP has been perceived as an efficient technology and is promoted as a preferred electrical generation resource by California energy policies.[3] Currently there are about 8,000 Megawatts (MW) of installed CHP capacity in California, mainly spurred by California's

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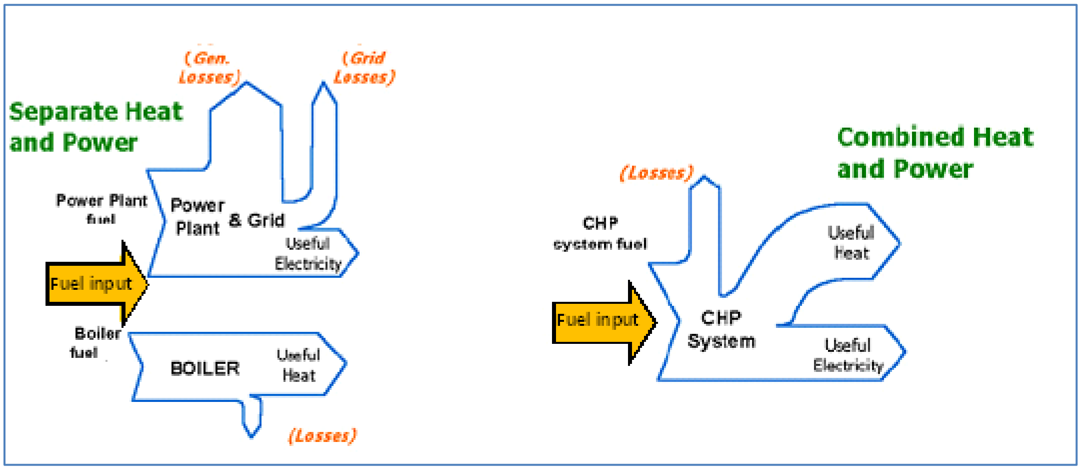
[2] CHP is also known as 'Cogeneration'

[3] The 2003 Energy Action Plan, adopted by California's energy agencies, established a "loading order" of preferred energy resources, placing energy efficiency as the state's top priority procurement resource, followed by renewable energy and distributed generation. Distributed generation may include CHP. For more information see: California Energy Commission, 2005, *Implementing California's Loading Order for Electricity Resources*

implementation of the Public Utilities Regulatory Policy Act (PURPA) of 1978.[4] These CHP units range in size from a few kW (e.g., units used in small commercial applications) to over 100 MW (e.g., units at refineries and in enhanced oil recovery fields). About 85% of the installed CHP facilities in the state are natural gas-fired topping-cycle units, also known as conventional CHP.[5] A small number of CHP units are renewable fuel-fired (e.g, wood or biomass fueled) or are bottoming-cycle (waste heat) units.[6] The current level of installed CHP capacity places California second nationally.[7]

Figure 1: Combined Heat and Power Systems vs. Separate Heat and Power Systems



Source: Figure adapted from American Council for an Energy Efficiency Economy *CHP Fact Sheet*

A number of existing California policies and programs support CHP installation and operation and there appears to be political desire for programs offering further support. Governor Brown's 2011 Clean Energy Jobs Plan calls for 6,500 MW of new CHP capacity by 2030.[8] In August 2012, President Obama issued an Executive Order setting forth a national goal of deploying 40,000 MW of new, cost effective CHP in the United States by the end of 2020 (in addition to the 80,000 MW of CHP capacity currently installed in the U.S.), and laying out a roadmap for the federal government to encourage states to meet the goal through state policies and technical

[4] Combined Heat and Power Installation Database: http://www.eea-inc.com/chpdata/. Supported by U.S. Department of Energy, Oak Ridge National Lab and maintained by ICF International.

[5] *Topping-cycle CHP* generates electric power first and uses excess heat for a productive purpose. The vast majority of the total installed capacity in the state is natural gas-fired topping cycle units. See: California Energy Commission, 2012, *Combined Heat and Power: 2011-2030 Market Assessment Report*, p. 35-36

[6] *Bottoming-cycle CHP* generates process heat first, typically for an industrial application, and subsequently captures excess heat to generate power. This configuration is also known as *waste heat CHP*, as waste heat from industrial process is used as input to generate power.

[7] Texas has the highest level of installed capacity with 17,319 MW, while New York is third with 5,559 MW. See: Combined Heat and Power Installation Database: http://www.eea-inc.com/chpdata/

[8] See: http://gov.ca.gov/docs/Clean_Energy_Plan.pdf

assistance programs.[9]

Environmental concern—and specifically the goal of greenhouse gas (GHG) emissions reductions—is a key driver behind political support for CHP. In the 2008 AB 32 Scoping Plan, the California Air Resources Board (ARB) adopted a statewide goal of 4,000 MW of new efficient CHP by 2020 as a compliance strategy to reduce GHG emissions under the California Global Warming Solutions Act of 2006 (Assembly Bill 32, or AB 32). The ARB estimated that this CHP measure would reduce 6.7 million metric tons (MMT) of carbon dioxide equivalents (CO_2e) in 2020.[10] A subsequent analysis by ICF International for the California Energy Commission (CEC) predicts the expected GHG savings from CHP in 2020 to be considerably lower, particularly when considering the interaction effects with the Renewable Portfolio Standards (RPS).[11] The CEC study found that the GHG savings from CHP are smaller than the ARB Scoping Plan estimate, even in the cases where CHP MW market penetration exceeds the ARB goal of 4,000 MW of additional CHP by 2020 (see Table 1).[12] Thus, CHP's place in the broader framework of California's energy policies, and whether CHP will help achieve California's long term energy and environmental goals, is worthy of additional study.

Table 1: Estimates of New CHP Contribution to 2020 GHG Goals

Study Name	**2020 New CHP Estimate (MW)**	**2020 GHG Reduction Estimate (MMT)**	
2008 ARB Scoping Plan	4,000	6.7	
2012 ICF for CEC		No RPS Interaction	With RPS Interaction
Base Case	1,499	1.8	0.5
High Case	4,865	5.5	2.0

Sources: California Air Resources Board, 2008, *Climate Change Scoping Plan, A Framework for Change*
California Energy Commission, 2012, *Combined Heat and Power: 2011-2030 Market Assessment Report*

As California continues towards an ever-cleaner energy supply, there is a need to place greater attention on the ability of CHP units to reduce GHG emissions relative to separate heat and power. If deployed and operated in an inefficient way, conventional fossil fueled CHP generating facilities, unlike renewable generation or bottoming cycle CHP, has the potential to increase GHG emissions.[13] The high-level policy directives creating MW targets for new CHP discussed above appear to promote all CHP configurations equally and do not differentiate conventional

[9] Office of the Press Secretary, White House Executive Order, August 30, 2012, *Accelerating Investment in Industrial Energy Efficiency*

[10] California Air Resources Board, 2008 *Climate Change Scoping Plan, A Framework for Change*, p. 44

[11] Installations of CHP units that reduce utility load reduce the amount of renewable resources that the utility must procure under the RPS. See a detailed description of this interaction below in section 4.3.3

[12] California Energy Commission, 2012, *Combined Heat and Power: 2011-2030 Market Assessment Report*, p. 11

[13] Bottoming cycle CHP is a form of waste heat recovery where electricity is a by-product of the industrial process. Therefore, bottoming cycle CHP with no supplement firing is considered to be a GHG-free electricity generation technology.

fossil-fueled CHP from renewable-fueled or bottoming cycle CHP.[14] The underlying assumption is that most, if not all, conventional CHP systems reduce GHG emissions compared to separate heat and power. This paper explores that assumption and finds that this may not be true as California continues to move toward a clean energy future.

This paper evaluates the GHG reduction potential of conventional CHP over a variety of example CHP system technologies (micro-turbine, gas turbine, fuel cell, and reciprocating engine) incorporating representative design and operating efficiencies. A framework of GHG analysis is proposed and a range of possible benchmark emissions of SHP (e.g. avoided grid and boiler emissions) are considered to measure the effectiveness of conventional CHP systems in reducing GHG emissions. The results of the analysis are designed to inform California's energy regulators and stakeholders addressing GHG emissions reduction from conventional CHP systems.

2. Background on Existing Policy Support for CHP in California

The majority of the existing CHP facilities in the state were developed and installed in response to the California Public Utilities Commission (CPUC)'s active implementation of PURPA from 1980 through the late 1990's (see Figure 2). Under PURPA CHP generators are entitled to sell power to utilities at the utility's avoided cost if the generator meets certain fuel efficiency criteria. Generators selling power under PURPA are referred to as "Qualifying Facilities" or "QFs."

To support the development of QFs, the CPUC required each of the major electric utilities to make available a series of "standard offer" (SO) power purchase agreements (PPAs) that were binding on the utility once signed by an eligible QF. That is, the PURPA program enabled CHP generators to "put" energy and capacity products priced at administratively-determined prices to the utilities regardless of need. The last legacy PURPA facility came on-line around the mid-1990s.[15] Payments under the 20-30 year PURPA SO PPAs were based on escalating prices that were forecast during the energy crisis of the 1980's and were often higher than market prices.[16] After the fixed price period, and especially as SO PPA expiration dates neared, disputes arose between the QFs, Investor Owned Utilities (IOUs) and ratepayer advocates involving SO contract terms, energy pricing, capacity payments, contract extensions, and the availability of new contracts. These disputes led to a 2007 CPUC decision adopting a new standard offer PPA and new avoided cost pricing terms for QFs.[17] However, many parties challenged the 2007 decision. As an alternative to litigation, the parties reached a settlement agreement, which the

[14] For example, the calculations underlying the ARB Scoping Plan estimates are based on the adoption (and expected GHG performance) of conventional CHP units.

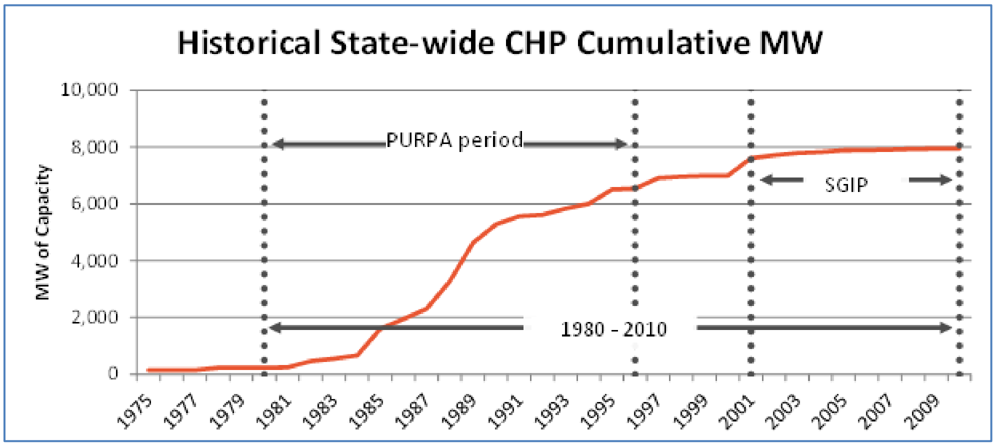
[15] We use the term "Legacy PURPA Facility" to refer to QFs financed using a PURPA SO PPA.

[16] Edison Electric Institute, 2006, *PURPA Making the Sequel Better than the Original*

[17] CPUC Decision 07-09-040

CPUC approved in D.10-12-035, and which became effective November 23, 2011. Currently, IOUs in California have about 130 legacy PPAs with PURPA CHP QFs. These 130 PPAs represent about 4,500 MW of nameplate capacity.[18]

Figure 2: Historical Cumulative California-wide CHP Capacity Over Time



Source: ICF International CHP database supported by US DOE http://www.eea-inc.com/chpdata/index.html

After the primary PURPA period, a number of small behind-the-meter CHP facilities were built in California, primarily incented by the CPUC's Self-Generation Incentive Program (SGIP). [19] The SGIP is the longest running incentive program supporting distributed generation technologies in the country and has undergone many changes since its inception in 2001. It initially provided incentives for renewable as well as for non-renewable distributed generation technologies (including CHP). Incentives were provided on an installed MW basis as an initial lump sum. The overall performance of the CHP projects installed during the initial period were found to have underperformed on several fronts such as system efficiency, annual utilization factors and GHG reductions.[20] In 2008, eligibility for SGIP incentives was limited to qualifying wind and fuel cell technologies pursuant to California Assembly Bill 2778 (2006). During this period, the SGIP excluded incentives for fossil-fueled CHP technologies. Subsequently, incentives for fossil-fuel consuming CHP technologies were conditionally brought into SGIP by CPUC Decision 11-09-015, pursuant to Senate Bill 412 (2009). The current structure of SGIP includes a performance-based incentive feature with payments keyed to successful continuation

[18] See: IOUs Semi-Annual QF Reports
PG&E Jan 2013 http://www.pge.com/includes/docs/pdfs/b2b/qualifyingfacilities/cogeneration/2013jan.pdf
SDG&E Jan 2013 http://www2.sdge.com/srac/Cogen_SPP_Final.htm
SCE July 2012 https://www.sce.com/wps/wcm/connect/4e63e04e-fe80-4ae2-babe-534fa99b463b/QFSemiAnnualReport.pdf?MOD=AJPERES&CACHEID=4e63e04e-fe80-4ae2-babe-534fa99b463b

[19] CPUC Self Generation Incentives Program (SGIP) See: http://www.cpuc.ca.gov/PUC/energy/DistGen/sgip/

[20] CPUC, 2011, *Self-Generation Incentive Program Tenth-Year Impact Evaluation,* p. 2-3

of electricity production and GHG performance.[21] Each proposed CHP facility is now evaluated on a project-specific basis to ensure that it reduces GHG.[22]

California Assembly Bill 1613 ("AB 1613") of 2007 also supports development of new CHP systems with generating capacity of not more than 20 MW.[23] New and repowered exporting CHP, that meet efficiency requirements issued by CEC, are eligible to receive a feed-in tariff (FIT). All IOUs are required to purchase excess power from eligible AB 1613 CHP facilities.[24]

Latest in the list of California CHP programs is the Qualifying Facility and Combined Heat and Power Settlement Agreement (QF/CHP Settlement) approved by the CPUC Decision 10-12-035 mentioned above.[25] This program became effective in November 2011 and created new CHP MW and GHG procurement targets for California IOUs. It resolved numerous outstanding QF issues and created *pro forma* PPAs to assist existing QF/CHP facilities in transitioning from legacy PURPA SO PPAs to the PPAs under the new program.

These CHP programs—designed, implemented, and revised separately over the past few decades—have varied efficiency or performance standards (see Table 2). These standards are not consistent in measuring the effectiveness with which conventional CHP systems reduce GHG emissions relative to SHP. In addition, continuous improvement in the efficiency of SHP resources and use of low carbon fuels (such as renewables) reduces the potential for conventional CHP to reduce GHG emissions and is not necessarily captured in the efficiency standards of existing programs.[26] Related policies, such as California's Emission Performance Standard (EPS), also could be improved with respect to representing the GHG impacts of CHP.[27]

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[21] CPUC June 2012, *Self-Generation Incentives Program Handbook*

[22] Each SGIP CHP applicant fills in a waste heat emissions worksheet with expected monthly electricity and thermal output information. Performance and system efficiencies of the operating facilities are monitored, on a monthly basis, by remote meter reading and data processing by Performance Data Providers (PDP). See: CPUC June 2012, *Self-Generation Incentives Program Handbook*

[23] AB 1613 (the Waste Heat and Carbon Emissions Reduction Act of 2007) implementation is shared between the California Energy Commission and the California Public Utilities Commission. See program efficiency requirements available on CEC website: http://www.energy.ca.gov/wasteheat/.

[24] CPUC, 2009, Decision 09-12-042 http://docs.cpuc.ca.gov/word_pdf/FINAL_DECISION/111494.pdf

[25] CPUC, 2011, Qualifying Facility and Combined Heat and Power Settlement Decision 10-12-035 http://www.cpuc.ca.gov/PUC/energy/CHP/settlement.htm

[26] Improvements in combined cycle technology continue to drive down the heat rates of new gas facilities and thus driving down grid emissions in California. See: California Energy Commission, 2011, *Thermal Efficiency of Gas Fired Generation in California.*

[27] The EPS prohibits acquisition of high emissions baseload electricity in California. See: 2006 Senate Bill 1368, Emission Performance Standards http://www.energy.ca.gov/emission_standards/

Table 2: CHP Programs and Applicable Efficiency or Performance Standards

Program or Standard	Efficiency or Performance Standard
PURPA QF[28]	42.5% minimum total system efficiency (LHV) $$Total\ System\ Efficiency_{PURPA} = \frac{Electricity\ Output + (0.5\ \times Useful\ Thermal\ Output)}{Fuel\ Energy\ Input}$$
AB 1613[29]	62% minimum total system efficiency (HHV) $$Total\ System\ Efficiency_{AB\ 1613} = \frac{Electricity\ Output + Useful\ Thermal\ Output}{Fuel\ Energy\ Input}$$
SGIP[30]	Performance Based Incentive - GHG performance Benchmark • Avoided Boiler Efficiency – 80% • Avoided Grid Emissions – 0.379 tonnes CO_2e/MWh
QF/CHP Settlement[31]	Double Benchmark • Avoided Boiler Efficiency – 80% • Reference natural gas-fired unit heat rate – 8,300 Btu/kWh (HHV)
Emissions Performance Standard (EPS)[32]	Prohibits load-serving entities in California from entering into a long-term financial commitments with units that cannot meet a GHG emissions performance standard of 1,110 lbs CO_2/MWh.

Note: HHV – Higher Heating Value of the Fuel; LHV – Lower Heating Value of the Fuel. Typically for natural gas HHV = 1.11* LHV

3. Framework for GHG Analysis of a CHP Unit

Conceptually, CHP reduces GHG emissions if the CHP facility produces fewer emissions than SHP sources (e.g., steam produced using a boiler and power purchased from the electric grid) to produce and deliver an equivalent amount of electricity and heat. The QF/CHP Settlement refers to this comparison to separate heat and power production as a "double benchmark" because the performance of the CHP is compared (benchmarked) against both a reference natural gas-fired boiler and a reference marginal electric grid emissions rate.

This concept can be mathematically formulated as follows:

[28] Code of Federal Regulations §292.205

[29] *Guidelines for Certification of Combined Heat and Power Systems Pursuant to the Waste Heat and Carbon Emissions Reduction Act.* California Energy Commission. 2010. See: http://www.energy.ca.gov/2009publications/CEC-200-2009-016/CEC-200-2009-016-CMF-REV2.PDF

[30] CPUC D-11-09-015

[31] CPUC D-10-12-035

[32] According to page 16 of CPUC D.07-01-039, the emissions rate for CHP for comparison to the EPS is "calculated by dividing the total GHG emissions from a cogeneration facility by the sum of its kilowatt-hour (kWh) output plus the usable thermal energy output (expressed in kWh) produced by the facility. For this calculation, the thermal energy output is converted from British thermal unit (Btu) into a kWh equivalent using the standard engineering conversion factor of 3,413 Btu per kWh."

CHP Direct Emissions

$$GHG_{CHP} = F_{MMBtu} * G_{CHP,tonnes\ CO2e/MMBtu}$$

$$\eta_{CHP-E} = \frac{\text{Electricity Output}}{\text{Fuel Input}} = \frac{P_{MWh}}{F_{MMBtu}} * 3.413$$

$$\eta_{CHP-H} = \frac{\text{Useful Thermal Output}}{\text{Fuel Input}} = \frac{H_{MMBtu}}{F_{MMBtu}}$$

Where,

GHG_{CHP} = Direct GHG emissions of a CHP unit

F_{MMBtu} = Amount of fuel used (in HHV) in the CHP unit

$G_{CHP,\ tonnes\ CO2e/MMBtu}$
= GHG emissions rate of the fuel input used in the CHP unit

η_{CHP-E} = CHP unit Electrical Efficiency

η_{CHP-H} = CHP unit Thermal Efficiency

P_{MWh} = Electricity produced (both used onsite and exported)

H_{MMBtu} = Useful thermal output produced

SHP Double Benchmark Emissions

$$GHG_{DB} = GHG_{Heat} + GHG_{Elec}$$

$$GHG_{Heat} = \frac{H_{MMBtu}}{\eta_B} * G_{B,\ tonnes\ CO2e/MMBtu}$$

$$GHG_{Elec} = P_{MWh} * G_{Grid,tonnes\ CO2e/MWh}$$

Where,

GHG_{DB} = GHG emissions of the seperate production of heat and power

GHG_{Heat} = GHG Emissions of the seperate production of heat (boiler)

GHG_{Elec} = GHG Emissions of the grid supplied electricity

η_B = Efficiency of the separate heat production source (boiler)

$G_{B,\ tonnes\ CO2e/MMBtu}$
= GHG emissions rate of the fuel in the seperate heat production source

$G_{Grid,\ tonnes\ CO2e/MWh}$ = Avoided grid emissions rate

A CHP units is net GHG reducing if

$$\mathbf{GHG_{CHP} < GHG_{Heat} + GHG_{Elec}}$$

Or,

$$\mathbf{F_{MMBtu} * G_{CHP,\ tonnes\ CO2e/MMBtu} < \frac{H_{MMBtu}}{\eta_B} * G_{B,\ tonnes\ CO2e/MMBtu} + P_{MWh} * G_{Grid,\ tonnes\ CO2e/MWh}}$$

As can be seen in the formula above, the level of GHG savings is closely related to the efficiency of the avoided boiler and avoided emissions of the grid. Figure 3 shows a graphical representation of this concept. As an example, we present the QF/CHP Settlement double benchmark standard: the reference natural gas-fired boiler is 80% efficient and a reference marginal emissions rate is 0.440 tonnes CO2e/MWh.[33]

Figure 3: Graphical Representation of a Double Benchmark Standard

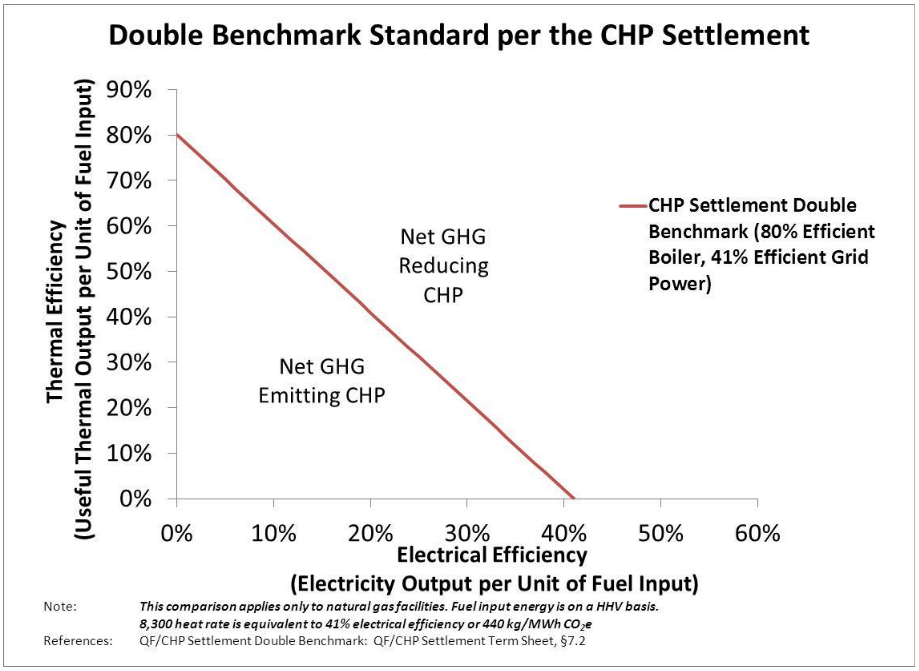


Figure 4 converts the performance standards of the existing CHP programs listed in Table 2 to a common pictorial representation. A tabular summary of the same information is shown in Table 3. Note that the EPS and AB 1613 standards have different slope of the benchmark line than the other programs. This is because EPS and AB 1613 standards treat the thermal output and electrical output from a CHP unit on an equivalent basis. We believe this equivalent treatment is inadvisable as electrical energy is a thermodynamically more ordered form of energy than thermal energy.[34] The other programs standards (PURPA, SGIP, CHP Settlement) differentiate between electricity and useful thermal output and the benchmark efficiency standards are set accordingly. It is also noteworthy that the SGIP standard is more stringent than the CHP Settlement and PURPA standards. SGIP provides incentives for small CHP units (generally less than 3 MW) whereas PURPA and the CHP Settlement primarily provide support for larger CHP systems (e.g., up to few 100 MW). This odd result—performance standards that are more lenient

[33] The QF/CHP Settlement electricity benchmark is 8,300 Btu/kWh HHV at the busbar and excluding line losses (equivalent to 0.440 tonnes CO2e/MWh emissions rate or 41% efficiency). The thermal benchmark is an 80% efficient boiler. See: CPUC, QF/CHP Settlement, Term Sheet Section 7.2. http://docs.cpuc.ca.gov/PUBLISHED/GRAPHICS/124875.PDF

[34] Physically it is impossible to convert 3.413 MMBtu of heat into 1 MWh of electrical energy. However, it is possible to convert 1 MWh of electrical energy to 3.413 MMBtu of heat.

for programs supporting larger CHP systems and more stringent for programs supporting smaller CHP—appears to have resulted from independent program design rather than intentional choice on the part of policymakers.

Figure 4: Graphical representation of CHP Performance Standards Across Programs

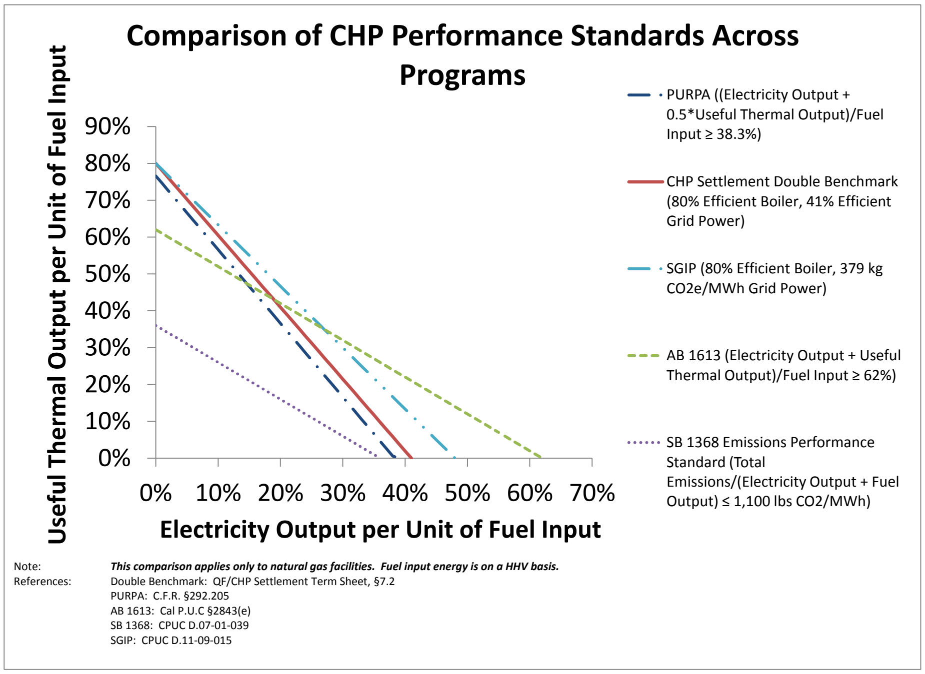


Table 3: Comparison of CHP Performance Standards Across Programs - Reference Electrical Unit and Reference Boiler Efficiency (derived from program standards listed in Table 2)

	Reference Electrical Generating Unit				Reference Boiler		
	Heat Rate (MMBtu /MWh)	**Equivalent Electrical Efficiency (%)**	**Tonnes CO_2e/ MWh**	**lbs CO_2e/ MWh**	**Boiler Efficiency (%)**	**Tonnes CO2e/ MMBtu Steam**	**lbs CO2e/ MMBtu Steam**
QF/CHP Settlement Benchmark	8.300	41.12%	0.4405	971	80.00%	0.0663	146
PURPA Efficiency Threshold	8.914	38.29%	0.4730	1,043	76.60%	0.0693	153
AB 1613	5.505	62.00%	0.2921	644	62.00%	0.0856	189
SGIP	7.142	47.79%	0.3790	836	80.00%	0.0663	146
Emissions Performance Standard	9.402	36.30%	0.4990	1,100	36.00%	0.1474	325
Assumes all fuel is natural gas. Values reflect the higher heating value of the fuel. Physical Constants: 0.05307 Tonnes CO_2e/MMBtu Nat Gas, 3.413 MMBtu/MWh, 2,205 lbs/Tonne.							

4. Methodology and Data

This section compares a variety of example conventional CHP system technologies' GHG performance relative to a range of possible SHP Double Benchmark standards. The key inputs to the analysis are: example CHP technology design efficiencies, operational efficiency (which is assumed to be lower relative to design efficiency), avoided grid emissions and avoided boiler efficiency.

4.1 Conventional CHP Design Profiles

The main types of technologies available for CHP set-ups are: gas turbines, reciprocating or internal combustion engines, fuel cells, and micro-turbines. The Environmental Protection Agency's (EPA) *Catalog of CHP Technologies* report provides an estimate of cost and design performance of a variety of CHP systems.[35] This report is based on surveys and input from CHP system manufacturers and vendors. The California Energy Commission funds studies which estimate statewide CHP potential in California. These CEC studies rely on the EPA's catalogue when making assumptions about how to model CHP systems performance.[36]

We analyze examples of representative CHP technologies as shown in the Table 4. The CHP systems design parameters are based on the 2012 CEC CHP report as derived from the EPA catalog.[37] The CEC report expects some improvements in CHP system design efficiencies over the time frame of 2010 to 2030, and has accordingly represented the CHP systems efficiencies in the intervals of five years. For this analysis, as an example of representative system design performance we have considered 2016-2020 performance characteristics for all technology types.

Although CHP technologies differ in their configurations and operations, two key design factors are common to all CHP technologies:

4.1.1 *Fuel required to generate electricity (or Electrical Efficiency)*: commonly expressed as a heat rate in Btu/kWh by vendors. To express the electrical efficiency as a percentage, the equivalent Btu content of a kWh of electricity (which is 3,412 Btu) is divided by the heat rate.

$$\text{Electrical Efficiency (\%)} = \frac{3{,}412}{\text{Heat Rate}} = \frac{Electric\ Output\ Energy}{Fuel\ Input\ Energy}$$

[35] US Environment Protection Agency, 2008, Combined Heat and Power Partnership *Catalog of CHP Technologies*

[36] These CEC studies occasionally adjust design parameters for some technologies based on the California market manufacturers and developers feedback; however the details of such adjustments are not listed in the report. See: California Energy Commission, 2009, *Combined Heat and Power Market Assessment* and California Energy Commission, 2012, *Combined Heat and Power: 2011-2030 Market Assessment*

[37] California Energy Commission, 2012, *Combined Heat and Power: 2011-2030 Market Assessment Report*, p. 91-99

4.1.2 *Thermal Efficiency:* Useful thermal energy produced per unit of electricity output is expressed as Btu/kWh by vendors. To express the thermal efficiency as a percentage, the thermal output (Btu/kWh) is divided by the heat rate (Btu/kWh).

$$\text{Thermal Efficiency (\%)} = \frac{Thermal\ Output_{Btu/kWh}}{\text{Heat Rate}_{Btu/kWh}}$$

$$Overall\ System\ Effciency\ (\%) = Electrical\ Efficiency\ (\%) + Thermal\ Efficiency\ (\%)$$

Table 4: Design Electrical and Thermal Efficiencies of the representative CHP technologies

Technology Type	Size (kW)	Heat Rate* (Btu/kWh)	Thermal Output (Btu/kWh)	Electrical Efficiency (%)	Thermal Efficiency (%)	Overall System Efficiency (%)
Micro-turbine	65	13,286	5,297	26%	40%	66%
	185	11,663	4,062	29%	35%	64%
	925	11,663	4,062	29%	35%	64%
Fuel Cell	300	7,640	2,046	45%	27%	71%
	200/400	9,500	2,484	36%	26%	62%
	1200	7,640	2,023	45%	26%	71%
Reciprocating or IC Engine	100	11,488	6,091	30%	53%	83%
	800	9,750	4,300	35%	44%	79%
	3000	9,400	3,850	36%	41%	77%
	5000	8,325	2,950	41%	35%	76%
Gas Turbine	3000	13,414	5,664	25%	42%	68%
	10000	10,800	4,062	32%	38%	69%
	40000	8,990	3,109	38%	35%	73%

*Note: Heat Rates are expressed in HHV
Source: Derived from 2012 CEC CHP report (Table 39 - 42) [38]

4.2 Conventional CHP Operational Profiles

Real-world conventional CHP operational performance can vary significantly from the designed system performance. Evaluation reports on the Self-Generation Incentive Program found that the operational performance efficiency of small CHP installed under SGIP were well below the

[38] California Energy Commission, 2012, Combined Heat and Power: 2011-2030 Market Assessment Report, p. 91-99

level of performance expected based on manufacturer's specifications.[39] To our knowledge no analogous studies exist on the operational efficiency of large Californian CHP.[40] We believe this is an area where additional operating data is needed.

The actual amount of thermal energy that is used for some productive purpose, such as space or water heating, can be less than the design thermal output of the CHP system. CHP systems' actual thermal efficiency is defined as follows:

$$Operational\ (Actual)\ Thermal\ Efficiency = \frac{Thermal\ Output\ Energy\ Used\ Productively}{Fuel\ Input\ Energy}$$
$$= Design\ Thermal\ Effciency * Thermal\ Utilization\ Factor$$

To conceptually demonstrate performance degradation or deviations from design values, two scenarios ("optimistic" and "pessimistic") are considered here. The major drivers for the system's GHG performance are thermal utilization, heat rate degradation over time and capacity factor. The optimistic scenario assumes that the CHP systems are operated to maximize the number of operating hours in a year and thermal utilization. Also in the optimistic scenario, the CHP systems do not exhibit degradation in heat rates over time.[41] The pessimistic scenario considers that the CHP systems may be oversized relative to thermal load, may exhibit heat rate degradation, and may experience longer periods of shutdown due to operational problems. Table 5 lists adjustments to the CHP systems key performance drivers between the optimistic and pessimistic scenarios created based on a review of publicly available reports.

[39] CPUC, 2011- 2012, *Self-Generation Incentive Program Tenth – Year Impact Evaluation* and *Self-Generation Incentive Program Eleventh – Year Impact Evaluation Reports*

[40] Recall that large CHP in California was primarily incented by PURPA. Although continual reporting of efficiency is required under this program, this information is not publicly disclosed.

[41] Note that these are the assumptions that CEC 2012 CHP market assessment report uses.

Table 5: CHP operational parameters impacting the system's GHG performance

Driver	Optimistic Scenario	Pessimistic scenario
Thermal utilization	80% for CHP < 5MW, 90-100% for larger systems.[42]	64% for CHP < 5MW, 72-80% for larger systems[43]
Heat Rate Degradation	No degradation	1% annual heat rate degradation[44]
Capacity Factor	80%[45]	64%[46]

4.3 Avoided Grid Emissions Factor

The SHP grid emissions factor plays a very important role in evaluating the GHG performance of a CHP unit. Typically, a unit of electricity generated by a distributed CHP generator is assumed to displace a unit of electricity generated from the resources serving the grid.[47] The CHP facility displaces (avoids) GHG emissions that would otherwise have been created by generating that power from the grid. Grid emissions factors vary from region to region as well as during the hours of the day and seasonally. In the following sections we explore a reasonable range of avoided grid emission factors.

4.3.1 United States Avoided Grid Emission Factor

Estimating the energy and emissions displaced by CHP requires an estimate of the nature of generation displaced by the CHP system. Accurate estimates can be made using a power system dispatch model to determine how emissions for generation in a specific region are impacted by the shift in the system demand curve and generation mix resulting from the addition of a new CHP system. However, these models can be complex, costly to run, and are often proprietary. In the absence of a publicly available widely accepted dispatch model, recorded historic emissions rates are used as proxy for avoided grid emissions.

[42] This value is based on the CEC 2012 CHP report. California Energy Commission, 2012, *Combined Heat and Power: 2011-2030 Market Assessment* Report, p. A3

[43] This value is 80% of the thermal utilization factor considered in the optimistic scenario, based on a rough estimate from the SGIP 11th year impact evaluation report. See Itron, Inc, 2012, *CPUC Self-Generation Incentive Program Eleventh-Year Impact Evaluation*, p.1-9. To compare with the CEC 2012 CHP report, compare the heat conversion efficiency with the available thermal energy and thermal utilization factors reported in the CEC 2012 CHP report.

[44] This value is based on Itron cost effectiveness report. Itron, Inc, 2011, *CPUC Self-Generation Incentive Program Cost-Effectiveness of Distributed Generation Technologies* Report, p.3-3

[45] California Energy Commission, 2012, *Combined Heat and Power: 2011-2030 Market Assessment* Report, p. A3

[46] This value is 80% of the capacity factor considered in the optimistic scenario, based on a rough estimate from the SGIP 11th year impact evaluation report. See: Itron, Inc, 2012, *CPUC Self-Generation Incentive Program Eleventh-Year Impact Evaluation* report, p. 4-17 to 4-18. To compare with the CEC 2012 CHP report, convert the capacity factor into hours of operation, or vice versa.

[47] The electricity displaced can be assumed to be that generated by resources "at the margin" (i.e., electricity generated in response to an additional unit of electricity demand). Inframarginal values can also be used if the CHP unit is assumed to displace a baseload resource rather than the marginal resource.

The US EPA CHP Emissions Calculator provides estimates of the avoided grid emissions based on the recorded GHG emissions in the eGRID database.[48] This CHP Calculator lists a number of avoided emissions factors representing historic emissions in NERC regions and sub-regions for three categories: "all generation", "all fossil average" and "non-baseload". This calculator recommends using the eGRID "all fossil average" emissions factor for estimating grid avoided emissions from a baseload CHP (capacity factors greater than 74%) and the "non-baseload" values for CHP with capacity factors less than 74%.[49] The coal component of these values in some US regions has a substantial impact on the emissions factor in these regions. Coal is less likely to run in a "non-baseload" fashion, so the "all fossil average" eGRID values tend to be higher emitting than the "non-baseload" values. The US EPA document, *Combined Heat and Power: A Clean Energy Solution*, takes the same eGRID data and calculates one nation-wide avoided grid emissions factor of 1,743 lbs CO_2e/MWh (using the "all fossil average" value) in their example calculation of CHP GHG reduction potential.[50] We include this value as one bound in our example in Section 5 below.[51]

4.3.2 California Avoided Grid Emission Factor

The issue of avoided GHG emissions has received significant attention in California. In California, new CHP is likely to displace grid emissions predominantly from combined cycle gas-fired generation. For example, ARB's 2008 estimate of avoided grid emissions factors is 0.432 tonnes CO2e/MWh (or 952 lbs CO_2e/MWh). [52] The ARB value is also based on recorded historic emissions. For comparison, the California "non-baseload" value in the eGRID database is 994 lbs CO_2e/MWh. Thus, the GHG emissions savings of an efficient CHP unit estimated based on these California's marginal emissions factor is considerably lower than a similar unit displacing the national "all fossil average" emissions factor.

In considering the long-term GHG impacts of new CHP it is also important to look beyond the current grid performance to improvements that might occur in the future. The CPUC GHG Calculator, developed by Energy and Environmental Economics, Inc. (E3), estimates the 2020 marginal grid emission factors for electricity based on the outputs a power sector dispatch model PLEXOS.[53] The model determines the marginal units and generator types, which are typically

[48] U.S. Environmental Protection Agency, 2012, *Fuel and Carbon Dioxide Emissions Savings Calculation Methodology for Combined Heat and Power Systems*

[49] U.S. Environmental Protection Agency, 2012, *Fuel and Carbon Dioxide Emissions Savings Calculation Methodology for Combined Heat and Power Systems*, p.25

[50] US Environmental Protection Agency, 2012, *Combined Heat and Power: A Clean Energy Solution*, p.8

[51] This can be thought of as an inframarginal (baseload) resource.

[52] California Air Resources Board, Cap and Trade Energy-Based Allocation factor – C.C.R Tittle 17 §95891(c). This can be thought of as an average of marginal resources.

[53] CPUC, 2010, *GHG Calculator* developed by E3 http://ethree.com/public_projects/cpuc2.php Used by CPUC and CEC to advise the California ARB on setting and implementing GHG standards for the electricity sector in the Joint Final Opinion on GHG Regulatory Strategies D.08-10-037

natural gas units. Table 6 shows 2020 marginal emissions factors and equivalent gas unit heat rates estimated for four TOU periods: summer high load hours, summer low load hours, winter high load hours, and winter low load hours, and the time weighted average of these factors.[54] We choose to employ the time weighted average avoided emissions value in developing our analysis in Section 5.

Table 6: California Avoided Grid Emissions Factors

Time period	Emissions factor (Tonnes CO2e/MWh)	Equivalent Gas Unit Heat Rate (Btu/kWh)
Summer High Load Hours	0.418	7,876
Summer Low Load Hours	0.382	7,198
Winter High Load Hours	0.400	7,537
Winter Low Load Hours	0.381	7,179
Time Weighted Average	0.400	7,537

Note: Summer is defined as May to September. Winter is the rest of the year. High Load Hours are defined as Monday through Saturday 7-22 hours (6x16). Low Load Hours (LLH) are the rest of the day.
Source: CPUC/E3 2008 GHG Calculator

4.3.3 Onsite Vs. Export: RPS Interaction and Accounting for Transmission and Distribution Losses

For CHP that displaces on-site electric load, there is a direct interaction effect with the Renewable Portfolio Standard (RPS) program.[55] Onsite CHP reduces utility demand for electricity and this, in turn, reduces the amount of renewable energy purchases needed for utilities to meet their percentage RPS targets. This interaction effect was explicitly recognized in setting the SGIP avoided emissions[56] cited in Table 2 and in the most recent CEC study to estimate CHP statewide potential.[57]

Another reason for potential disparate treatment of CHP serving on-site load vs. export CHP is transmission and distribution (T&D) losses. In theory, CHP units that serve on-site load avoid T&D losses that would occur in delivering power from the grid generating unit to serve the load. In practice, many CHP plants both export power and serve onsite load, so drawing a clear distinction between these two cases can be challenging. For example, the SGIP grid factor in Table 2 includes a T&D adjustment (which makes the benchmark standard less stringent) and a

[54] CPUC, 2010, *GHG Calculator : Greenhouse Gas Modeling of California's Electricity Sector to 2020: Updated Results of the GHG Calculator Version 3b update*

[55] RPS program requires investor-owned utilities, electric service providers, and community choice aggregators to increase procurement from eligible renewable energy resources to 33% of total procurement by 2020. Refer CPUC website for the RPS program details: http://www.cpuc.ca.gov/PUC/energy/Renewables/

[56] This RPS-interaction adjustment makes the SGIP standard more stringent. See: CPUC D.11-09-015

[57] California Energy Commission, 2012, *Combined Heat and Power: 2011-2030 Market Assessment* Report, p.8-9

RPS adjustment (which makes the benchmark standard more stringent). This is despite the fact that the SGIP program now allows projects to export up to 25% relative to the on-site consumption on an annual basis.[58]

4.3.4 Avoided Grid Emission Factors Range Used in this Analysis

We incorporate three of the avoided grid emissions factors discussed above for the CHP GHG performance analysis below:

Table 7: Representative National and Regional Avoided Grid Emissions Factors

Reference Avoided Grid Factors	lb CO_2e /MWh	Tonnes CO_2e /MWh	Heat Rate MMBtu /MWh	Equivalent Electrical Efficiency (%)	Source
2009 U.S. "all fossil average" avoided grid emissions	1,743	0.791	14.897	23%	EPA CHP Calculator
2020 California (CA) avoided marginal grid emissions	882	0.400	7.537	45%	CPUC GHG Calculator
2020 CA avoided marginal grid emissions adjusted for 33% RPS and 6.9% T&D losses[59]	628	0.285	5.371	64%	
Assumes all fuel is natural gas. Physical Constants: 0.05307 Tonnes CO2e/MMBtu Nat Gas, 3.413 MMBtu/MWh, 2,205 lbs/Tonne					

4.4 *Avoid Boiler Emissions*

Typical examples of heat demand at facilities considering CHP include steam for industrial process equipment, steam or hot air for space heating and/or appliance hot water. In the absence of CHP, these heat demands are met by onsite natural gas boilers, space heaters, and hot water heaters. Efficiencies of these devices may also improve over time. The ARB estimates an efficiency of a relatively efficient industrial boiler today to be 85%.[60] This ARB value is also consistent with the range presented in the CEC boiler survey installed between 1990 and 2012, with average boilers efficiency of 86% and some new boilers attaining design efficiencies of up to 95%.[61] The CEC appliances database for gas-fired water heaters shows the average efficiency of 83% and some new water heaters attaining design efficiencies up to 93-95 %.[62] The efficiency of the installed gas-fired space heaters is found to be lower than the industrial boilers and water heaters efficiencies in the CEC database. Average efficiency of space heater systems is 70%,

[58] See the 2012 SGIP Handbook: http://www.cpuc.ca.gov/NR/rdonlyres/A821B0B1-4D8B-44FB-A5C5-07F1BD6A53BE/0/SGIP_Handbook2012_v23.pdf

[59] California average system losses for transmission and distribution ranged from 5.4 percent to 6.9 percent during 2002 to 2008. See: California Energy Commission, 2011, *A Review of Transmission Losses in Planning Studies*

[60] Allowance Allocation Appendix J of the Cap and Trade staff report, page J-53
http://www.arb.ca.gov/regact/2010/capandtrade10/capv4appj.pdf

[61] CEC Appliances Database, Heating Products- Boilers: http://www.appliances.energy.ca.gov/

[62] CEC Appliances Database, Water Heater Products – Gas Water Heaters http://www.appliances.energy.ca.gov/

with newer systems attaining up to 80% design efficiency.[63] We incorporate two efficiency standards, 80% and 85%, for separate heat sources in the CHP GHG analysis below.

5. Results

5.1 *Range of Double Benchmark Standards*

The variability in the SHP avoided emissions (avoided grid emissions and avoided boiler emissions) presents a range of possible double benchmark standards. Figure 5 shows three such double benchmark standards. The same information is presented in a tabular format in Table 8.

Figure 5: Range of Representative Double Benchmark Standards

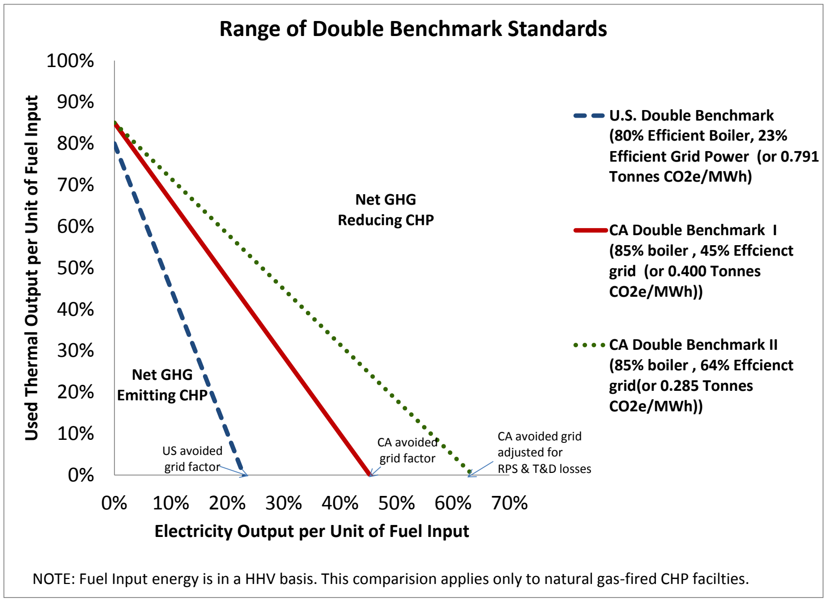


Table 8: Summary of Representative Double Benchmark Standards - Reference Electrical Unit and Reference Boiler Efficiency

Representative Double Benchmark Standards	Reference Electrical Generating Unit				Reference Boiler		
	lb CO2e /MWh	Tonnes MT /MWh	Heat Rate MMBtu /MWh	Equivalent Electrical Efficiency (%)	Boiler Efficiency (%)	MT/ MMBtu Steam	lbs CO2e / MMBtu Steam
2009 U.S. SHP Benchmark	1,743	0.791	14.897	23%	80%	0.066	146
2020 CA SHP Benchmark I	882	0.400	7.537	45%	85%	0.062	138
2020 CA SHP Benchmark II (adjusted for RPS interaction and T&D losses)	628	0.285	5.371	64%	85%	0.062	138
Assumes all fuel is natural gas. Physical Constants: 0.05307 Tonnes CO2e/MMBtu Nat Gas, 3.413 MMBtu/MWh, 2,205 lbs/Tonne							

[63] CEC Appliances Database, Heating Products , Gas Space Heaters http://www.appliances.energy.ca.gov/AdvancedSearch.aspx

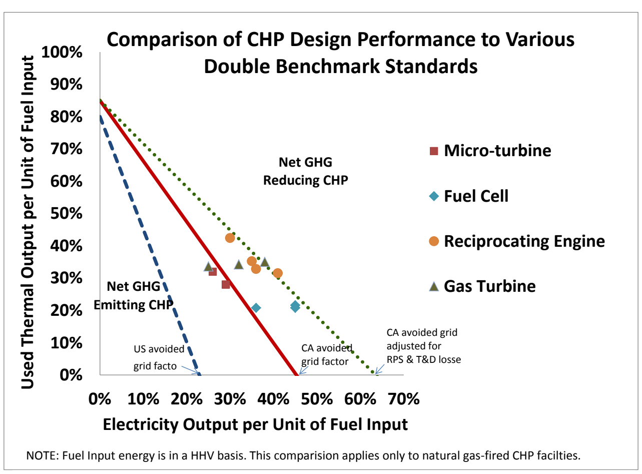
5.2 Comparison of Conventional CHP Systems Performance to Double Benchmark Standards

Figure 6 shows comparison of example CHP technologies performance relative to the three double benchmark standards. CHP technologies (i.e., micro-turbines, fuel cells, reciprocating engine and gas turbine) are represented by typical electrical and thermal efficiencies (as discussed in section 4.1). Two scenarios (optimistic and pessimistic) represent the deviation in design vs. operational performance of CHP systems (as discussed in section 4.2). A representative CHP system is net GHG reducing if its performance parameters (i.e. electrical and thermal efficiency coordinates) fall above the relative SHP double benchmark line. Otherwise the representative CHP system is net GHG emitting relative to SHP.

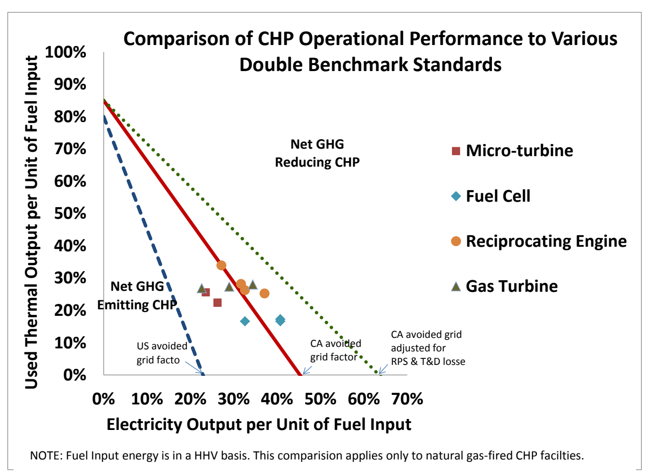
All of the example CHP units we examined are net GHG reducing when compared to the 2009 U.S. SHP Benchmark (considering 80% boiler efficiency and U.S. "all fossil average" avoided grid emissions) in both optimistic and pessimistic performance scenarios. However, relative to the 2020 CA SHP Benchmark I (85% boiler efficiency and CA avoided grid emissions) performance of the CHP technologies is mixed. The reciprocating engine and fuel cells are net GHG reducing. The micro-turbines are net GHG emitting (i.e. they are more emitting than the relative SHP). The performance of CHP systems degrades when considering pessimistic scenario performance assumptions such as less total thermal utilization and degradation in the system heat rate over time. Many of the net GHG reducing CHP units change to net GHG emitting sources (see Figure 6 (b)).

After adjusting for operational performance, all CHP systems are net GHG emitting relative to the 2020 CA SHP Benchmark II (85% boiler efficiency and CA avoided grid emissions adjusted for 33% RPS and 6.9% T&D losses).

Figure 6: Comparison of CHP Design and Operational Performance (Optimistic vs Pessimistic Scenario) to Representative Double Benchmark Standards



a). Comparison of CHP Technologies Design Efficiencies (Optimistic Scenario) to Double Benchmark Standards



b). Comparison of CHP Technologies Operational Efficiencies (Pessimistic Scenario) to Double Benchmark Standards

The results of GHG reduction potential of a CHP technology type can also be expressed in annual tonnes of CO_2e saved per MW of the CHP installed capacity. Expressing performance in this way accounts for temporal effects of performance such as reduced capacity factor. Table 9 and Table 10 list annual GHG reduction potential of CHP technologies for the design performance (optimistic) and operational performance (pessimistic) scenario. For example, a 10 MW gas turbine system reduces 3,270 tonnes CO_2e/MW (or 32,700 tonnes CO_2e annually) relative to the U.S. SHP Benchmark (80% boiler efficiency and U.S. avoided grid emissions) in the optimistic scenario. These GHG emissions savings estimates are comparable to the U.S. EPA *Combined Heat and Power: A Clean Energy Solutions* case study example for a 10 MW CHP technology system.[64] The same 10 MW gas turbine system reduces only 433 tonnes CO_2e/MW (or 4,330 tonnes CO_2e annually) relative to the CA SHP Benchmark I (85% boiler efficiency and CA avoided grid emissions). Thus, the GHG emissions savings of an efficient CHP system estimated based on California's SHP benchmark are considerably lower than a similar unit displacing the national SHP sources. The 10 MW gas turbine CHP system is net GHG emitting, with an emission factor of -372 tonnes CO_2e/MW (or emitting 3,720 tonnes CO_2e annually), relative to the CA SHP Benchmark II (85% avoided boiler efficiency and CA marginal emissions factor adjusted for RPS interaction and T&D losses).

Table 9: Annual GHG reduction potential of CHP Technology Types per MW of the Installed Capacity (optimistic performance scenario)

Technology Type	Size (kW)	Electrical Efficiency (%)	Actual Thermal Efficiency (%)	Tonnes CO2e/ MW relative to US SHP Benchmark *	Tonnes CO2e/ MW relative to CA SHP Benchmark I*	Tonnes CO2e/ MW relative to CA SHP Benchmark II*
Micro-turbine	65	26%	32%	2612	-240	-1045
	185	29%	28%	2696	-131	-937
	925	29%	28%	2696	-131	-937
Fuel Cell	300	45%	22%	3482	700	-106
	200/400	36%	21%	2932	141	-665
	1200	45%	21%	3454	673	-132
Reciprocating Engine	100	30%	42%	3553	683	-122
	800	35%	35%	3510	679	-126
	3000	36%	33%	3461	638	-167
	5000	41%	32%	3664	855	50
Gas Turbine	3000	25%	34%	2597	-266	-1072
	10000	32%	34%	3270	433	-372
	40000	38%	35%	3662	839	33

*Note: The negative sign indicates the CHP technology type is net GHG emitting.

[64] The US EPA study finds that GHG savings from a representative 10 MW CHP system is 42,751 tonnes CO2e annually. See: US EPA , 2012 *Combined Heat and Power: A Clean Energy Solutions* , p. 8

Table 10: Annual GHG reduction potential of CHP Technology Types per MW of the Installed Capacity (pessimistic performance scenario)

Technology Type	Size (kW)	Electrical Efficiency (%)	Actual Thermal Efficiency (%)	Tonnes CO2e/ MW relative to US SHP Benchmark*	Tonnes CO2e/ MW relative to CA SHP Benchmark I*	Tonnes CO2e/ MW relative to CA SHP Benchmark II*
Micro-turbine	65	24%	26%	1500	-771	-1416
	185	26%	22%	1648	-605	-1250
	925	26%	22%	1648	-605	-1250
Fuel Cell	300	41%	17%	2479	257	-387
	200/400	33%	17%	1965	-263	-907
	1200	41%	17%	2459	238	-406
Reciprocating Engine	100	27%	34%	2279	-4	-648
	800	32%	28%	2356	100	-544
	3000	33%	26%	2339	89	-555
	5000	37%	25%	2559	318	-326
Gas Turbine	3000	23%	27%	1454	-825	-1469
	10000	29%	27%	2127	-134	-778
	40000	34%	28%	2514	264	-381

*Note: The negative sign indicates the CHP technology type is net GHG emitting.

6. Discussion

This paper presents simple conceptual examples to demonstrate how to properly evaluate the GHG performance of conventional natural gas-fired CHP systems. The GHG performance of the CHP systems depends on the technology type and system performance as well as on the relative SHP source emissions. The Double Benchmark standards considered provide a range of avoided grid and boiler emissions at the national and at California's regional level in the near-term and long-term. Given these examples, we are concerned that conventional gas-fired CHP systems may have limited long-term GHG emissions reductions potential in California.[65] The California electric grid continues to get cleaner, making it harder for CHP to reduce emissions. Conventional CHP systems are likely to continue to be substantially more effective in reducing GHG emissions at the national level, particularly in the regions where coal generation is being displaced.

We also note that not all Combined Heat and Power (CHP) reduces greenhouse gas emissions; CHP systems can be net emitting if deployed and operated in an inefficient manner, particularly when natural gas is the avoided fuel on the relevant electric grid. Ideally, CHP systems are operated only when there is a thermal demand for the system's usable thermal output. In such instances, overall efficiency and GHG performance of the CHP system is optimized. Various operational factors can reduce thermal utilization, such as actual thermal load being lower than design thermal loads and/or unexpected shutdown of thermal equipment. CHP systems may also experience heat rate degradation over time. Improved monitoring and maintenance can reduce

[65] Other configurations of CHP such as renewable or bottoming cycle CHP may provide better GHG performance.

the rate of heat rate degradation and improve the overall utilization of the accompanying thermal systems.

Historically, policy support has played a key role in CHP development in California. This paper provides a comparison across the variety of standards that exist in California related to CHP GHG performance. We believes these standards should be updated to create better harmonization across programs and reflect improvements over time in the performance of the separate heat and power production systems that CHP must outperform in order to reduce GHG emissions.

Well-constructed policies which incentivize CHP facilities to perform as designed continue to be necessary for CHP to maintain a high level of operating efficiencies and reduce the maximum amount of GHG emissions. Programs to promote CHP due to GHG reduction benefits should include robust monitoring of CHP operational performance. Greater transparency should be provided about the GHG reduction performance of CHP in California operating under the existing incentive programs.

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