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Preliminary Estimates of Combined Heat and Power Greenhouse Gas Abatement Potential for California in 2020

Prepared for the
Energy Systems Integration Program
Public Interest Energy Research
California Energy Commission

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Acronyms and Abbreviations

BAU	business as usual
CARB	California Air Resources Board
CEC	California Energy Commission
CEUS	California Commercial End-use Survey
CHP	combined heat and power
CPUC	California Public Utilities Commission
EIA	United States Energy Information Administration
GHG	greenhouse gas
GWP	global warming potential
IPCC	Intergovernmental Panel on Climate Change
kt/a	thousand metric tons per year
Mt/a	million metric tons per year
PEM	proton exchange membrane
PIER	Public Interest Energy Research
PV	photovoltaic
RPS	renewable portfolio standard
$/t	dollars per metric ton

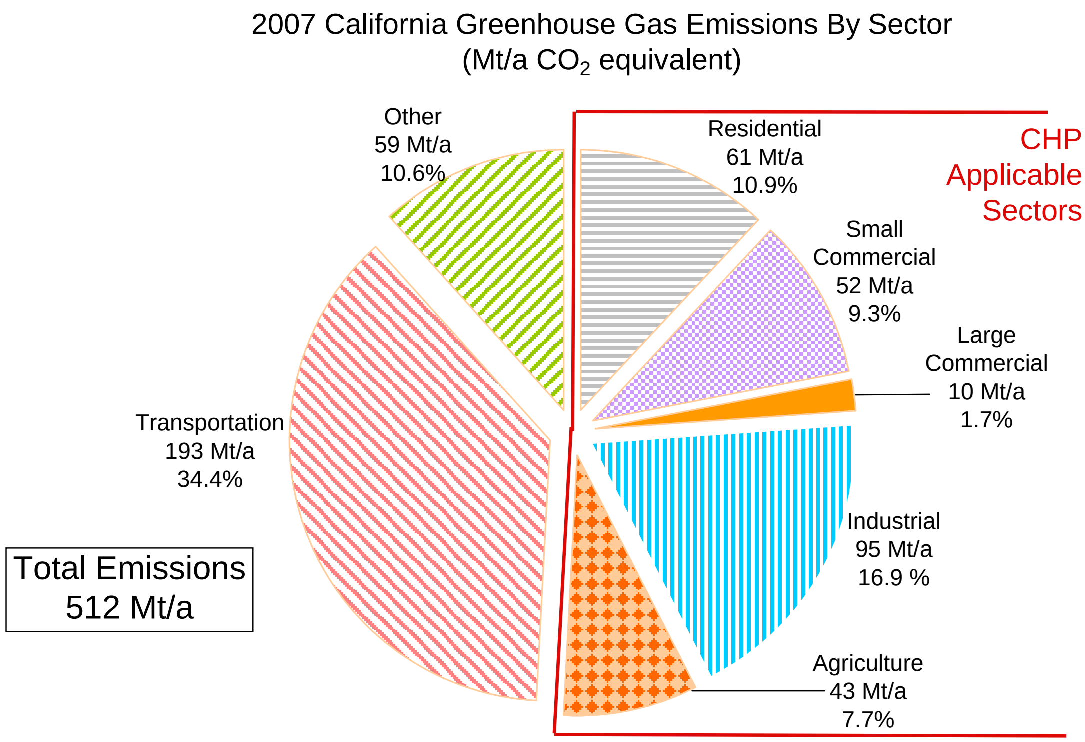
1. Problem Statement

The objective of this scoping project is to help the California Energy Commission's (CEC) Public Interest Energy Research (PIER) Program determine where it should make investments in research to support combined heat and power (CHP) deployment. Specifically, this project will:

- Determine what impact CHP might have in reducing greenhouse gas (GHG) emissions,
- Determine which CHP strategies might encourage the most attractive early adoption,
- Identify the regulatory and technological barriers to the most attractive CHP strategies, and
- Make recommendations to the PIER program as to research that is needed to support the most attractive CHP strategies.

This study derives a range of potential GHG emissions abatement estimates for the state of California in year 2020 achieved by wider deployment of CHP. Additionally, the study estimates the contribution CHP might make towards the State's AB-32 objective of reducing GHG emissions to 1990 levels by 2020. This work seeks to shed light on how much GHG emissions might be reduced at various levels of CHP penetration, and not to forecast the likely level under any particular economic or policy regime. Thus, the question being addressed is akin to "how much CO_2 abatement *could* be achieved in 2020 if a given percentage of car owners stop driving and take mass transit," rather than the question "how much CO_2 abatement *will* mass transit save the state in 2020?" Note that drivers are heterogeneous in driving patterns, vehicle preferences, etc., and so the ones that opt for mass transit may not represent the average or the biggest emitters. Also, mass transit may not always be a GHG improvement. One passenger on an otherwise empty bus is a bigger emitter than a car carrying only its driver. Likewise with CHP, systems are heterogeneous and not all will be an improvement over conventional energy supply. Any analysis of CHP's potential benefits must consider these issues, and while we do not intend to address such questions in this work, any policy intended to promote CHP should be crafted to avoid one-passenger-bus problems.

This analysis is done using a combination of findings from the literature and models of CHP penetration. This study required analysis of the large and diverse range of CHP opportunities across the entire economy. The ongoing efforts being made across the board to limit GHG emissions and the coexistence of many programs makes this study more complex. Particularly notable are efforts to lower the carbon intensity of the power generation sector, by various means, such as the renewable portfolio standard (RPS) established by SB-1078 and the AB-1368 purchase power emission standard. Such efforts have the effect of reducing the potency of any electricity consumption displacement, be it by CHP, energy efficiency, or any other means. Further, gauging the benefits of CHP proves particularly difficult. First, it is assumed here that CHP will rely on fossil fuel combustion, i.e. as a non-carbon-free alternative, however CHP cannot be assumed to be universally GHG preferable to grid power. Given that the grid's GHG footprint is expected to change significantly over the period under study here, a careful comparison between on-site emissions and grid emissions poses a tricky problem. Second, while CHP is well developed in California's industrial and food processing sector, its limited adoption in the buildings sector (residential and commercial) is in part due to our mild climate, which limits potential use of waste heat for space conditioning. In fact, the attractive uses for waste heat in many circumstances will be cooling or other non-traditional applications, leaving analysis of untapped CHP to rest on rather limited real-world experience. Third, the circumstances of CHP hosts are highly heterogeneous such that the GHG abatement performance of systems cannot be readily generalized, particularly after the most attractive sites have been exploited and deployment moves to less favorable locales. Consequently, global estimates of CHP potential rest on an array of possibilities quite heterogeneous in character. Fourth, as mentioned above, the type of CHP assumed here is fairly conservative, i.e. natural-gas-fired generation with heat recovery for direct application to known loads. However, the possibility of exploiting alternative fuels and possibly changing the nature of the loads, i.e. participation in demand response-type programs themselves could significantly alter the GHG abatement potential. For example, if a farm can only burn propane in a generator to provide electricity and use the waste heat for cleaning, the economics may not be appealing. However, if the farm could burn crop waste and use the waste heat for a lucrative additional business activity, then the picture might be radically altered. Likewise, aggregations of customer loads, possibly in the form of microgrids, are not considered.



Source: California Energy Commission

Figure 1. Estimated 2007 California GHG emissions (CO_2 equivalent) by sector

According to the California Energy Commission, under its business as usual (BAU) scenario, California will continue to increase GHG emissions from today's level of about 500 Mt/a of CO_2 equivalent[1] to about 600 Mt/a in 2020 (CEC 2006b). Further, the California Air Resources Board (CARB) estimates that a reduction of 174 Mt/a in emissions is needed by 2020 to return to 1990 levels (CARB 2007).

Figure 1 and Figure 2 show the 2007 and 2020 breakdowns of GHG emissions among seven main sectors. The total 2020 state-wide emissions in Figure 2, 560 Mt/a, are less than the CEC forecast of 600 Mt/a because Figure 2 assumes that the state's RPS target of 33% by 2020 is met, whereas the CEC estimate simply extrapolates historic data. Not surprisingly in California, transportation accounts for the greatest single source of emissions reduction opportunities. Most sectors of our economy are *reasonably* GHG efficient by U.S. standards, but our transportation sector clearly is not. Focus on

[1] This total includes CO_2, methane, nitrous oxide, and other high global warming potentials (GW gases (HFCs, PFCs, SF_6). Herein, the conversion for CO_2 is based on their global warming potentials (GWPs) as estimated in the Intergovernmental Panel on Climate Change's (IPCC) 2007 assessment (IPCC 2007).

transportation opportunities for GHG emissions reductions are, therefore, an obvious target; nonetheless, CHP GHG abatement potential exists in each of the sectors in the right-hand half of the pie in Figure 2. In other words, about half of all California's GHG emissions are amenable to amelioration by CHP application, so its potential is substantial and should have a central policymaking role

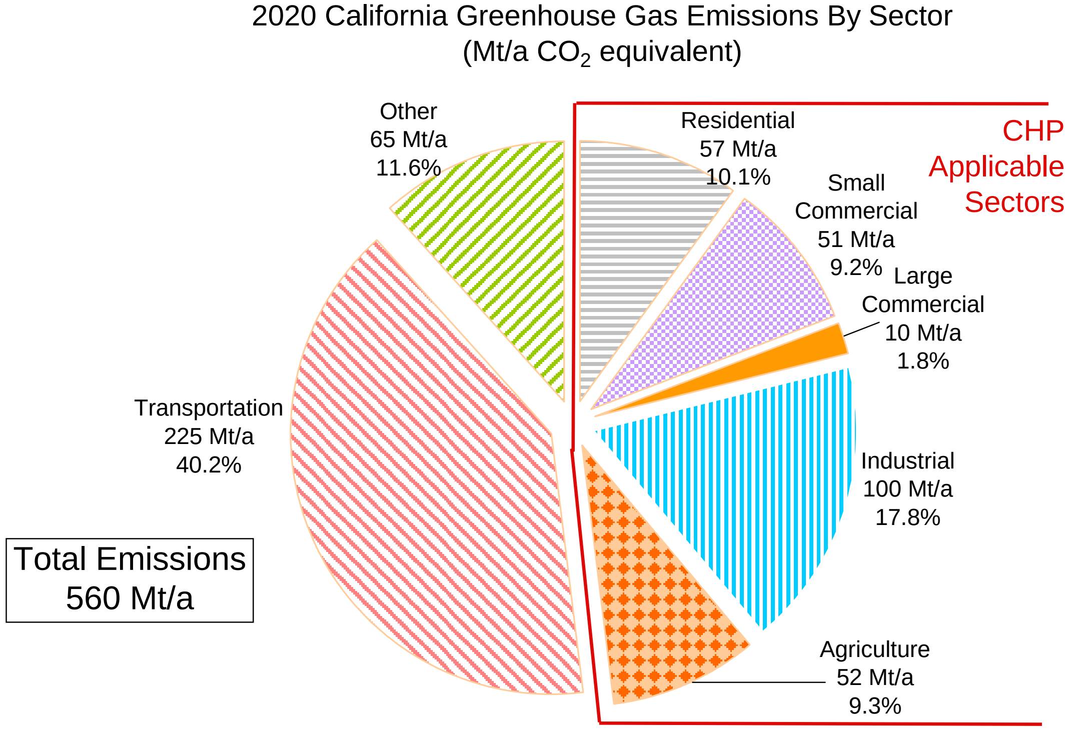


Figure 2. Forecasted 2020 California GHG emissions (CO_2 equivalent) by sector

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The emissions for the *residential*, *commercial*, and *industrial* sectors are estimated by the sum of the on-site combustion of natural gas and petroleum products as well as the remote power plant emissions associated with their electricity consumption. For the year 2020, the emissions that result from on-site combustion are a linear extrapolation from historical emissions rates between 1990 and 2004. *Agricultural* emissions include methane and nitrous oxide converted to CO_2 equivalents based on the 100-year global warming potential (GWP), as estimated in the Intergovernmental Panel on Climate Change's (IPCC) 2007 assessment (IPCC 2007). The *other* category includes non-agricultural emissions of non-CO_2 gases as well as high GWP gases (HFCs, PFCs, SF_6).

2. Results

This section presents results from the CHP GHG abatement analysis. Four CHP penetration scenarios with the two following electricity grid carbon-intensities are considered:

- **Standard efficiency grid power**: 50% of grid electricity comes from central station natural-gas-fired combined cycle generation, and the other half comes from natural-gas-fired single cycle plants.

- **High efficiency grid power**: 100% of grid electricity is from natural-gas-fired combined cycle plants.

This assumption represents the range from roughly the current mix of electric generation to the ideal situation where all central station plants were efficient combined cycle plants.

The four penetration scenarios are simply: **low**, **medium**, **high**, and **maximum**. The *maximum* scenario assumes 100% CHP penetration, and is presented as an upper bound. The level of penetration in all scenarios is expressed as a fraction of the total technical potential by sector, as explained in Section 3. For commercial and industrial sectors, technical potential refers to the peak electrical demand; at low penetration levels, installed systems would have high capacity factors and consistent uses for waste heat. However, at higher penetration levels, less ideal candidates for CHP begin adopting and so capacity factors and efficiencies decrease. This trend is captured in the analysis. The residential sector potential refers to meeting the entire heat load with CHP; for the agriculture sector technical potential refers to conversion of all methane emissions from manure management in California, extrapolated to 2020 from historic data reported by the California Energy Commission (CEC 2006b).

Table 1 and Table 2 show the results for the standard and high efficiency cases. Negative costs imply situations in which it is cost-effective to adopt CHP irrespective of the carbon benefits. Negative emissions represent situations where CHP leads to a net *increase* in state GHG emissions. In the event of either (or both) of these situations, an abatement cost is meaningless and not reported. These tables report GHG emission reductions from agricultural methane capture/conversion separately.

The overall GHG savings are modest, ranging from 1-7 Mt/a across the low, medium, and high scenarios. Potential is more limited in the high efficiency case, but are potentially significant in the commercial and residential sectors. In the industrial sector, the CHP potential is already well known and accounted for, limiting the benefit from this sector. Results underscore the importance of grid carbon intensity. Natural-gas-fired CHP is GHG preferable to grid power only when the waste heat can be utilized and the gap between the efficiency of on-site generation and central station generation is narrow enough for the transmission losses and displaced heating fuel to tip the balance towards CHP. This is evidenced by the dramatic decrease in GHG emissions reductions from the standard grid efficiency in Table 1 to the high efficiency grid case in Table 2. The corollary is of course that high efficiency on-site technologies, such as fuel cells, could make a big difference to the results.

Note that for many sectors, carbon emissions reductions increase from the low to the medium penetration scenarios, but decrease in the high and/or maximum penetration scenarios. CHP system efficiency decreases as penetration increases: the most attractive sites, i.e. those with a use for much of the waste heat, are assumed to adopt first; however, as penetration levels increase, CHP becomes less favorable. Typically, CHP is only more carbon efficient than the grid electricity it displaces when the waste heat from the generation offsets additional fuel consumption. Given the quite clean grid generation being displaced, inefficient CHP systems can ultimately lead to a net increase in emissions. This is evidenced in the industrial sector of the maximum scenario.

Table 1. Base case results with standard grid efficiency

		Low	Medium	High	Maximum
Small Commercial	**CO_2 emissions reduction (kt/a)**	956	2,640	3,257	2,286
	cost (M$/a)	-422	-1,307	-1,755	-1,583
	abatement cost ($/t)	n/a	n/a	n/a	n/a
Large Commercial	**CO_2 emissions reduction (kt/a)**	606	1,059	744	869
	cost (M$/a)	-204	-469	-412	-553
	abatement cost ($/t)	n/a	n/a	n/a	n/a
Industrial	**CO_2 emissions reduction (kt/a)**	570	1,459	1,299	-9
	cost (M$/a)	-237	-605	-551	-549
	abatement cost ($/t)	n/a	n/a	n/a	n/a
Residential	**CO_2 emissions reduction (kt/a)**	242	568	1,210	9,878
	cost (M$/a)	496	1,063	2,482	21,827
	abatement cost ($/t)	2,051	1,872	2,051	2,210
Agriculture	**CO_2 emissions reduction (kt/a)**	97	320	484	969
	cost (M$/a)	-17	-55	-83	-166
	abatement cost ($/t)	n/a	n/a	n/a	n/a
Total	**CO_2 emissions reduction (kt/a)**	2,471	6,046	6,995	13,992
	cost (M$/a)	-367	-1,318	-237	19,142
	abatement cost ($/t)	n/a	n/a	n/a	1,368
Agriculture - Offset From Methane Conversion					
	CO_2 equivalent emissions reduction (kt/a)	970	3202	4852	9704

Table 2. Base case results with high grid efficiency

		Low	Medium	High	Maximum
Small Commercial	**CO_2 emissions reduction (kt/a)**	351	645	384	-1,693
	cost (M$/a)	-422	-1,307	-1,755	-1,583
	abatement cost ($/t)	n/a	n/a	n/a	n/a
Large Commercial	**CO_2 emissions reduction (kt/a)**	347	354	-19	-353
	cost (M$/a)	-204	-469	-412	-553
	abatement cost ($/t)	n/a	n/a	n/a	n/a
Industrial	**CO_2 emissions reduction (kt/a)**	232	542	307	-1,596
	cost (M$/a)	-237	-605	-551	-549
	abatement cost ($/t)	n/a	n/a	n/a	n/a
Residential	**CO_2 emissions reduction (kt/a)**	-5	-11	-23	-186
	cost (M$/a)	496	1,063	2,482	21,827
	abatement cost ($/t)	n/a	n/a	n/a	n/a
Agriculture	**CO_2 emissions reduction (kt/a)**	81	268	406	813
	cost (M$/a)	-17	-55	-83	-166
	abatement cost ($/t)	n/a	n/a	n/a	n/a
Total	**CO_2 emissions reduction (kt/a)**	1,007	1,799	1,055	-3,016
	cost (M$/a)	-367	-1,318	-237	19,142
	abatement cost ($/t)	n/a	n/a	n/a	n/a
Agriculture - Offset From Methane Conversion					
	CO_2 equivalent emissions reduction (kt/a)	970	3202	4852	9704

The agricultural sector results are quite interesting, and demonstrate the great benefit of avoiding methane emissions. The potential role of CHP may seem limited, but to the extent that it could stimulate the capture of methane, it could be highly beneficial. On its face, agriculture is the most promising sector evaluated in this report, but this analysis only considered methane emissions as one of this sector's many GHG sources. On the other hand, the viability of controlling these emissions is open to doubt.

Table 3 summarizes the GHG emissions reductions for the standard efficiency natural gas power plant case, high penetration scenario. This represents the best case scenario for CHP in this analysis. A reasonable estimate of the overall GHG abatement potential seems to be around 1% of all state GHG emissions. While this may not seem significant, consider Figure 2, which shows that total residential and commercial emissions in 2020 will be about 118 Mt. Relative to this total, the 7 Mt savings represent about 6%, which is in the same range as the total from water and space heating. In other words, the high potential GHG emissions savings from CHP are comparable to saving all the emissions caused by all water and space heating in both the residential and commercial sectors.

Table 3. 2020 GHG emissions with and without CHP, assuming standard grid efficiency and high CHP penetration

	emissions without CHP (Mt/a CO2 eq)	emisions with CHP (Mt/a CO2 eq)	emissions reduction (Mt/a CO2 eq)	% reduction
Residential	56.5	55.3	1.2	2.1%
Small Commercial	51.3	48.0	3.3	6.4%
Large Commercial	10.0	9.3	0.7	7.4%
Industrial	99.8	98.5	1.3	1.3%
Agriculture	51.8	51.3	0.5	0.9%
Transportation	225.1	225.1	n/a	n/a
Other	65.2	65.2	n/a	n/a
Total	***559.8***	***552.8***	***7.0***	***1.2%***

3. Approach

This section describes the approach used for each of the sectors as well as for estimating displaced power sector emissions.

For each penetration scenario, a *penetration value* is assumed. For small commercial, large commercial, and industrial sectors, this is the fraction of all required electrical capacity currently supplied by the central grid that is provided by CHP. For the residential sector, the penetration value is the fraction of heat load that is met by recovered heat from CHP (i.e. CHP systems are sized to the heat loads) and for the agriculture sector, the penetration value is the fraction of methane emissions from BAU manure management that are utilized in CHP systems. The *capacity factor* is the ratio of electricity generated by the CHP system to electricity that could possibly be generated by the CHP system, i.e. if the system continuously ran at rated capacity, and *overall efficiency* is the simple ratio of useful energy out over fuel energy in. Average capacity factors are assumed to decrease with increasing penetration because the most economically attractive, first-developed sites are likely those with a consistent use for CHP, i.e. high capacity factors. The overall efficiency of the marginal installed unit also decreases as penetration increases because the earliest adopters will tend to be those with a large and consistent use for waste heat, i.e. able to achieve high overall efficiency.

Assumptions about penetration rates, capacity factors, and average system efficiency for all sectors are listed in subsection 3.8.

3.1 Small Commercial

Current energy use data for small commercial buildings was collected from the California Commercial End-use Survey (CEUS) (CEC 2006a). Here, *small* refers to buildings with peak loads less than three MW. While of course somewhat arbitrary, this cut-off was chosen as approximately the minimum-sized facility that would likely be considered a promising *traditional* CHP host, i.e. would have a significant heat load and a minimum electrical load of at least one MW. Energy use forecasts for 2020 were obtained by assuming an annual increase of 1.3% in peak demand and energy consumption[2]. Table 4 lists the small commercial buildings considered and their energy characteristics. For each building type, the installed capacity of CHP was assumed to be of one representative type, e.g. 100 kW reciprocating engines were applied to small offices.

Table 4. Small commercial buildings: 2020 energy use forecast and assumed representative CHP

Building Type	Statewide Peak Electric Load (MW)	Statewide Electricity Consumption (GWh)	Generator
Small Office (< 30,000 sq ft)	1,694	5,735	100 kW Reciprocating Engine
Large Office (> 30,000 sq ft)	3,025	14,148	1 MW Reciprocating Engine
Restaurant	1,452	7,244	100 kW Reciprocating Engine
Retail	2,662	7,153	100 kW Reciprocating Engine
Food Store	1,210	11,946	100 kW Reciprocating Engine
Refrigerated Warehouse	387	2,315	1 MW Reciprocating Engine
Unrefrigerated Warehouse	726	2,986	1 MW Reciprocating Engine
School	1,452	4,020	1 MW Reciprocating Engine
Lodging	666	3,963	1 MW Reciprocating Engine
TOTAL	***10,970***	***49,175***	

[2] This is the average rate of increase from 1990 to 2005 from data reported in CEC (2006b).

A *capacity factor* was used in this analysis to determine the energy production of an installed CHP system. Conventional sizing heuristics such as meeting the base load or the heat load would result in high capacity factors, and are appropriate for low CHP penetration levels. However, as penetration levels increase, CHP capacity would be installed at sites and in capacities less economically compelling, i.e. with lower generation capacity factors and less use for waste heat. Consequently, capacity factors and system efficiencies for small commercial CHP systems were assumed to be a decreasing function of penetration value. Figure 3 illustrates how an annual load duration curve for the small commercial sector was used to determine the relationship between penetration and capacity factor. On the vertical axis, K_p is the peak load of the sector, K_b is the base load, and K_a is the peak load met by CHP. Area G_a is the amount of electricity generated by CHP each year, and the area I_a is the potential for electricity not produced because the equipment cannot be fully utilized. Thus, the capacity factor is ($G_a/[G_a + I_a]$). This capacity factor is further scaled by a factor, *f*, to account for practical limits on a commercial CHP system. For this analysis, a linear approximation of the capacity factor function shown in Figure 3 was used.

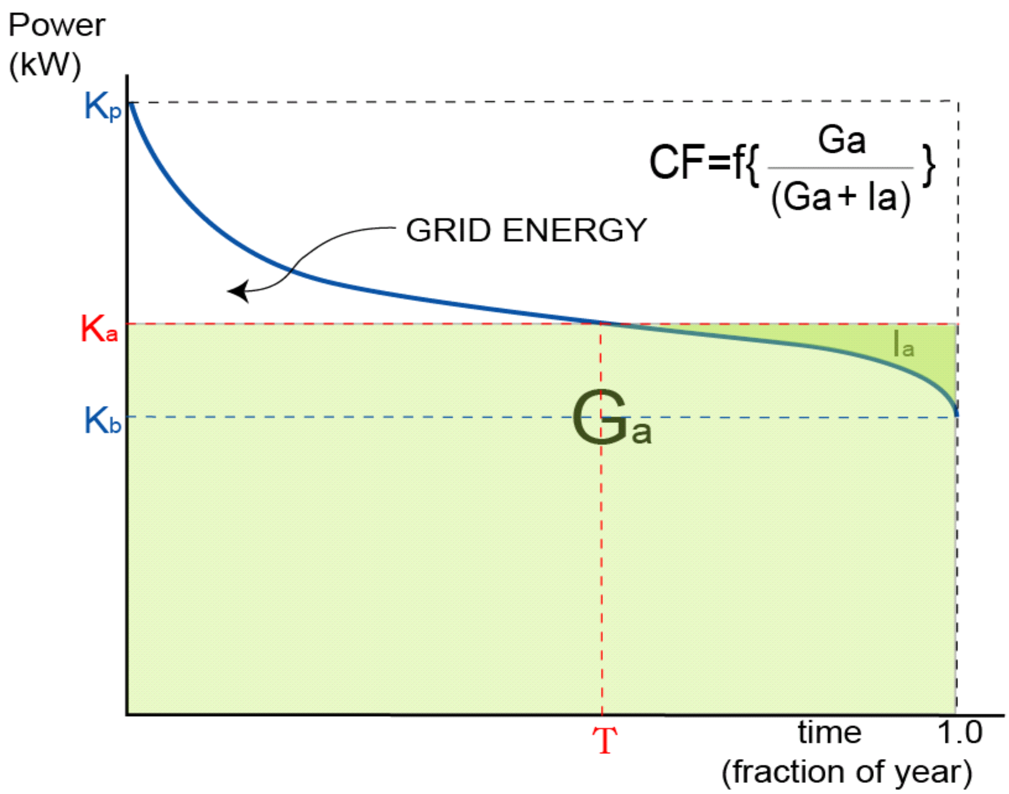

Figure 3. Calculating capacity factors for small commercial buildings

In addition to the capacity factor, the combined efficiency of a CHP system will be a key determinant of its GHG abatement potential. The combined efficiency is the fraction of fuel energy input that is ultimately utilized as either electricity or heat. Note that if CHP heat is collected but there is no use for it, thermal energy is not included in the efficiency calculation. The most efficient CHP systems for this sector were assumed to be 70% efficient and the least were assumed to be 35% efficient (equivalent to no waste heat utilization), with intermediate unit efficiency a linear interpolation between the boundary values. Using these assumptions, the average efficiency for a given penetration level could be determined.

3.2 Large Commercial

Current energy use data for large commercial buildings were collected from the California Commercial End-Use Survey (CEUS) (CEC 2006a). Here, *large* refers to buildings with peak loads greater than three MW. Energy-use forecasts for 2020 were obtained by assuming an annual increase of 1.3% in peak demand and energy consumption; this is the average rate of increase from 1990 to 2005 from data reported in CEC (2006b). Table 5 lists the large commercial buildings considered, their energy characteristics, and the representative CHP system. For each building type, the installed capacity of CHP was assumed to be of one representative type. For example, 100 kW reciprocating engines were applied to small offices.

As with the small commercial sector, capacity factors and system efficiencies are assumed to decline as penetration levels increase. The peak load of the sector is equivalent to the CHP capacity required to meet the entire load of the sector; this is the technical potential for CHP. Knowledge of the peak load and approximate shape of the load duration curve allow for estimates of capacity factors at various levels of CHP penetration. The capacity factors and system efficiencies assumed for this analysis are reported in Section 3.8. Professional judgement based on a review of case studies and building energy simulations guided these assumptions.

Table 5. Large commercial buildings: 2020 energy use forecast and assumed representative CHP installation

Building Type	Statewide Peak Electric Load (MW)	Statewide Electricity Consumption (GWh)	Generator
College	605	3,055	5 MW Reciprocating Engine
Health	1,089	5,520	5 MW Reciprocating Engine
Miscellaneous	2,662	13,091	5 MW Reciprocating Engine
TOTAL	***4,357***	***21,665***	

3.3 Industrial

Estimates of the technical CHP potential for industrial sector sites are from the California Energy Commission (CEC 2005), which estimates the current capacity of industrial sites that do not already have CHP installed. The capacity values from this report have been scaled by 1.3% per year from 2005 to 2020[3] to estimate the technical potential in 2020. The industries, capacity estimates, and representative CHP systems are listed in Table 6. Capacity factors and system efficiencies are various levels of CHP penetration were assumed in the same manner as those for the large commercial buildings (Section 3.2) and are reported in Section 3.8.

[3] This is the average rate of increase from 1990 to 2005 from data reported in CEC (2006b).

Table 6. Industrial sites: 2020 energy use forecast and assumed representative CHP installation

Industry	Statewide Peak Electric Load (MW)	Generator
Textiles	118	1 MW Reciprocating Engine
Lumber and Wood	67	3 MW Gas Turbine
Furniture	76	1 MW Reciprocating Engine
Paper	634	5 MW Gas Turbine
Chemicals	1,039	3 MW Gas Turbine
Petroleum Refining	357	40 MW Gas Turbine
Rubber/Misc Plastics	324	1 MW Reciprocating Engine
Primary Metals	169	10 MW Gas Turbine
Fabricated Metals	274	1 MW Reciprocating Engine
Machinery/Computer Equip	311	1 MW Reciprocating Engine
Transportation Equip	522	10 MW Gas Turbine
Instruments	489	1 MW Reciprocating Engine
Miscellanious Manufacturing	66	1 MW Reciprocating Engine
Food Processing	1,219	5 MW Gas Turbine
TOTAL	**5,664**	

3.4 Residential

For the residential sector, it was assumed that the CHP systems would be installed to meet heat loads, providing electricity as a by-product. Under this paradigm, CHP systems in single- and multi-family homes are assumed to have system efficiencies near the maximum technically possible, but to have low capacity factors because of infrequent heat loads. Penetration levels here refer to the fraction of residential sector heat loads that are met by CHP. The representative CHP system for the residential sector is a 1 kW proton exchange membrane (PEM) fuel cell. Heat loads for the residential sector in 2020 were based on a linear extrapolation of historic residential fuel consumption from 1990 to 2004 (CEC 2006b).

3.5 Agriculture

The only CHP option considered for the agriculture sector was that fired by methane produced from manure digestion. Methane is a potent greenhouse gas; significant GHG reductions can be achieved by combustion of methane to produce carbon dioxide (a relatively less potent GHG) and water. For this analysis, it was assumed that the conversion of methane to carbon dioxide is not credited to CHP, but is reported separately. However, the carbon emissions reductions achieved by offsets to grid electricity and fuel for heating are attributed to CHP, and reported along with the GHG reductions for the other sectors. Clearly, there are a large and diverse set of CHP opportunities in agriculture that are not considered here, and this is likely a rich area for future work.

3.6 Energy Prices

Forecasts of 2020 natural gas prices are taken from the Energy Information Administration (EIA 2007a). Forecasts of electricity prices in California in 2020 are linear extrapolations of historic electricity prices from 1990 to 2005 from EIA (2007b). Prices from both of these sources are reported by sector: residential, commercial, and industrial. For this analysis, the following rates are applied to the following sectors:

- **residential rate** – applied to the residential sector
- **commercial rate** – applied to the small commercial sector
- **industrial rate** – applied the large commercial, industrial, and agricultural sectors.

This application of rates produces the forecast in Table 7 in 2005 dollars.

Table 7. 2020 forecasts of California electricity and natural gas prices

	Natural Gas		Electricity
	($/MMBTU)	($/MJ)	($/kWh)
residential	10.54	0.0100	0.14
commercial	8.67	0.0082	0.15
industrial	5.90	0.0056	0.12

3.7 Greenhouse Gas Emissions from Grid Electricity

Central grid electricity in California is quite diverse, being produced by a variety of sources: fossil fuels, nuclear, and renewables, including hydroelectric. For this analysis, it was assumed that CHP would displace electricity produced by natural gas. This section explains why this assumption is adopted and the two power supply cases that are used. Figure 4 shows projections of California's total electric power supply (in-state generation plus imports), disaggregated by fuel. This analysis is fundamental to correctly estimating any CO_2 emissions offset at power plants by on-site generation, which is usually the biggest effect of CHP. Demand is assumed to be increasing at a constant rate from 1990 onwards. It is further assumed that output from coal-fired plants is maintained at current levels. In the current analysis this has a small effect on results, but if on-site gas-fired CHP could substitute for out-of-state coal generation, then clearly the GHG emission reduction could be much more significant. Generation from nuclear, and currently existing non-hydro renewables (solar, wind, geothermal, and biomass), are assumed to be constant, with new renewables penetration increasing to meet the RPS targets of 20% in 2010 and 33% in 2020. Hydroelectric generation follows a diminishing trend in output based on historical generation. Under these assumptions, it was found that generation from natural gas actually diminishes over the next 13 years.

A precise accounting of the generating plant and therefore its emissions displaced by changed electricity poses a complex problem, as described in Price *et al*, 2002. Most notably, predicting how the power plant fleet will differ, what its cost structure will be, as well as the regulatory environment in which it operates are all factors affecting the likely outcome. For the purposes of this work, simple assumptions were applied that span some of the major approaches commonly used. Figure 4 is deliberately drawn with the low marginal cost (primarily fuel costs) resources in the bottom, and the high marginal cost fossil-fired resources at the top. Of all the sources listed here, non-cogeneration natural gas sources have the highest marginal costs, i.e., variable $/kWh costs, and would therefore be the last in an economic dispatch order. In other words, if there is demand reduction for any reason, the resources at the top of the figure will be displaced before ones towards the bottom. It is assumed that during this forecast period, natural gas will be the highest cost fuel so natural gas generation appears at the top. Together, these assumptions lead to the conclusion that only non-cogeneration natural-gas-fired generation will be displaced by CHP in the low, medium, and high penetration scenarios considered in this analysis. The highest total CHP generation in any scenario in this study is 69 TWh in 2030, whereas the forecasted level of non-cogeneration natural gas generation in 2030 is 73 TWh[4]. The

[4] The ratio of cogeneration to non-cogeneration power production in California in 2030 is assumed to remain at current levels (~34% cogeneration), as determined from data from the California Energy Commission (CEC 2007b).

remaining task is to determine the efficiency of the displaced generation. There may be an effort to replace existing single-cycle generation by combined cycle generation, but this would be limited by the high economic cost of high penetrations of combined cycle plants operating at low capacity factors. Consequently, the two cases used here represent two levels of combined cycle penetration, 50% and 100%.

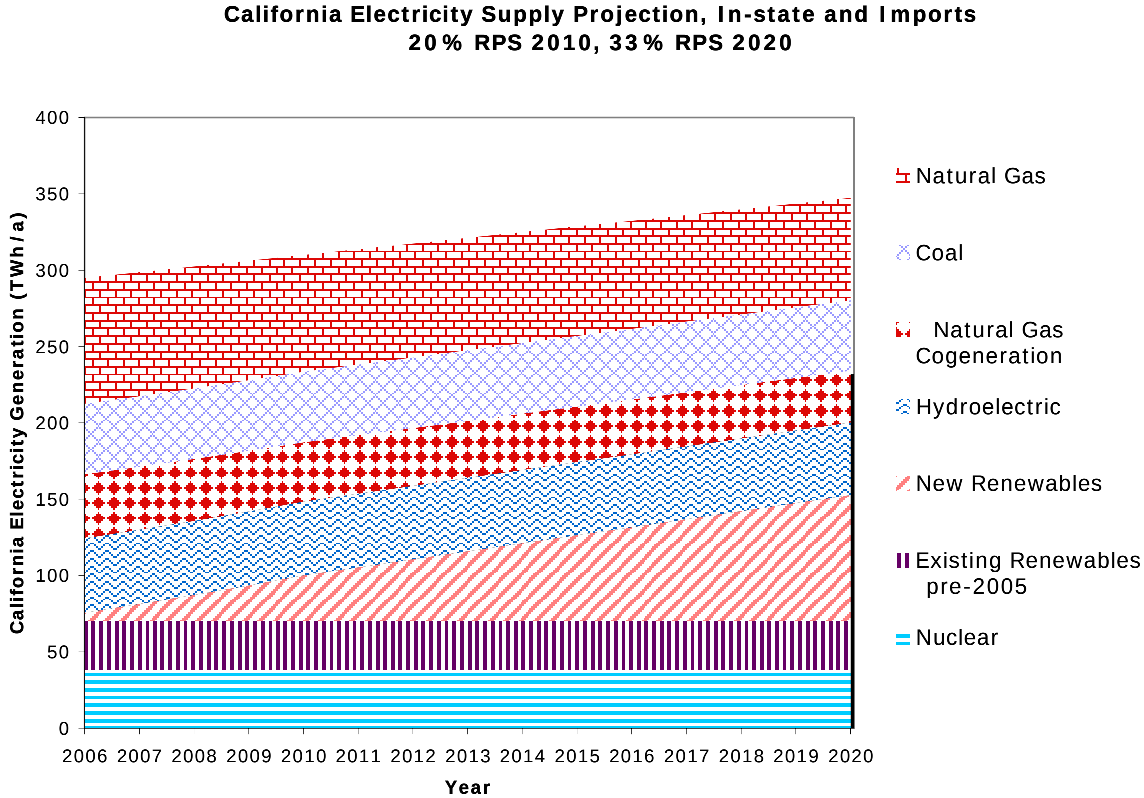

Figure 4. California electricity supply projection, in-state and imports

Natural gas plants providing power to California are a mix of high efficiency combined cycle plants and more standard single cycle steam and combustion turbine plants. Two cases were considered, as described in Section 2 and repeated here:

- **standard efficiency natural gas generation**: 50% of electricity from central grid natural gas plants is from combined cycle plants, the other 50% is from single cycle plants.
- **high efficiency natural gas generation**: 100% of electricity from central grid natural gas plants is from combined cycle plants.

The marginal carbon dioxide emissions factor for the standard efficiency case is 0.47 kg CO_2/kWh. The marginal CO_2 emissions factor for the high efficiency case is 0.39 kg CO_2/kWh. Table 8 states the assumptions made to determine these emissions factors.

Table 8. Assumptions used to determine marginal emissions factors

Electrical Efficiency of Combined Cycle Plant	50%
Electrical Efficiency of Single Cycle Plant	35%
Transmission and Distribution Losses	7%
Natural Gas Emissions Factor (kg CO_2/MJ)	0.0503

3.8 Scenario Assumptions

Table 9 lists the scenario assumptions for the commercial and industrial sectors, Table 10 the agricultural sector, and Table 10 the residential sector.

Table 9. Penetration scenario assumptions for commercial and industrial sectors

	small commercial	large commercial	industrial
percentage of total technical adoption potential			
maximum penetration	100%	100%	100%
high penetration	50%	50%	50%
medium penetration	33%	33%	33%
low penetration	10%	10%	10%
capacity factor			
maximum penetration	40%	43%	40%
high penetration	62%	50%	50%
medium penetration	65%	70%	70%
low penetration	65%	85%	85%
CHP system efficiency			
maximum penetration	45%	53%	45%
high penetration	61%	50%	65%
medium penetration	64%	60%	70%
low penetration	68%	80%	75%

Table 10. Penetration scenario assumptions for agricultural sector

	percentage of total manure methane capture	percentage of waste heat utilized to offset fuel usage
maximum penetration	100%	10%
high penetration	50%	10%
medium penetration	33%	10%
low penetration	10%	10%

Table 11. Penetration scenario assumptions for residential sector

	multi-family	single-family
% of heat load met CHP		
maximum penetration	100%	100%
high penetration	25%	10%
medium penetration	10%	5%
low penetration	5%	2%
capacity factor of CHP units		
maximum penetration	10%	10%
high penetration	20%	15%
medium penetration	20%	15%
low penetration	20%	15%

4. Limitations of Analysis

Gauging the effect of widespread CHP deployment on GHG would be challenging at any time, but poses a particularly difficult conundrum at present. Because so many scenarios are possible in response to AB-32, all estimates are being built on quicksand. Some of the other major issues are:

- This effort is an analysis of *potential* not *adoption*. Because customer circumstances are so heterogeneous, global analyses of CHP potential must always be viewed skeptically. Realizing the potential would require powerful policy initiatives, incentives, etc. Further, the engineering and economics of CHP are quite complex and not amenable to rule-of-thumb analyses. Consideration of other factors, such as coincidence of heat and electrical loads, variability of loads, etc. is critical in selecting systems and their operating schedules.
- The analysis has not considered the potential value of absorption cooling, but California's heating requirements for buildings are minimal and major heat sinks are limited opportunities. The use of waste heat for cooling will certainly be economically attractive in some circumstances and might provide extra carbon abatement potential; however, it should be noted that absorption cooling does not displace large amounts of electricity, albeit valuable electricity required during peak times.
- A modest effort has been made to consider the critically important issue of displaced grid power carbon intensity changing over time, depending on the mix of future generation assets. Only two cases are considered. In fact, a variety of changes might occur by 2020, and are probable over the longer term. For example, we may see the emergence of carbon sequestration and coal gasification combined cycles, or a resurgence of nuclear power. While most of these technologies tend to be capital intensive and unlikely to appear in load-following roles, some, such as biofuel turbines or a storage technology, might be low marginal cost yet flexible generating assets. Also note that if grid load shapes become flatter, higher capital cost technologies may be the marginal units that are being displaced.
- In a similar vein, massive efforts at energy efficiency would tend to reduce the electrical load available for displacement by CHP as well as the heat requirements.
- This study has been conservative in its expectations that structural changes will be few, as befits a study looking towards a relatively short time horizon; however, some significant changes could begin to emerge over the study period. One of particular note might be the aggregation of loads into microgrids that would provide favorable conditions for CHP, as well as adoption of other GHG friendly technologies.
- A very small set of technologies have been considered, turbines, reciprocating engines, and one small fuel cell, and their performance is fixed at present day levels. Others, such as Stirling engines (already being deployed in the residential sector in Europe) and larger fuel cells might well be attractive towards the end of our study period, looking out to 2020.
- Deployment of CHP might stimulate adoption of other GHG abatement technologies, such as solar thermal assistance.

5. Conclusions

This study is a modest scoping exercise intended to estimate the GHG abatement potential of CHP in California. The results show that under the assumptions used, the potential is modest but promising, in the 1-7 Mt/a range. Not surprisingly, the small commercial sector emerges as a key untapped opportunity, especially smaller buildings. CHP has already penetrated deeply into the industrial sector, and prospects for residential applications are heretofore relatively unexplored and therefore uncertain. Agriculture emerges as a complex story, in which CHP itself may not be promising, but to the extent that it stimulates the use of opportunity fuels and avoids methane emissions, it could deliver a significant benefit.

Future analysis work on the topic of this report appears most necessary in the following areas:

- exploration of prospects in agriculture, especially identification of opportunity fuels, CHP systems that can use it, and business models for farms that might enable better utilization of waste heat
- development of alternative scenarios in which more fundamental changes in the economy might foster the economic viability and adoption of more CHP, e.g. limitations of the expansion of tradition power supply might to some degree force decentralized generation or more localized food production creates more diverse business and therefore CHP opportunities for farms
- analysis of small commercial buildings to identify the most beneficial CHP applications, especially ones that involve cooling and/or local aggregation of loads
- investigation of more technologies that may be applicable in residential applications and their possible interaction with residential-scale renewables
- much more attention is justified for multi-family dwellings, as well as the possible aggregation of single-family loads
- continued analysis of microgrid technology that can create favorite conditions for the integration of CHP with other GHG abatement measures, such as small-scale renewables deployment, end-use energy efficiency, local control of power quality and reliability, etc.

6. Recommendations

While this project represents only a modest effort to gauge the role CHP might play in the state's energy future, some preliminary recommendations to the PIER program on potential areas of research focus are noteworthy. The intent is to present a few general areas of research that PIER could pursue to provide clear local benefit to California at the levels of spending possible for the program.

- Develop a detailed method for calculating CO2 emissions from central grid electricity
While the Public Utilities Commission (CPUC) and the CEC have a joint open docket (R.06-04-009) on developing GHG protocols for electricity providers, this is such a complex question that research should still be directed at various aspects of this problem. Estimating the GHG abatement benefit of CHP (and other customer-side technologies) critically depends on accurately estimating the power plant emissions displaced. To achieve a beneficial GHG effect, CHP operation should be aligned with times and places in which CHP provides a net decrease in GHG emissions, but system owners may not feel the incentive to respond accordingly. For example, CHP units might not be operated at night because off-peak electricity prices are low, but marginal grid emissions might be high, especially when coal becomes the marginal fuel. Note that the marginal generation displaced by lower grid purchases may change significantly over the life of a CHP system as the power system becomes greener and the overall fuel mix changes, so beneficial operations would change accordingly.

- Explore technology packages rather than simple CHP systems
This study has considered only a somewhat conservative notion of CHP technology, predominantly heat engines with simple waste heat recovery. The limited existence of opportunities for such systems in California limits estimates of the potential benefits of CHP to the state. However, such CHP systems operating in other modes, e.g. with building cooling assisted by solar thermal collection or photovoltaic (PV) backed up by CHP for nighttime and winter use, might offer more attractive GHG abatement potential. PIER should explore the potential of such technology packages rather than of ones only in isolation, and their possible organization in microgrids. It is often the case that requirements for integration of such systems offer the best opportunity for government involvement. Further, decision making on establishment of such arrangements will be primarily on the customer side of the meter, so research should focus there.

- Identify the most promising GHG-mitigation CHP applications
As illustrated in this analysis, at high penetration rates, CHP units installed on the margin can cause a net *increase* in the GHG footprint if sites have limited use for waste heat. PIER should identify the most promising applications, regions, and CHP system control strategies from a GHG mitigation perspective, both in total magnitude of GHG emissions reduction and in $/t cost of CO_2 reduction. The CEC can then develop technologies favorable to these applications.

- Research small-scale CHP systems
While there are obvious challenges, residential scale CHP shows considerable promise for GHG abatement. Residential CHP has been pursued in Europe and Japan, with only limited success to date. PIER should investigate work that has been done in this area and gauge its relevance to California conditions. If technologies arise that are more suited to our circumstances, they could be developed. Again, combinations of technologies may prove the most attractive, although the hassle factor is a major barrier to residential applications. As mentioned above, multi-family applications may be the most promising in the short-run, and aggregated single-family loads later.

- Develop a residential screening tool
While many software tools have been developed for evaluating CHP potential and economics in the traditional large scale applications, little has been done to provide such advice for residential scale systems.

- Explore agricultural CHP business models
The agricultural sector represents an interesting challenge. One possible role for CHP is an unusual one as a catalyst for broader methane capture. There is broad scope for CHP use in new activities. PIER could explore potential synergies between existing agriculture and other businesses, e.g. making use of CHP waste heat (and CO_2 rich exhaust) for greenhouses, cheese production or other downstream processing. In fact, other applications may not be agriculture related.

- Develop CHP control algorithms and systems
CHP technology is deceptively simple. Running a reciprocating engine and recovering the waste heat doesn't seem to offer much of a technical challenge. The reality is actually quite complex, given highly variable loads, complex tariffs, noise and emissions constraints, maintenance requirements, and the considerable uncertainty in all these parameters, The variable nature of grid GHG displacement adds yet another complexity. Sophisticated control systems will be required to capture the abatement potential of CHP, while remaining economically attractive.

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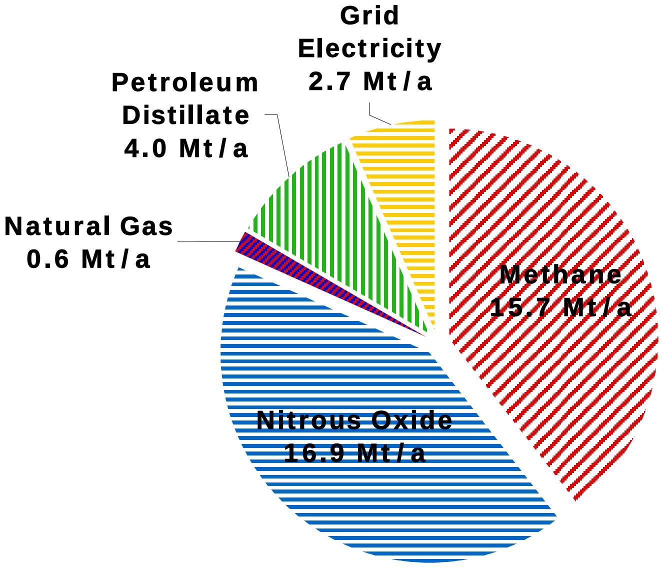
Appendix A. Agricultural GHG Emissions

As shown in *CA GHG Inventory 2006, CEC #600-2006-013-SF*, Figure 5 displays carbon dioxide equivalent emissions from California agriculture, which totals 39.9 Mt/a. This represents approximately 8% of the California total, including out-of-state power sector emissions.



Source: CA GHG Inventory 2006, CEC #600-2006-013-SF

Figure 5. 2001 California agricultural GHG emissions (CO_2 equivalent)

In Figure 5, note several observations. First, because nitrous oxide (NO_X) and methane (CH_4) are such a powerful GHGs, they dominate overall agricultural emissions. Second, the biggest energy use source of emissions is from fuels burned by farm machinery. Third, the total use of carbon emitting fuels is small. This data set suggests that the most effective CHP opportunity for agriculture would be methane capture for power generation with modest opportunities for application of waste heat. Given that the methane emissions come from a multitude of sources, they cannot all be covered here and this effort focuses only on manure digestion. Finally, one of the more interesting aspects of agricultural CHP is that loads are not a given in the same way they tend to be in commercial building applications. If on-site generation were pursued by a farm, the availability of waste heat may well spur the owners, who tend to be highly entrepreneurial, to pursue other business opportunities based on the available heat.

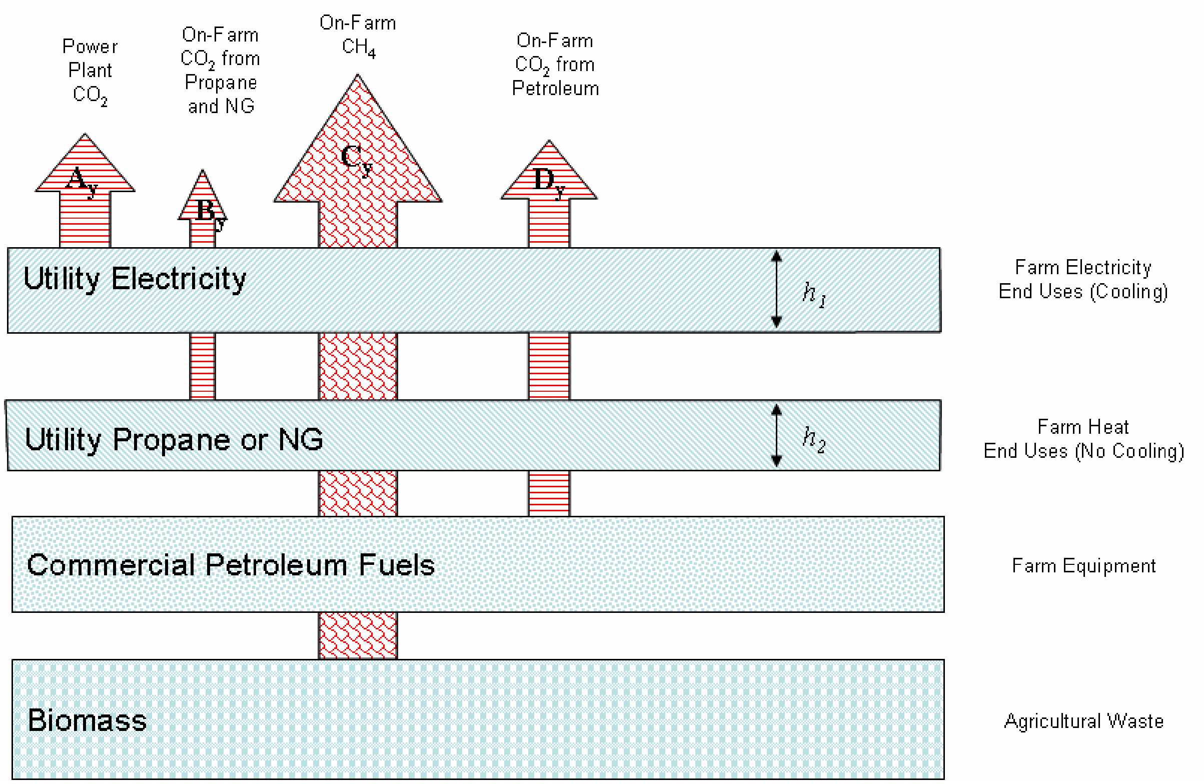


Figure 6. GHG emissions from agriculture without CHP

Figure 6 shows the approach used herein. Outflows of GHG from farm operations are in the form of power plant emissions for remotely generated electricity (Ay), on-site fossil fuel use for heat (By), farm use of distillate fuels (Dy), and the emissions of methane from waste decay (Cy).

Figure 7 shows the configuration after installation of methane-fired CHP at the farm. Power plant emissions are now reduced (An < Ay), as are emissions from heat production (Bn < By), but use of liquid fuels remains unchanged (Dn = Dy). In contrast to typical CHP installations, the biggest GHG gain in this case comes from reduced methane emissions (Cn << Cy). Whether or not the big gain from methane abatement can be credited to the CHP installation is open to argument, so in the results table, the GHG benefits coming directly from CHP are reported separately from the methane abatement benefit. As noted above, in this analysis the size of the farm electricity and heat loads are unchanged, i.e. h1 and h2 do not change.

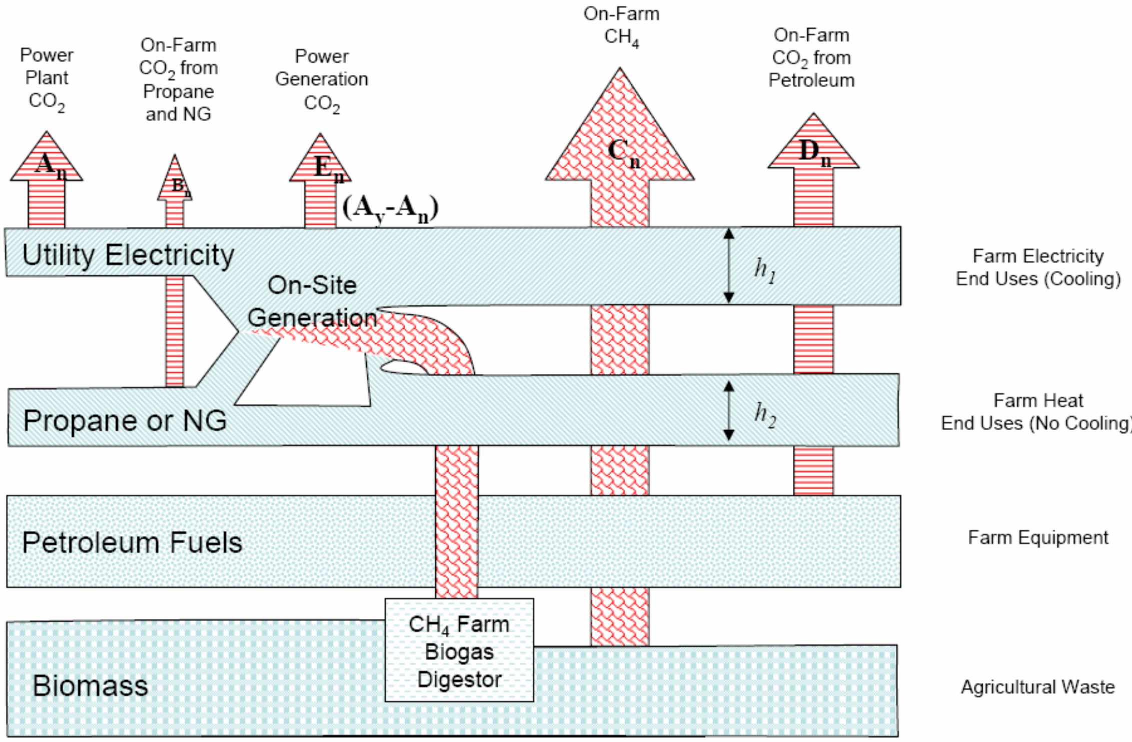


Figure 7. GHG emissions from agriculture with CHP