Should UC Berkeley Use Community Choice Aggregation (CCA) to Achieve Zero-Carbon Electricity By 2025?

A Life-Cycle Assessment Perspective of UC Berkeley's Electricity-Buying Options

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Abstract

Community Choice Aggregation (CCA) is an option that citizens of a local community obtain together from state power authorities to purchase electricity from renewable source. In the near future, UC Berkeley will likely be given the option to purchase electricity through renewable sources through CCA at Alameda County. The UC Berkeley Office of Sustainability would like to explore how well the CCA option will help meet its goal of carbon-neutrality in electricity use by 2025 and the associated environmental impacts of such a choice.

A portfolio of the renewable energy sources likely available to UC Berkeley through CCA is obtained from the California Public Utilities Commission. A Life-Cycle Assessment (LCA) of the power mix is performed on five different power mix scenarios to study the CO_2 emissions, major air pollutants, and other relevant environmental metrics of electricity from CCA. LCAs of different power-generation establishments comparable to our CCA's portfolio of renewable energy sources will be consulted and used in our analysis. A weighted average of the per-MWh life cycle emission factors is calculated for each of the five power mix scenarios. MCE's Deep Green has lower environmental impact than any other power mix. Sensitivity analysis shows that MCE's portfolio is highly sensitive to the LC GHG emission factor from electricity generated with landfill gas due to its sizable portion of electricity from landfill gas. Due to the large uncertainty in the LC emissions data, no definite conclusion can be drawn about the environmental superiority of MCE's power mix over PG&E's when they are compared in other four scenarios.

Additionally, a Life-Cycle Cost Analysis (LCCA) is performed based on levelized cost of electricity (LCOE) from each generation technology. Results shows that MCE's portfolio has lower LCOE, though it is not conclusive from data that MCE has definite cost advantage over PG&E's mix. Because results are inconclusive about the environment benefit and the potential cost, it is recommended that the Office of Sustainability should stay with PG&E rather than joining CCA in the near future.

Executive Summary

The goal of this project is to evaluate UC Berkeley's potential option to purchase electricity from a Community Choice Aggregator (CCA). A life-cycle perspective will be applied to compare the potential environmental and economic impacts or benefits from buying electricity from PG&E or a CCA. Experience of Marin Clean Energy (MCE)'s first two full years will be compared to PG&E in different power mix scenarios.

Life cycle emissions data of power generation facilities comparable to those in PG&E's network and MCE's renewable portfolio are collected from LCA literature. The results are show in the following table.

Life Cycle Emissions	GWP (kg CO2-eq/MWh)	NOx (kg NOx-eq/MWh)	SO2 (kg SO2-eq/MWh)	PM (kg/MWh)
Natural Gas	544	0.58	0.320	0.0015
Nuclear	36.2	0.08	0.192	0.0042
Large Hydro	36.7	0.02	0.011	0.0053
Small Hydro	7.4	0.02	0.004	0.0057
Solar PV	18.0	0.03	0.060	0.0700
Solar Thermal	42.5	0.09	0.059	0.0352
Wind	11.0	0.04	0.030	0.0095
Biomass	39.0	0.51	0.090	0.2500
Landfill Gas	3572	0.52	0.765	0.0021
Geothermal	243	0.01	0.0031	0.0013
Coal	1105	1.86	2.23	0.6417
Unspecified	540	0.73	0.68	0.152

Life cycle emission factors for relevant power-generation technologies in MCE and PG&E's power mix portfolio. The highlighted values are the 5 power generation technology with the highest emission factors in each impact category.

LCA data shows that while most renewables show better environmental performances, some have worst performance and/or large uncertainty associated with their LC emissions. Specifically, electricity from landfill gas may carry a large life cycle GHG emission factor due to low utilization rate and lower efficiency in burning the landfill gas for electricity generation. Large hydro also may have large life cycle GHG uncertainty from flooded vegetation and microorganisms in reservoirs. These two parameters are investigated in sensitivity analysis.

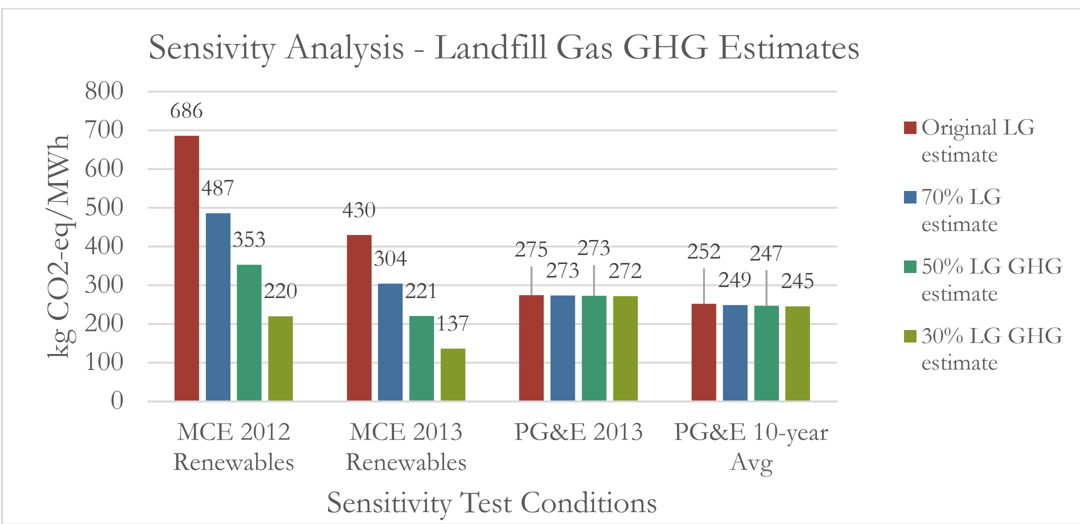
A weighted-average of those life cycle emission factors is then applied to each of the five power mix portfolios: 1) MCE Deep Green; 2) MCE Renewables 2012; 3) MCE Renewables 2013; 4) PG&E 2013; and 5) PG&E 10-year average from 2011-2020 as reported on its *Renewable Procurement Progress Report*. The calculated LC emission factors are presented in the following table.

Scenarios / LC emissions	MCE Deep Green (1)	MCE Renewables 2012 (2)	MCE Renewables 2013 (3)	PG&E 2013 (4)	PG&E 10-yr Avg (5)
CO2-eq (kg/MWh)	11	686	430	275	252
NOx-eq (kg/MWh)	0.040	0.327	0.136	0.331	0.303
SO2-eq (kg/MWh)	0.030	0.249	0.127	0.259	0.237
PM (kg/MWh)	0.010	0.088	0.026	0.042	0.046

Side-to-side comparison of life cycle impacts of the five power mix scenarios.

MCE Deep Green shows better environmental performance than PG&E's power mix, but its renewables has much worse LC GHG emissions. Comparing PG&E's 10-year average to its earlier year (2013) shows improvement in environmental performance as a result of its procuring more electricity from renewables.

Sensitivity study shows even at higher large hydro LC GHG estimations PG&E's power mixes still have lower LC GHG emission factor than MCE's. Its portfolio also show less sensitivity to the lower estimates of landfill gas emission factor. However, MCE's LC GHG emission factor changed significantly when landfill gas emission factor is lowered to 50% of its original estimate as shown in the graph below.



Scenarios LC GHG emission factors recalculated with 30%, 50x, and 70x the original landfill gas (LG) GHG estimates.

MCE's 2013 portfolio have lower LC GHG emission than PG&E's when landfill gas estimate is lowered to 50%. This high sensitivity shows the result in this project is inconclusive.

Levelized cost of electricity results based on 2009 CEC estimates shows lower levelized cost of in MCE's power mix, but the difference was not large enough to be conclusive that MCE's power mix is lower in cost.

Based on the results presented, it is recommended that UC Berkeley keeps buying electricity from PG&E while being on watch for a better opportunity to lower its environmental impacts through its electricity purchase in the future.

1. Introduction

For most part of last century, public utilities companies in the United States had largely enjoyed monopolistic freedom to choosing their own sources of electricity generation. Retail electricity consumers served by utilities did not have much choices in choosing where their electricity come from. Because large public utilities are mostly investor-owned utilities (IOUs), profit-maximization is a main consideration for their operations and that in turn drives the decisions about the sources of energy that they procure to generate electricity to serve their customers. As a result, coal and other fossil fuels remain a favorite source of energy for electricity generation in the United States.

This monopolistic electricity generation and delivery structure was challenged when Massachusetts passed its first Community Choice Aggregation (CCA) law in 1997 [Local Energy Aggregation Network, 2014]. Community Choice Aggregation is a group purchasing option where local communities or power districts with their loads grouped together are given the freedom to produce or purchase by contract their own source of electricity. The IOUs will remain responsible for delivering electricity by maintaining their networks, metering and billing the customers. Some objectives of CCA include more competitive electricity rates, returning choice of energy sources to consumer, and opportunities for a faster transition to cleaner, more localized, and more sustainable sources of electricity.

California State Legislature passed its Community Choice Aggregation in 2002. Since then, California Public Utilities Commission (CPUC) has approved the CCA plans in Marin County, San Francisco, and Somona County only [Local Energy Aggregation Network, 2013]. However, growing interests in CCA has driven more than 15 local communities in California to start exploring this option, including Alameda County, which has started a $1.3M feasibility study this past June [Matt O'Brien, 2014]. In the near future, Berkeley could be offered the opportunity to buy electricity from a cleaner, renewable energy supplier through a new community choice aggregator.

To accelerate the transition to renewable energy, California has also passed Senate Bill 1078 in 2002 and revised it with Senate Bill 2 in 2011 that sets renewable portfolio standards (RPS) for the IOUs in the state, electric service providers, and community choice aggregators to have at least 33% renewable energy in their retail electricity sales by 2020 [CPUC, 2014]. The bills clearly listed "…biomass, solar thermal, photovoltaic, wind, geothermal, fuel cells using renewable fuels, small hydroelectric generation of 30 megawatts or less, digester gas, municipal solid waste conversion, landfill gas, ocean wave, ocean thermal, or tidal current…" as the types of energy resources that count towards the RPS [California Legislature Information, 2011]. In 2013, the three large IOUs in the state, Pacific Gas & Electric (PG&E), San Diego Gas & Electric (SDG&E), and Southern California Edison (SCE) reported 23.8%, 23.6%, and 21.6%, respectively, which have met the intermediate target of 20% renewable energy between 2011 and 2013. Under the ambitious standards, California as a whole is moving fast towards a more diversified energy source portfolio.

The UC Berkeley Office of Sustainability has set its own goal for the campus's electricity use. As stated in its 2014 report on climate change adaptation, UC Berkeley aims to be carbon neutral in its electricity use by 2025 (Pascal Polonik, 2014). Towards this goal, the Office of Sustainability is considering community choice aggregation as an options to procure carbon-neutral electricity, which may become a real option in the near future.

2. Problem Statement

While it is almost a consensus that all of the renewable energy sources listed in the renewable portfolio standards (RPS) bill are preferable to fossil fuels, they do not have the same impacts on the environment. Although the operations of some of these renewable energy facilities could be considered emission-free, manufacturing, transportation, and installation of equipment necessary to add capacity to the electrical network to meet new demands from CCA could have different, non-zero impacts on the environment. As a large consumer of electricity, UC Berkeley is conscious of the possible impact of its choice on the environment and the potential economic cost in such a decision. In reaching carbon neutral electricity goal, the Office of Sustainability tries to minimize potential impacts to the environment and cost to the University. This would require a more careful study of the impacts through life-cycle impact assessments (LCIAs) of the different renewable technologies that are currently in use or likely to be in use by the new CCA. Because CCA is an alternative to the current electricity provider PG&E, it is useful to compare the environmental impacts between choosing CCA and keep buying electricity from PG&E over the next 20 years. A study of the trends in energy costs of renewable energy sources will also be done to see if the cost of this switch to CCA will be economically sustainable. The final goal of this project is to quantify potential environmental impacts and economic costs and weigh them against the benefits of procuring carbon-neutral electricity through CCA.

3. Background

Power Mix Portfolios

To study the environmental impacts of the electricity purchased from a utility or a CCA, it is important to know the sources of the energy it used for electricity generation as detailed as possible. The Renewable Portfolio Standards set by 2002 California Senate Bill 1078 comes with compliance reporting requirements from 2011. The compliance reports details electricity procured by each type of renewable energy resource by individual IOUs and CCAs and is available at http://www.cpuc.ca.gov/PUC/energy/Renewables/. Because Marin Clean Energy is the only CCA that is fully operational and has energy mix portfolio submitted to CPUC, its energy mix portfolio will be used to compare with that of PG&E. Both MCE and PG&E have made some progress towards the RPS goal. **Figure 1** & **Figure 2** below shows the relative abundance of the each renewable energy source as reported in their 2014 Procurement Progress Report. It should be noted that, because of its relatively small size and still being in the growth stage, MCE's power mix portfolio varies substantially from year to year and is not certain yet for the next few years. It is useful to consider MCE's power mix scenarios from both 2012 and 2013 as two different scenarios. PG&E has procured enough to meet its goal through 2019 and the total procurement and relative abundance after 2017 are quite stable.

Role of Life Cycle Assessment in Informing Decision-Making

Life cycle assessment is a methodology that takes exhaustive inventories of energy and materials inputs and outputs at each stage of a product's life, from cradle to grave, and thus offers the most comprehensive evaluation of the total environmental impacts of through a product's life. It is considered a valuable tool for informed environmental decision-making. Although UC Berkeley's explicit goal of is to achieve carbon-neutral electricity by 2025, it cannot ignore the other environmental impacts could be caused by adding new generation facilities. In a critical review of LCAs done on different electricity generation technologies, Turconi, et. al, [2013] concluded that it is meaningless to compare them based on GHG emission alone because LCAs based on multiple environmental metrics, e.g. SO_2 and NOx emissions, can lead to different conclusion than LCAs based on GHG emissions alone. Reliance on GHG emissions alone could lead to problem-shifting. Meaningful comparisons between technologies could be achieved only when all LCAs on electricity generation include all three phases of their life cycles: fuel provision, operation, and infrastructure as variations in environmental impacts from these three phases differ greatly from technology to technology. In the life cycle perspective, there is no such thing as zero-carbon electricity, but the choices that UC Berkeley faces has an environmental component that can be best addressed using the LCA method.

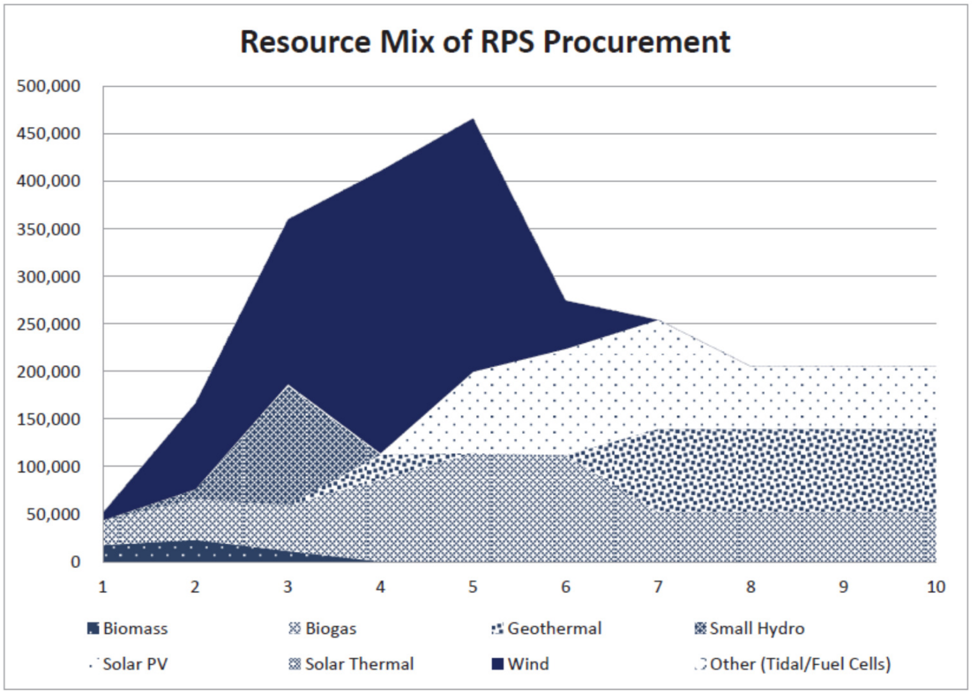


Figure 1 *Marin Clean Energy procured renewable energy resources. Year 1 correspond to the year 2011. The unit of the vertical axis is MWh of electricity procured.* ***Source****: MCE RPS Procurement Compliance Report (2014)*

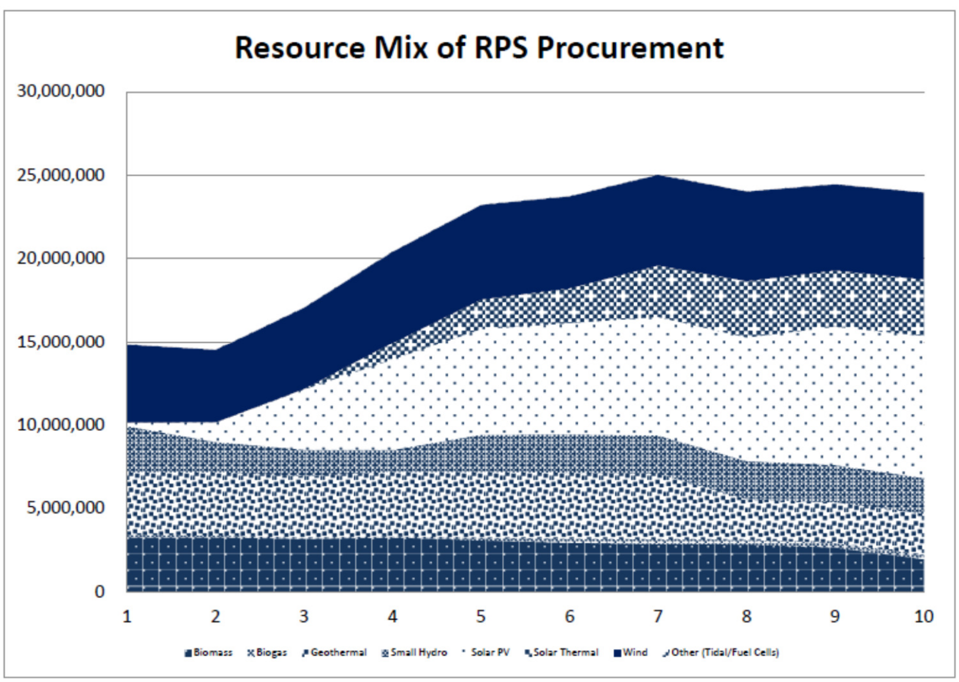


Figure 2 *PG&E procured renewable energy resources. Year 1 correspond to the year 2011. The unit of the vertical axis is MWh of electricity procured.* ***Source****: PG&E RPS Procurement Compliance Report (2014)*

Levelized Cost of Electricity (LCOE)

Comparing electricity prices between the two alternatives over the next 20 years is virtually impossible because exact prices of electricity in the future are difficult to predict much like the way stock prices and other commodity prices are difficult to predict. On the other hand, costs of electricity generation are somewhat predictable. A useful metric that may inform decision-making is the levelized cost of electricity (LCOE), which is an estimate of price-competitiveness of different new power generation technology. [USEIA, 2014] LCOE includes common costs in the life cycle of a plant, including "capital costs, fuel costs, fixed and variable operations and maintenance (O&M) costs, financing costs, and an assumed utilization rate for each plant type." The USEIA warns that there is regional difference in LCOE. Therefore, use of California CEC's estimates will be more appropriate (Klein, 2009). The formula used to calculate LCOE in the CEC report is

$$\text{Levelized cost} = \sum_{t=1}^{T} \frac{Cost_t}{(1+r)^t} * \frac{r*(1+r)^T}{((1+r)^T - 1)}$$

The total net present value of cost components $Cost_t/(1+r)^t$, is summed together and then calculate the annual payment with interest payment at interest rate r required to off the present value over the specific period T. The assumed period T of debt is equals the equipment year and varies with different technology. Table 18 and 19 in that report lists the assumed value of debt rate and T used in the model.

The values given in the CEC report are estimates for plant going in-service in 2009 or in 2018. In this project, median LCOE for a power plant going in-service in 2018 from an IOU is assumed. For comparison between different power generation technologies, Klein [2009] explained that close LCOE estimates cannot be used in decision-making, but values that differ by an order of magnitude. In the present project, interpretation of LCOE result between different portfolios will be using this rule of thumb as a guide.

Life Cycle Assessments of Solar Thermal Electricity Generation

Large-scale solar thermal electricity generation with solar energy was first commercialized in the US with the Solar One project in California since 1984. Since then, four different concentrated solar power (CSP) technologies have been developed and deployed for commercial electricity generation world-wide [Rahman, et. al, 2015]. CSP technologies capture thermal energy from sunlight to heat a working fluid to drive an electricity-producing turbine or store it with a heat storage system to help smooth out the intermittency in generation. From PG&E's Progress Report [2014], solar thermal will start supply a portion of electricity in 2013 and make up a substantial portion of PG&E's renewable energy beginning 2014. This is due to the completion of the Ivanpah project in Invanpah Dry Lake, California [Bright Source Energy, 2014]. It is a power tower solar thermal project consists of 3 units covering an area of 3,500 acre of desert and capable of delivering 377 MW of net power. The expected capacity factor is Life Cycle Assessments have been conducted for CSP but most focus on life cycle GHG emissions only. Skone, et. al. [2012e] has completed the most comprehensive LCA study of a 250 MW net power output model solar thermal tower with expected capacity factor of 0.27 and a solar insolation of 3.558 x 10^4 MW/m^2. This is comparable to 0.31 capacity factor and 3.099 x 10^4 MW/m^2 solar insolation expected for the Ivanpah project. The life cycle emission factors from Skone, et. al [2012e] are 42.5 kg CO2-eq/MWh, 0.09437 kg NOx-eq/MWh, and 0.0592 kg SO2-eq/MWh, and 0.0352 kg of PM/MWh. Because Skone, et. al included transmission and distribution stage of the life cycle in his paper which is outside of this project's boundary, that portion is subtracted from those given in Skone, et. al [2012e].

Life Cycle Assessments of Solar Photovoltaics (PV) Electricity Generation

Photovoltaics (PV) panels allow sunlight to be directly converted into electricity. They had been quite costly to build but due to recent drop in cost and rise of fuel cost in conventional power plants [Solarpraxis AG, 2014], we see utility-scale PV power plants with multi-megawatt capacity being commissioned world-wide [Denis Lenardic, 2014]. All of the top 10 PV power plants by capacity were commissioned within the last 3 years. Because PV technologies are still developing rapidly for higher energy conversion efficiency and lower material input and cost [T.M. Razykov, 2011], vast amount of LCAs have been done for different PV technologies and in different countries, so much so that it motivated several review articles [Gerbinet, 2014; Fthenakis, et. al, 2012] and Turconi's review also included PV electricity generation. Most of those LCAs are purely process LCAs based on SimaPro and EcoInvent softwares. Fthenakis pointed out that PV panels LCA should include raw materials production, solar cell and PV module production, Balance of System (BOS) (systems that connects PV systems to the electric power system, e.g. wiring, inverters for conversion from DC to AC current, transformers, and structural supports) production, system operation and maintenance, system decommissioning, and disposal or recycling, but some LCAs of PV panels exclude Balance of System (BOS) in their scope of study and study those components separately. His paper included references to two studies of BOS LCAs, one is for rooftop installation [Alsema, et. al, 2006] and another is for a 3.5 MW PV plant installed in Springerville, Arizona [Mason, et. al, 2006]. Even then, these LCAs are still far from complete, as they often omit end-of-life stage due to lack of data, and include only GHG emission in impact assessment and omit NOx, SO_2, and other emission from electricity used in production. Furthermore, Turconi pointed out that LCA studies of PV are inherently location-dependent due to variability of electricity production level to climate conditions and the different sources of electricity used in PV modules manufacturing.

Marin's Clean Energy has contracted to purchase solar energy from a 23-megawatt PV plant from Cottonwood project for twenty-five years, starting in 2015 [Power Engineering, 2014]. To evaluate the environmental impacts of electricity from that solar PV power plant, I use data from a report by Fthenakis, et. al [Fthenakis, et. al, 2011] because it has the most up-to-date life cycle inventory data from First Solar's cadmium telluride(CdTe) thin film modules from both its Perrysburg, Ohio plant and Frankfurt, Germany plant in 2008. It also includes not only data for GHG emission, but also criteria air pollutants (NOx and SO2) data. The LCA in this report is based on these assumptions: 1) Southern Europe irradiation of 1700 $kWh/m^2/yr$; 2) Expected life time of 30 years for the PV modules; 3) electricity use during production is from European electric grid; and 4) CdTe solar conversion efficiency for the modules manufactured in 2008 was estimated to be 10.9%; and 5) a performance ratio (PR) of 0.75, which account for loss during DC to AC conversion and other systemic loss. BOS included in the analysis is rooftop installation. With these assumptions, GHG emission is 18 g of CO_2-eq/kWh, NOx emission is for 30 mg of NO_2-eq/kWh, and SO_2 emission is 60 mg of SO_2-eq./kWh.

A final note about these photovoltaics LCAs is that these studies do not allow for easy comparison with results from LCAs of other electricity generation technologies because solar PVs do not exactly provide the same service as others because of their intermittency subject to weather condition [Turconi, 2013].

Life Cycle Assessments of Electricity Generation from Wind

Along with solar PVs, wind energy has grown very fast as a renewable source of energy for electricity generation, from almost zero MW in 1980 to 35,000 MW in 2009 (Wiser and Bolinger, 2010). Marin Clean Energy's Deep Green Electricity program procures 100% renewable energy from wind farms in Idaho through a contract with Exelon Energy's Idaho wind project and Washington wind project [MCE, 2014a]. These are all land-based wind projects with utility- scale horizontal-axis 3-blade turbines. However, other details of those projects are lacking. The best estimate may come from a process called "harmonization".

A harmonization study screens and analyzes LCAs for different systems with various boundary and scopes and adjust the values from interested impact categories in those studies to a predefined set of harmonization parameters for comparability. The National Renewable Energy Lab led a wind power LCA harmonization project for both on-shore and off-shore wind power generation and the results is published in a paper by Heath and Dolan [Heath and Dolan, 2012]. Their harmonization study reviewed only published LCAs for utility-scale, 3-blade turbines that are at least 150 kW in rated capacity and whose rotor blades are not made of wood, steel, or aluminum. Only studies that had detailed description of system boundaries and assumptions and included upstream emission estimation are used in their studies. The technical factors for harmonization are capacity factor, GWPs (some wind LCAs reported individual GHGs emissions and are converted to CO2 eq.), operating lifetime, and system boundary. The capacity factor is the actual electricity generated to the maximum potential electricity generation over the course of a year. It effectively normalizes both turbine efficiency characteristics and site choices from different LCAs. Heath and Dolan noted that while wind farms operate at different capacity factors in practice, the mean onshore turbines from screened literature was 30% and 40% and are close to the capacity-weighted average from a survey of operating turbines. Wind LCAs had been done with different assumptions about lifetime of the wind turbines, ranging from 10 years to 100 years, but most reported 20 years as lifetime, and one manufacturer (Vestas) specifically design life of 20 years [Vestas, 2012]. Heath and Dolan harmonized the LCA results by lifetime of turbines to be 20 years by holding the total lifetime emission constant while changing the lifetime to twenty years. System boundaries needed to be harmonized because only 22 of the 67 estimates of GHG emissions that passed their quality screening included upstream (resources procurement, production, manufacturing, and installation of turbines), ongoing (maintenance and operation), and downstream (Disposal or recycling) stages. For those studies that had omitted ongoing and/or downstream stages, the median of the emissions from the rest of the studies were added in their harmonization process. The formula used for harmonization in this study is

$$\frac{CO_2 + \left(CH_4 * 25 \frac{g\ CO_2-eq}{g\ CH_4}\right) + \left(N_2O * 298 \frac{g\ CO_2-eq}{N_2O}\right)}{\textit{Capacity factor} * 8760 \frac{hours}{year} * \textit{Lifetime} * \textit{Nameplate capacity}}$$

After harmonization by all four factors, the mean and median life cycle GHG emission for onshore (land-based) turbines is 15 g of CO_2-eq/kWh and 11 g of CO_2-eq/kWh, respectively, while the maximum GHG emission is 45 g of CO_2-eq/kWh.

Some limitations of the harmonization study pointed out by the authors are: 1) lack of integration of assessments in other impact categories; 2) conversion loss from turbine to grid is omitted and only generated electricity is included, which the authors estimated to be <=10%; 3) none of the LCAs accounted for the backup system necessary to supply the electricity when turbines are not moving, there could be loss of efficiency in conventional generators as backup systems. Pehnt and colleagues [Pehnt, et. al, 2008] put the efficiency penalty at up to 8% for a 12% wind penetration rate, or up to 80 g of CO_2-eq/kWh added to the life cycle GHG emission based on modeling on the German electric grid. In this project, we will ignore the generation conversion efficiency because it is likely to be small.

Because electricity from wind turbines does not directly involve combustion, other emissions are generally small compared to conventional fossil fuel power plants. Criteria air pollutant emissions only come from manufacturing wind turbine are usually included in wind LCAs, according to Turconi [2013]. The ranges of NO_x and SO_2 emission factors reported in Turconi's review are 0.02–0.06 kg of NOx/MWh, and 0.02–0.04 kg of SO_2/MWh and are highly sensitive to the electricity mix of the manufacturing site. Life cycle PM is 0.0095 kg/MWh from Stoke and Horvath [2011]'s value based on international data. Without details about the manufacturer of those sites, the average values of these emissions will be used in this project.

Life Cycle Assessments of Biopower

Biopower allowed by the California Renewable Portfolio Standards (RPS) include biomass, digester gas, biodiesel, landfill gas, and municipal solid waste. PG&E procured substantial amount of electricity biomass-burning plants (20.7% of RPS-eligible procurement) [PG&E, 2014] while MCE purchased 16.1% in landfill gas-generated electricity and only 8.9% from biomass, respectively [MCE, 2014b]. Only insignificant amount of electricity (<5% of the total RPS procurement and an even smaller percentage of total retail electricity sold) were purchase in other bioelectricity categories and will be omitted from this project. Any amount of biopower not in the remaining categories will be counted as electricity from biomass for the PG&E and as electricity from landfill gas for MCE.

Life Cycle Assessments of Electricity from Landfill Gas

Few LCAs have been published for landfill gas for electricity generation alone. Most landfill LCAs include other solid waste treatment options such as incineration or landfilling without biogas recovery for comparison. One such study is from the solid waste treatment facility in Rome, Italy [Cherubini, et. al, 2009]. The paper presented 4 different scenarios (treatment options): landfill, landfill gas capturing (50%) burning for electricity, MSW sorting and treatment, and incineration. Plant operation is included in the LCI but collection is not. The input for electricity is methane (CH_4) extracted from landfill gas, which for the Rome case is 58%Vol of CH_4 and the rest is mainly CO_2. Since this CH_4 in landfill gas is not from a fossil origin, it is not counted in the inventory. For each scenario that provides energy output, its "gross GHG emission" is further discounted to become "net GHG emission". It was found that net GHG emission with the third option becomes negative, but that option combines biogas enrichment and incineration of sorted inorganic waste, which may not be the standard treatment option. For our purpose, capturing 50% of the landfill biogas and burning for electricity would be the most suitable scenario to use in our analysis. According to the data from the Rome facility, electricity produced per year is estimated to be 2.43 x 10^8 kWh, and the net

GHG, SO2, NOx, and PM emissions are 966 kt CO_2-eq, 186 t SO_2-eq, and 126 t NOx-eq,, and 0.502 t PM, respectively. The per-kWh values of those impacts are calculated to be 3,572 kg CO_2-eq/MWh, 0.765 kg SO_2-eq/MWh, 0.519 kg NO_x-eq/MWh, and 2.07 x 10^{-3} kg/MWh.

The actual impact of landfill gas burning is facility dependent. The amount of landfill gas captured in this Rome plant is only 50%, and it could increase electricity generation to reduce its impact. The efficiency of the turbine used in the Rome case is 28%. A recent Brazillian landfill study yielded 2,864 kg CO_2-eq/MWh with assumptions that captured 75% of biogas from landfill and burned in a 33% efficient reciprocating ICE engine. [Leme, MMV, et. al, 2014] At the same time, Cherubini, et. al.[2009] showed that landfill is not the best environmental options as more energy can be recovered in sorting plant with electricity and biogas production. But without knowing technical details of facilities that supply landfill gas electricity to MCE, it is assumed that the Rome case is applicable in our analysis.

Life Cycle Assessments of Electricity from Biomass

There are numerous LCAs done on biomass energy because of the diversity of possible feedstock ranging from woody construction and demolition (C&D) wastes and other organic wastes in urban centers, to woody forest residues and agricultural residues, to dedicated energy crops [Heath, et. al, 2011]. Turconi [2013] pointed out that environmental impacts of electricity generation from biomass power plants is highly dependent on the fuel feedstock used and that the accounting schemes of GHG emissions from biofuels and biomass used for electricity generation can be tricky. He argued that the use of residual biomass is generally assumed to have "zero burden" since residual biomass will decompose into CO_2, CH_4 and other GHG if left to decay but dedicated energy crops have water and energy inputs and thus environmental impacts just like other agricultural products. Those feedstock tend to cause extreme values in life cycle GHG emissions and eutrophication potentials. Without knowing specific feedstock or types of generators used by the many individual biomass electricity generators that sell electricity to PG&E and MCE, it is assumed that PG&E and MCE's purchase of biomass energy is diverse enough and no energy crops are in the feedstock to those power plants due to abundance of forest residues and urban wood wastes and agricultural residue [California Research Bureau, 2005] so that median value of GHG and NOx emissions in Turconi's review are good estimates. Turconi reported GHG, SO2, and NOx, emissions are 39 kg CO2-eq/MWh [Range: 8.5-130], 0.09 kg SO2-eq/MWh [Range: 0.03-0.94] and 0.51 kg NOx-eq/MWh [Range: 0.08-1.7], respectively. Heath, et. al [2011] reported similar median results from their biomass LCA harmonization project for GHG emissions across feedstock categories. Their reported values are 20 kg CO_2-eq/MWh for sawmill residues [Range: 0-110], 30 kg CO_2-eq/MWh for forest residues [Range: 0-170], and 40 CO_2-eq/MWh for urban residues

[Range: 10-60]. While imprecise, estimate of PM emission is taken from international literature. [Gagnon, 2002] The estimate of life cycle PM emission from biomass combustion is 0.255 kg/MWh.

Life Cycle Assessment of Electricity Generation from Digester Gas

Based on the eGRID 2010 (USEPA, 2014) database, three digester gas-burning plants produced electricity in PG&E's service territory in California in 2010. The source of these anaerobic digested gas is from wastewater sludge. Life cycle emission factors of electricity is based on Stoke and Horvath's analysis of a case study with data from an unnamed California utility [Stoke and Horvath, 2010]. The anonymous plant produces 40,000 MWh annually from 91,000 Ml (1000 m^3 = 1 Ml) of wastewater. The total life cycle GHG emission was calculated to be 55 kg/Ml (million liters) of wastewater. Converting to life cycle GHG emission for electricity generation from this plant, it is 91,000 x 55/40,000 = 125.1 kg/MWh. In similar manner, life cycle NOx, SOx, and PM emission are calculated to be 1.91 kg NO_x-eq/MWh, 1.07 kg SO_2-eq/MWh, and 0.66 kg PM/MWh. While Stoke and Horvath warns of case-specific nature of wastewater LCA, it is closest in geographical relevance (California) and includes one of the most comprehensive life cycle system boundary in their study, it is the most usable set of data found. A few details such as the use of "high-strength organic waste" to increase electricity production and unreported sources of materials inputs during the operation phase suggest that the case study indicates that this is not a typical wastewater treatment plant and is likely to have underestimated the life cycle emissions.

Life Cycle Assessments of Natural Gas Electricity Generation

Electricity is generated from natural gas in two major designs of natural gas power plants: natural gas combined cycle (NGCC) and natural gas combustion turbine (NGCT). The LCAs of electricity from NGCC in the United States has been conducted by Skone, et.al [2012], and Spath and Mann [2000]. Additionally, the National Renewable Energy Lab has completed its systemic LCA harmonization project for natural gas-fired power plants for life-cycle GHG emissions from literatures that are chosen to reflect "…a modern facility operating in the United States" [NREL, 2014] and the result is presented in a paper [O'Donoghue, et. al, 2014]. The most notable feature of the natural gas LCA harmonization project is that it included only those studies that followed accepted LCA method (ISO14040), and put a consistent system boundary on all studies by "harmonizing" those that failed to include certain well-studied stages, i.e. adding power-plant construction stage, operation stage, or liquids unloading from gas extraction if a study failed to include those. The standardized system boundary is show in the following diagram. The mean life cycle GHG emission factor for electricity from natural gas is 510 kg CO_2-eq/kWh.

For a more precise life cycle emission factors for PG&E's natural gas plants, values from Stoke and Horvath's paper [2011] with the 2010 eGRID [USEPA, 2014] data were updated following the procedure they took. The operation and maintenance stage emissions from Spath and Mann [2000] were replaced with the average emission from those gas-fired power plants operated within PG&E's service territory [2014]. I calculated the GWP to be 544 g CO_2-eq/kWh, which agrees fairly well with the harmonization study and is close to 514 kg CO_2-eq/kWh for an average baseload natural gas plant calculated by Skone, et. al [2012a]. This indicates that difference between those operating in PG&E's grid is not significantly different from the national average. For NO_x and SO_2 emission factor, I applied a similar procedure and estimated them to be 0.58 g NOx-eq/MWh and 0.32 g SO_2-eq/MWh, respectively. Most of the NOx and SO2 were emitted during the natural gas production and distribution but not during the electricity generation stage due to application of emission control technology, which is accounted for in the "average power plant". PM emission data is from Skone, et. al [2012a] for average NGCC and domestic NG mix, estimated at 0.0015 kg/MWh.

Life Cycle Assessments of Electricity Generation from Small Hydroelectricity Plants

Small hydroelectricity plants are those with capacity of less than 30 MW and are usually "run-of-river" type of plants, i.e. does not have its own reservoir and minimal alternation to the river. Detailed environmental and economic impact assessments of two selected small hydroelectricity reference sites in the US was performed by Oak Ridge National Lab and Resources for the Future [ORNL/RFF, 1994]. One of the reference site was in Southeast and the other is in Pacific Northwest. Even though these sites are geographically close to California, the authors stressed that the actual life cycle impacts of each project is highly dependent on the site of hydroelectricity plant and cannot be generalized, especially assessments of social and economic impacts, such as loss of habitats for endangered species, loss of the fishing and recreational opportunities and more. Hydroelectricity plants also offer benefits that are sometimes not explicitly quantified in an LCA study, such as flood control ability and as energy storage for intermittent renewable energy technologies, flexible production capability of the electric grid, water management capability. Those impacts and benefits will not be considered in this project.

Although not all small hydroelectricity plants are run-of-river, but they are more likely than large hydroelectricity to be so [Kumar, A., et. al, 2011]. For small hydros in this project, it is assumed that all of them are run-of-river. The estimated life cycle GHG emission of is 7.4 g CO_2-eq/kWh (median of literature review by Kumar,et. al), although estimates range from 4-14 g CO_2-eq/kWh in literature. For life cycle emissions of NOx, SO2, and PM, values from Stoke and Horvath [2011]'s estimate of US average will be used in our estimates. They are 0.019 kg NOx-eq/MWh, 0.004 kg SO_2-eq/MWh, and 0.0057 kg/MWh, respectively.

Life Cycle Assessment Results of Electricity Generation from Large Hydroelectricity Plants

The median life cycle GHG emission from Kumar, et. al [2011] is about the same as that for small hydro plants. However, because the large hydro plants usually include building of reservoirs, which involve flooding of vegetated areas, land-use change (LUC) emission during construction and decommissioning need to be taken into account. In addition, covered vegetated area could turn organic matter into large amount of potent CH_4 gas under anaerobic condition over the lifetime of the reservoir. Horvath [2005] pointed out the a large uncertainty in GWP dependent on size of flooded area, carbon density of the ecosystem, and temperature dependent (which influence rate of decay) in the flooded area. Using parameters given in the Glen Canyon hydroelectricity plant, Horvath estimated the additional GHG could be as high as 2,969 kg CO_2-eq/MWh if the same project was built in a tropical rainforest. Pacca [2007] also gave a large estimate of an additional 380 kg CO_2-eq/MWh added to the life time GHG emission to the electricity produced at the Hoover dam. Skone, et. al [2012b] estimated life cycle CO2-eq. emission of large hydro to be 43.8 kg CO_2-eq/MWh based on the scenarios of a newly constructed "conventional" dam with reservoir in the US using technical data from Colorado and Wisconsin, assuming a 2,080 MW dam-reservoir-hydro plant system with capacity factor of 37% and lifetime of 80 years. Land use change and emission during operation from reservoir were included in the calculation. Skone and colleagues also included an estimated land use change GHG emissions during construction for different regions in the US. After land use change GHG emission for US is substituted with that of US West (US Avg: 9.4 kg CO_2-eq/MWh; US West: 8.6 kg CO_2-eq/MWh) and T&D portion is subtracted from the total, and remove the effect of transmission loss, the life cycle GHG emission for a large hydro in US West is (43.8 – 9.4 + 8.6 – 3.3) x (1 – 0.07) = 36.7 kg CO_2-eq/MWh. Because this study included most details relevant to our region and included land use change emissions, it gives the best estimates for the purpose of estimating emissions from PG&E's large hydro plant. The life cycle estimate of NOx, SO2, and PM emission from large hydro are 0.0173 kg NOx-eq/MWh, 0.0112 kg SO_2-eq/MWh, 0.00527 kg/MWh. These life cycle NOx, SO2, and PM emission values will also be used for small hydro plants.

While Skone and colleagues's estimate is more conservative than Horvath [2005] and Pacca [2007], they still gave large uncertainty from reservoir emission during the plants' operation depending on reservoir capacity, plant lifetime and reservoir emission factor. The upper estimate given is 130 kg CO_2-eq/MWh. A sensitivity study will be done based on this maximum value of GHG for electricity generation from large hydro.

Life Cycle Assessment Results of Electricity Generation from Nuclear Power Plants

Skone et. al. [2012c], studied the life cycles of Gen II ("existing") and Gen III light-water reactors, which include pressurized water reactor (PWR) and boiling water reactor (BWR). Life cycle stages included in the study are nuclear fuel acquisition, fuel assembly transport, nuclear power plant, electricity transmission and distribution(T&D), and end use. Its functional unit was "MWh of electricity delivered to end user", and assumed a 7% loss for transmission and distribution, which is beyond the scope defined in this paper and will be subtracted.

PG&E operates the Diablo Canyon Nuclear Power Plant, which includes two pressurized water reactor (PWR) [Mayeda and Riener, 2013]. Each of the two reactors has 1100 MW capacity. Together they generated about 9.3% of the total California's electricity in 2011. Data from Skone, et. al (2012c)for GenII LWR reactors will be used in this project.

Skone reported life cycle GHG emission for existing reactor (Gen II) for default fuel enrichment mix (52% gaseous diffusion and 48% centrifuge) as 39.5 g CO_2-eq/kWh, with 3.3 g CO_2-eq/kWh from T&D loss. So within our scope of study, life time GHG emission factor estimation is 36.2 g CO_2-eq/kWh. The life cycle NOx, SO2, and PM are estimated at 0.0759 kg NOx-eq/MWh, 0.192 kg SO_2-eq/MWh, and 0.00423 kg/MWh, respectively.

Life Cycle Assessment Results of Electricity Generation from Geothermal Plants

Skone, et. al [2012d] also completed LCA for flash steam geothermal power plants with the five life cycle stages listed above in the nuclear power plants section. Most of the GHG emissions occurs at operation stage, when a mixture of "geofluid" that includes CO_2, water, and other fluids is injected into the well to absorb geothermal energy and comes back as steam to drives a turbine to produce electricity. The steam is released into the atmosphere. The reported life cycle GHG emission is 241.9 kg CO_2-eq/MWh with transmission and distribution loss subtracted (not within the scope of this project), and NO_x emission is 0.01253 kg NO_x-eq/MWh, SO2 emission is 0.003107 kg SO_2-eq/MWh, and PM emission is 0.001317 kg/MWh.

Life Cycle Assessment of Electricity Generation from Coal

California doesn't produce electricity with coal, but there is an unspecified portion of the electricity in the system imported from WECC Southwest, whose system supply include generation from coal power plants [CEC, 2014]. The life cycle emission factors estimates are taken from Skone, et. al's most recent study [2010] and then divided by (1- loss rate) in transmission and delivery (assumed to be 7% in the model) and replace emission factor from the operation stage with 2010 eGRID data for Southwest grid coal power plants emissions. The resulting emission factors are 1105 kg CO_2-eq/MWh, 1.86 kg NO_x-eq/MWh, 2.232 kg SO_2-eq/MWh, and 0.6417 kg/MWh.

4. Approach/Model

Goal & Scope Definition

The goal of this project is to quantify life-cycle environmental impacts of building new renewable energy facility to accommodate the electricity demand of communities choosing to obtain electricity through CCA, and compare that with continuing to purchase electricity through PG&E over 20 years, starting from year 2015. Based on results from Turconi, et. al., all phases of life-cycle of renewable electricity generation facilities are considered in the impact assessment. Therefore, the scope of includes impacts from construction of generating facilities, acquisition of fuel (if applicable), operation and maintainance, decommissioning of the generating facility. This is known as the "cradle-to-grave" LCA. **Figure 3** below summarizes the system boundary of this study.

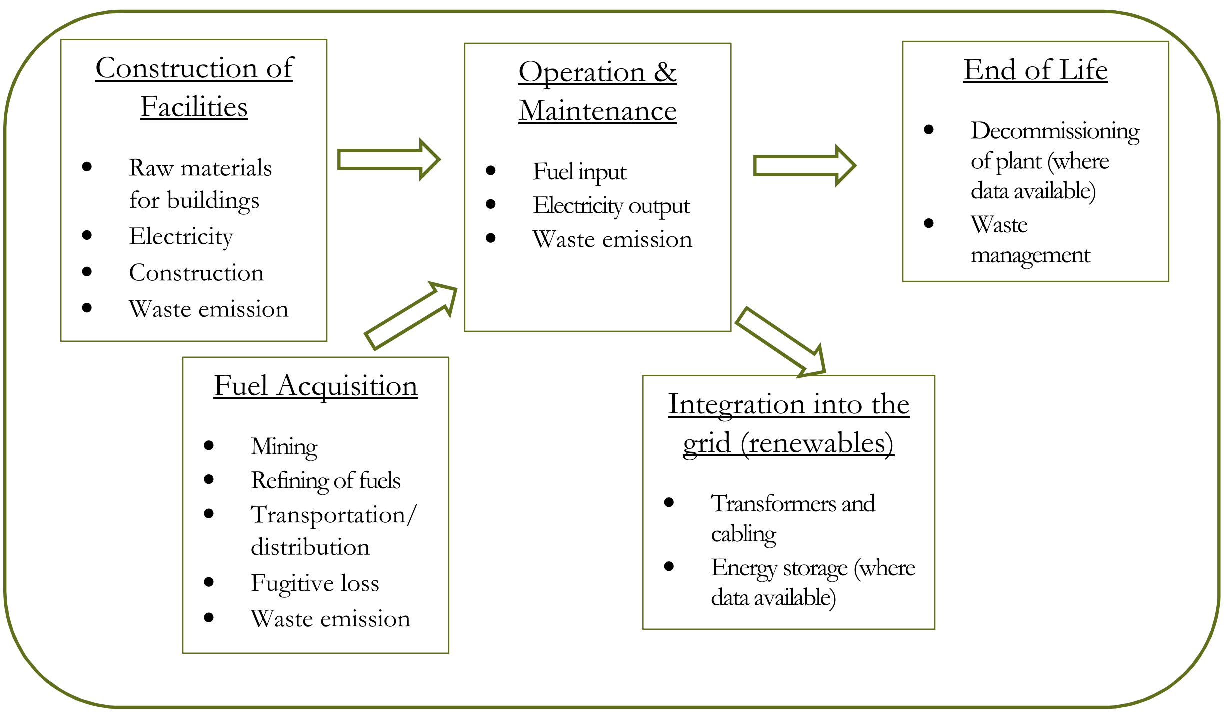


Figure 3 – A generic system boundary that account for all relevant power generation technologies.

Since PG&E has existing facilities for coal and other non-renewables, construction phases may be ignored as damage has already been done. It may be interesting to take away the impact from construction phase and see if how that influence the comparison for sensitivity study.

Greenhouse Gas, SO_2, and NO_x, PM emissions are considered in our impact analysis, as these are most commonly included data from past LCA studies of different electricity generation technologies. The data obtained are, where possible, for California or location of the generating facility.

Economic sustainability is also a concern of the Office of Sustainability. Therefore, the levelized cost of electricity (LCOE) estimates will be collected from relevant reviews for comparison over the 20 years.

Finally, there are social consequences that associate with the potential choice with CCA. Those consequences will not be explored in this study. Different power generation technologies also provide different services besides electricity generation. For example, landfill's main function is a solid waste management solution, while hydroelectricity plant can provide flood control services. Those will not be considered in this study, either.

Methods

This study will be a meta-analysis of previous LCA literature on electricity generation from different generating technologies. Data for GHG, NOx, SO2, and PM emissions will be collected from published papers or technical reports with life cycle analyses of systems that are representative of plants operating in the United States and, preferably California. Specifically, attention will be paid to ensure that system boundaries described above. Because some renewable energy technologies are still in a fast pace of development and technical parameters could be changing quite fast, latest life cycle assessment results will be used. Whenever possible, emission factors of those studies will be adjusted to the latest emission factors from PG&E's power plants using 2010 eGRID data from US EPA [2014]. For comparability between different power generation technologies, the same system boundary applies for all of them and a consistent functional unit is defined for all of them below. There are also assumption in this study that will be described below. After the life cycle emission data is collected for all power generation technologies, a weighted-average life cycle GHGs, NOx, SO2, PM emission factors will be calculated for MCE's power mix portfolio for its Deep Green (100% renewable) Program and Light Green (50% renewable) programs, and PG&E's, in 2012 and 2013. Their environmental impact will be compared based on comparison of these weighted average. The five power mix scenarios explored are MCE Deep Green (Scenario 1), MCE Renewables 2012 (Scenario 2), MCE Renewables 2013 (Scenario 3), PG&E 2013 (Scenario 4), and PG&E 10-Year Average (Scenario 5). The PG&E 10-Year Average is chosen because PG&E already has procured large enough quantities in renewable in the next few years through long-term contracts to allow a reasonable trend to be seen. It will acquire increasing amount of solar thermal and solar PV in the next few years. For the life cycle cost estimations, it is difficult to predict the future market price of electricity from PG&E and MCE. However, the levelized cost of electricity (LCOE) for each power generation technology is a good estimate for future generation costs.

Data will be collected for the different power generation technologies from the California Energy Commision [CEC, 2009]. A similar weighted average will be used to compare the different power mix portfolios. Subsidies are available for some renewable technologies and will be included.

Model Assumptions/Limitations

Because PG&E's goal for 33% renewable by 2020 has not been fully materialize, it is assumed that PG&E will meet that goal through its planned projects. This project will also assume two different scenarios where the CCA serving Berkeley in the future will add capacity with the same energy resources portfolio as Marin Clean Energy in 2012 and 2013, respectively. For the different electricity generation technology, only amount of electricity generated in megawatt-hour (MWh) is counted. This will not count any loss in the electricity transmission and distribution network (grid loss) nor the use of electricity at the customer's side. This will not distinguish electricity generated at peak hours, which some renewable energy technologies are only capable intermittently.

In reviewing the relevant LCAs for different power generation technology, authors often use different lifetime for a particular power generation technology. It is easy to see that the longer the assumed lifetime of a power generation facility is, the lower the construction and decommission phase contribute to the overall life cycle emission factors. As with all infrastructure, the service life is often different than what the designers expect, it is difficult to judge what the design lifetime of structure should be, especially with developing renewable energy technologies, with which we have limited experience [Lemer, 1996]. When a LCA literature is selected as representative of a typical power plant in the PG&E and Marin Clean Energy's, it is assumed that the chosen lifetime is deemed appropriate by the professional judgment of LCA author, and therefore, valid to compare the results of their LCA studies. For example, the life cycle emission factor from a wind turbine based on a 20-year service life is considered comparable to emission factor from a nuclear reactor based on a 40-year life time.

Functional Unit

Although there are multiple environmental goals and economic goals to compare between the two choices facing UC Berkeley, it is necessary to use one functional unit, defined as emissions for "each MWh of electricity generated and delivered to the grid". For comparisons of global warming potential (GWP), it is customary to use kg of CO_2-eq./MWh of electricity generation as the functional unit. The CO2-eq emission in this study is normalized to the 100-year GWP given in the 2007 IPCC assessment report on radiative forcing [Forster, et. al, 2007]. The values used are 34 for methane (CH_4), 298 for nitrous oxide (N_2O), and

22,800 for sulfur hexafluoride (H_2S). For NO_x emission, kg of NO_x per MWh of electricity generation is the functional unit. Similarly, for acidification potential, kg of SO2-eq./MWh of electricity generation is used as the functional unit. For cost of electricity generation, levelized cost of electricity (LCOE) is expressed in dollars per MWh for comparison.

5. Findings and Results

Determining Unspecified System Power Life Cycle Emissions

According to the CEC [2014], California imported 19,750 GWh of unspecified power from WECC Northwest and 17,305 GWh from WECC Southwest. Unspecified power usually come from hydro and natural gas plants from Northwest and coal and natural gas plants from the Southwest. Without any uncertainty, unspecified system power from Northwest is assigned 50% from large hydro and 50% from natural gas, and unspecified system power from Southwest is 50% from coal and 50% from natural gas. After weighing each source of electricity in the unspecified mix, I determined the following life cycle emission factors for unspecified power: 539.9 kg CO_2-eq/MWh, 0.73 kg NO_x-eq/MWh, 0.68 kg SO_2-eq/MWh, and 0.152 kg/MWh in PM emission.

Summary of LCA Results for Different Electricity Generation

The life cycle GWP, SO_2, NO_x, and PM emission factors for each generation technology is summarized in the table below. All values have been converted to the unit of kg/MWh. Uncertainty in GHG emissions are estimated based on results reported in the selected LCA or reviews or are own estimations.

Life Cycle Emissions	GWP (kg CO2-eq/MWh)	NOx (kg NOx-eq/MWh)	SO2 (kg SO2-eq/MWh)	PM (kg/MWh)
Natural Gas	544	0.58	0.320	0.0015
Nuclear	36.2	0.08	0.192	0.0042
Large Hydro	36.7	0.02	0.011	0.0053
Small Hydro	7.4	0.02	0.004	0.0057
Solar PV	18.0	0.03	0.060	0.0700
Solar Thermal	42.5	0.09	0.059	0.0352
Wind	11.0	0.04	0.030	0.0095
Biomass	39.0	0.51	0.090	0.2500
Landfill Gas	3572	0.52	0.765	0.0021
Geothermal	243	0.01	0.0031	0.0013
Coal	1105	1.86	2.23	0.6417
Unspecified	540	0.73	0.68	0.152

Table 1 – Life cycle emission factors for relevant power-generation technologies in MCE and PG&E's power mix portfolio. The highlighted values are the 5 power generation technology with the highest emission factors in each impact category.

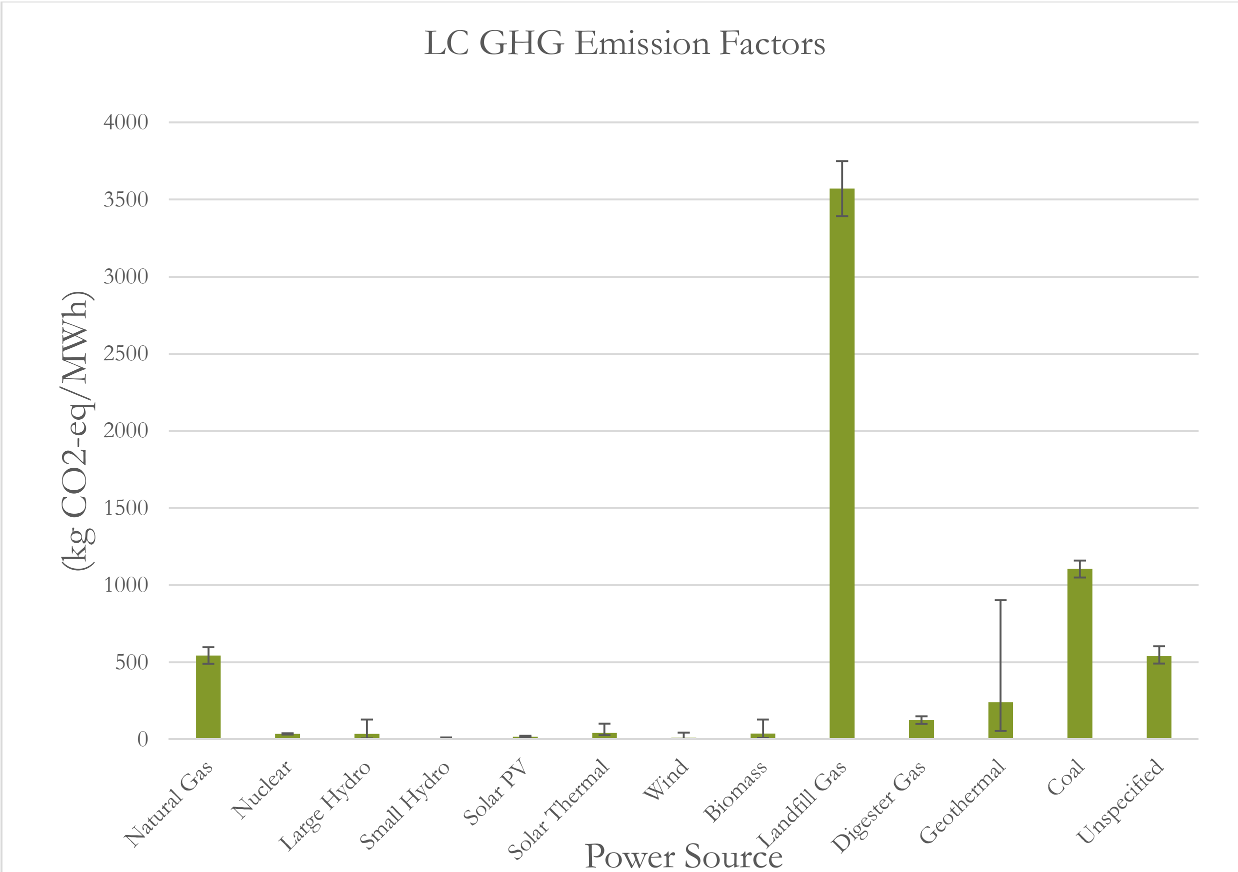


Figure 4 – LC GHG emission factor from differ power generation sources (technologies).

This list of life cycle emission factors highlighted a few notable results:

- While "renewable" energy, as defined in the RPS law in the California, usually are less carbon-intensive, they do not always have lowest life cycle emission factors. Notable exception are nuclear and large hydros, which are "non-renewable" but may have lower life cycle GHG emission than solar thermal or biomass.
- Unspecified system energy could be a significant contributor to GHG and other emissions.
- Wind energy and hydros are the best performer in many of the selected impact categories and, therefore, are environmentally preferable.
- Different generation technologies have different degrees of uncertainties as seen in **Figure 4**. Geothermal, landfill gas, biomass, and large hydro have large uncertainties that are sensitive to either location, operation practices at the plant, or sources of fuels.
- Landfill gas is a renewable energy source, but to capture it requires much resource and is inefficiency. As a result this technology emits a lot of GHGs in its life cycle.

Evaluating Life Cycle Emission Factors of Electricity in Power Mix of Marin Clean Energy (MCE)

Scenario 1 – MCE Deep Green

The power mix of MCE's Deep Green program in 2013 consists solely of wind power, therefore, its emission factors are simply those of wind power generation. This is the most ideal power mix of all. However, the current state of technology does not allow all electricity that Alameda County consumes come from wind energy alone due to the intermittent nature of wind. Large scale energy storage project will need to exist as backup when wind turbines are not turning. The environmental impact of such energy storage devices are not studied here.

Scenario 2 – MCE Renewable Portfolio 2012

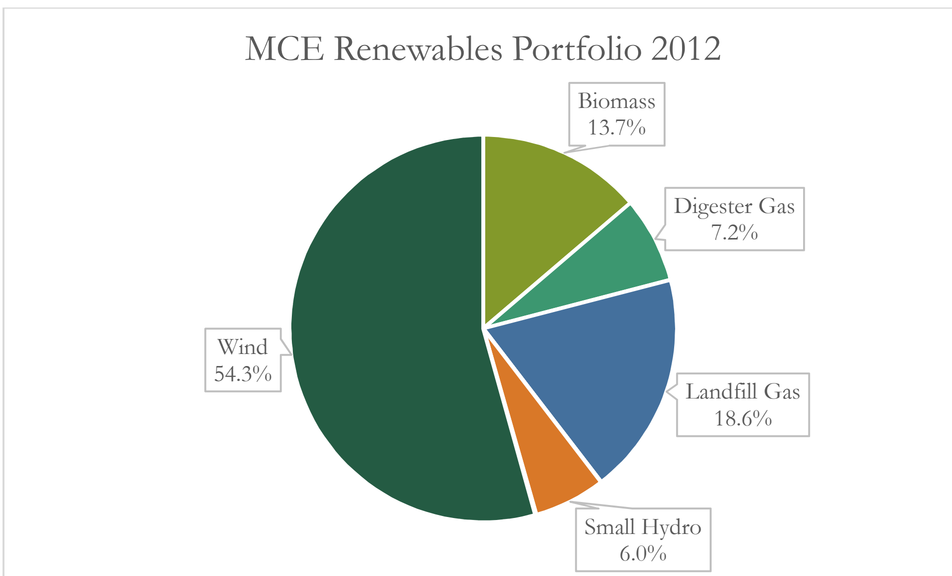


Figure 5 MCE power mix 2012. Source: MCE RPS Compliance Report (2014)

The MCE Renewable Portfolio 2012 is shown in **Figure 5**. In its first full year of operation, MCE bought a majority of renewable electricity from wind and landfill gas.

The total amount of renewable energy procured by MCE in 2012 was 166,522 MWh. The power mix's life cycle emission factors is a weighted average: the product of percent of the each power source in the portfolio times the emission factor of that source given in Table 1, all summed together. The result is the life cycle emission factors for this portfolio. The result is presented in **Table 2**.

Life Cycle Emissions	kg/MWh
CO2-eq	686.1
NOx	0.327
SO2 (kg/MWh)	0.249
PM (kg/MWh)	0.088

Table 2 *Life cycle emission factors of MCE's 2012 renewable portfolio.*

Because of the large life cycle GHG emission factor associated with electricity from landfill gases, the overall GWP of consuming 1 MWh of electricity from MCE's renewable sources is 686.1 kg CO2-eq. To put it in perspective, that is higher than getting 1 MWh from PG&E's natural gas power plants, which MCE set out to replace.

Scenario 3 – MCE Renewable Portfolio 2013

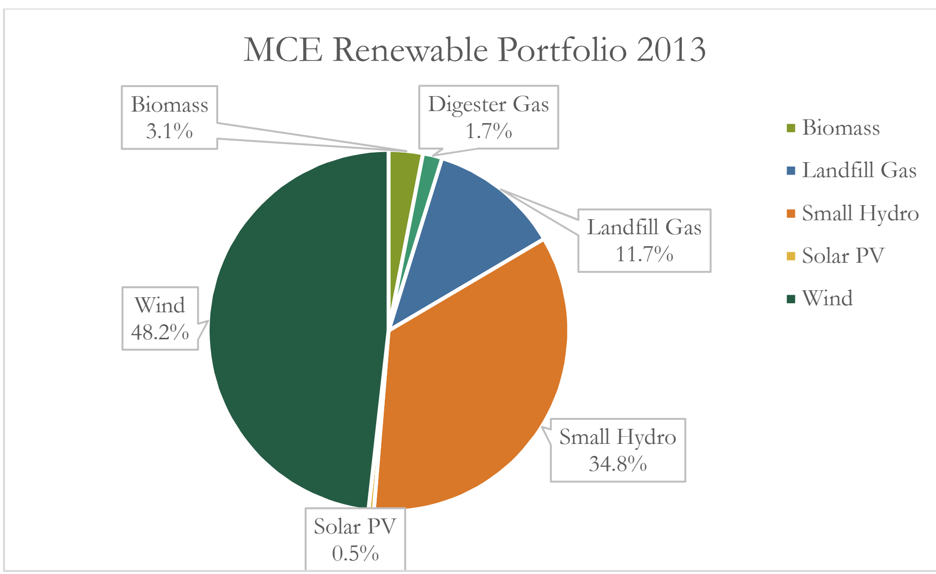


Figure 6 *MCE power mix 2013. Source: MCE RPS Compliance Report (2014)*

The MCE Renewable Portfolio 2013 is show in **Figure 6**. Compared to its 2012 renewable portfolio, there are significant changes in 2013. Wind continues to be a large part of MCE's portfolio while small hydro became a significant portion of its portfolio in 2013.

Life cycle emissions	kg/MWh
CO2-eq	429.9
NOx-eq	0.135
SO2-eq	0.127
PM	0.026

Table 3 *Life cycle emission factors of MCE's 2013 renewable portfolio.*

The life cycle emission factor for this power mix scenario is shown in **Table 3**. Because of the still sizable percentage of the landfill gas, GHG emission is still high. The total renewable energy purchased by MCE is 360,267 MWh, more than doubled the amount from the previous year. A higher percentage of hydro and lower percentage of landfill gas lowered helped reduce the dominating contribution to GWP. Reduction is also seen in NO_x and SO_2, and PM emission due to lower biomass combustion.

Scenario 4 – PG&E Portfolio 2013

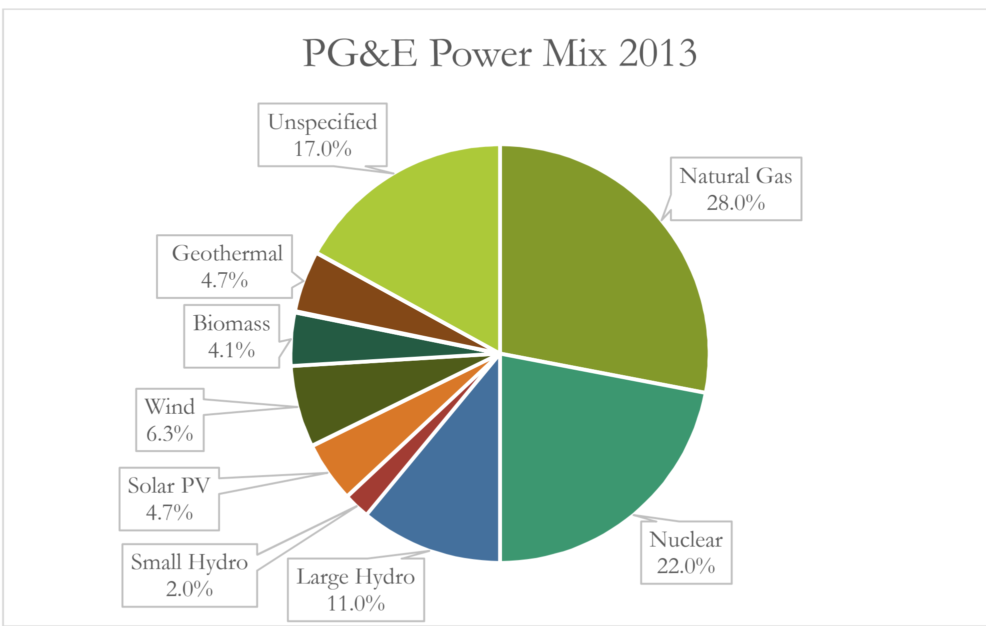


Figure 7 *PG&E power mix 2013. Source: MCE RPS Compliance Report (2014)*

PG&E's 2013 power mix is a good reference point to we can compare MCE's renewable portfolios in 2012 and 2013 and PG&E's progress during 2011 to 2020. PG&E has a much larger electricity retail electricity volume. In 2013, PG&E sold 75,705,039 MWh of electricity. That is more than 200 times that of MCE's renewable procurement and about 75 times MCE's 2013 retail volume of 1,110,487 MWh [PG&E, 2014]. Its power mix is shown in **Figure 7**.

Half of the electricity from PG&E came from natural gas and nuclear. The most sizable renewable source in this mix is wind and followed by geothermal, which is far from carbon-neutral from the life cycle perspective. Life cycle emission factors are calculated in the same manner as before using procurement data from PG&E's *Renewable Procurement Progress Report* [2014], but includes non-renewable sources such as natural gas, nuclear, large hydro, and unspecified system mix. The result is shown in **Table 4**.

Life cycle emissions	kg/MWh
CO2-eq	274.6
NOx-eq	0.331
SO2-eq	0.259
PM	0.042

Table 4 *Life cycle emission factors of PG&E's 2013 portfolio.*

PG&E's 2013 portfolio is significantly lower in life cycle GHG emissions due to its low percentage of electricity from landfill gas. However, its NOx, SO2, and PM life cycle emissions are each about twice as high as those values in MCE's portfolio. This is not surprising since burning of natural gas and coal (from unspecified portion). While PG&E's power mix may save significant amount of GHG emission, it's worse at other impact categories. This represents the current state of environmental impact of electricity from PG&E.

Scenario 5 – PG&E 10-Year Average Portfolio

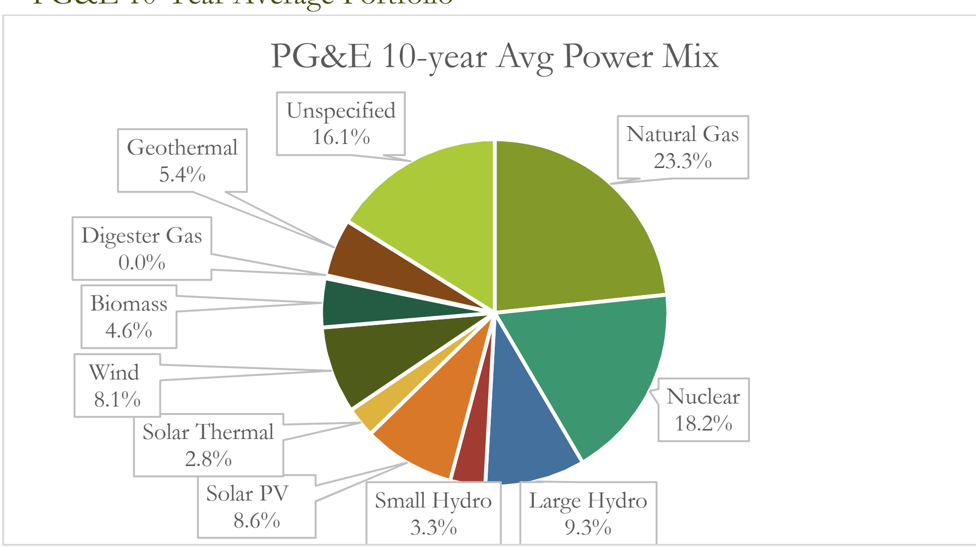


Figure 8 *PG&E's 10-year average power mix 2011-2020 based on its procurement progress.* ***Source:*** *PG&E RPS Compliance Report (2014)*

PG&E's portfolio has shown a somewhat stabilized trend towards 2020. This scenario aims to capture some of that trend (more solar PVs and solar thermal) while not discounting the contributions from other sources. The 10-year average is obtained by calculating the total electricity procured from each source over the 10 year period from 2011 to 2020, and then divide each by the total procurement to obtain the relative abundance of electricity from each source within renewable procurement over the 10 years. Municipal solid waste as an electricity source has been phased out by PG&E since 2011. Its contribution from 2011 is in the order of about ~1/1000 of the 10-year total retail and is omitted from the total. Because of lack of procurement data on the non-renewables, their relative abundances were estimated from the imprecise power content labels from 2012 and 2013 [PG&E, 2014a]. Assuming renewable is 33% of total at 2020 and beyond, the 10-year power mix scenario is shown in **Figure 8**. When the 33% goal is met, PG&E's share of electricity from nuclear and natural gas shrink. Solar PV replaced wind as the most used renewable source of electricity at PG&E while the Ivanpah Project puts itself on the pie supplying ~3% of PG&E's retail. The life cycle emission factors of this power mix are calculated and presented in **Table 5** below.

Life cycle emissions	kg/MWh
CO2-eq	252.1
NOx-eq	0.303
SO2-eq	0.237
PM	0.046

Table 5 *Life cycle emission factors of PG&E's 10-year average portfolio.*

This power mix scenario has life cycle emissions that are about 10% less CO2, NOx, and SO2 compared to Scenario 4 but PM emission is slightly higher due to the larger share of solar PV and solar thermal. This shows that PG&E will make considerable progress over the next few years when compared to 2013.

Comparing the Environmental Impacts of Different Power Mix Scenarios

Table 6 offers a side-to-side comparison of the life-cycle environmental impacts the five different power mix scenarios.

Scenarios / LC emissions	MCE Deep Green (1)	MCE Renewables 2012 (2)	MCE Renewables 2013 (3)	PG&E 2013 (4)	PG&E 10-yr Avg (5)
CO2-eq (kg/MWh)	11	686	430	275	252
NOx-eq (kg/MWh)	0.040	0.327	0.136	0.331	0.303
SO2-eq (kg/MWh)	0.030	0.249	0.127	0.259	0.237
PM (kg/MWh)	0.010	0.088	0.026	0.042	0.046

Table 6 *Side-to-side comparison of life cycle impacts of the five power mix scenarios.*

For comparing global warming potential (GWP), all the values in LCA studies reviewed have been conveniently given in units of kg CO2-eq on a 100-year basis. Based on MCE's specific renewable power mixes in 2012 and 2013, it has the higher global warming potential (GWP) than PG&E's power mix. However, its Deep Green program, which used solely wind energy in 2013, has the lowest GWP. The value between the Deep Green program and other portfolio differs by at least an order of magnitude. By convention, only difference of this magnitude matters. Other portfolios are considered comparable and there is no material difference between their GWPs.

NOx emissions can cause a variety of human health and environmental issues. Based on the LC emission factors of each scenario, the Deep Green program also outperforms the rest by an order of magnitude, and therefore, preferable. NOx emissions in scenarios 2-5 show some differences, but can be considered immaterial.

SO_2 emissions has acidification potential. Based on the LC emission factors of each scenario, the Deep Green program also has significantly lower SO_2 LC emission factor and is preferable. SO_2 emissions in scenarios 2-5 show some differences, but can be considered immaterial.

Particulate matter (PM) can cause various respiratory health issues and cancer. The result above show lower PM emissions from the Deep Green scenario, but it cannot be considered a significant difference between Deep Green and scenarios 3-5.

Levelized Cost of Electricity (LCOE) Comparison between Power Mix Scenarios

Power Generation	LCOE (2018 $/MWh)
Natural Gas	159
Nuclear	273
Large Hydro [1]	160
Small Hydro [1]	160
Solar PV	295
Solar Thermal	289
Wind	108
Biomass	162
Landfill Gas *	79
Digester Gas *	79
Geothermal	128
Coal	142
Unspecified	155

Table 7 *Median LCOE found in CEC report.* ***Source****: CEC (2009)* *1. Large hydro and small hydro are assumed to have the same LCOE. 2. Data unavailable from CEC, value used is from NREL Open EI (2014).*

The LCOE data for each generation technology from CEC [2009] and OpenEI [2014] for in-service year 2018 is compiled in **Table 7**. Value for solar technology shown is perhaps outdated, but is the latest publicly available version from CEC. The weighted average of the LCOE of each portfolio is calculated in similar way as the LC emission factors. **Figure 9** shows how the LCOE of each portfolio compare side-by-side to each other. Nuclear power plants, natural gas plants, and solar plants have the highest LCOE. However, as a result of development of solar power technology and tax credits, has led to large drop in cost during the last decade or so [USEIA, 2014] and it has continued that trend since 2009. That trend was not reflected in these rough estimation of LCOE. Because PG&E has acquired addition capacity with solar purchases since 2013, its LCOE is likely overestimated. Data from biogas was taken from OpenEI, which could lead to additional uncertainty. By Klein's rule of thumb, these LCOE shows neither PG&E nor MCE has cost advantage.

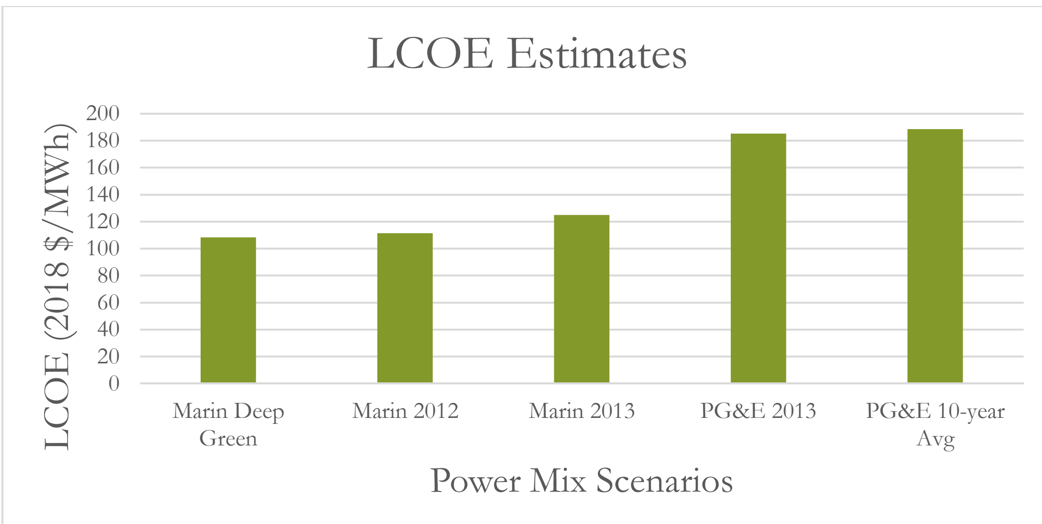


Figure 9 *PG&E's 10-year average power mix 2011-2020 based on its procurement progress.* ***Source:*** *PG&E RPS Compliance Report (2014)*

6. Sensitivity Analysis

The analysis of life cycle emission factors of the scenarios may be heavily influenced by values of each individual source technology. It is necessary to find out to what extent that large uncertainty from large hydroelectricity plants influence the life cycle GHG emission factor of the different power mix scenarios. As noted by Horvath [2005] and Pacca [2007], estimation of the life cycle GHG emission of large hydroelectricity plants may be seriously underestimated. It may go as high as ~2500 kg CO_2-eq/MWh. Another source of large uncertainty lies in the estimation of GHG emission from power generation from landfill gas. The case study was based on a landfill in Rome, Italy [Cherubini, et. al, 2009]. Based on the case parameters, it may reduce GWP by increasing its gas capture and utilization rate or use a more efficient burner. It is possible that the Rome case is an outlier and landfills in California could be performing significantly better than the Italian landfill. Therefore, two parameters will tested in this sensitivity analysis: GHG emission factor of large hydroelectricity [only affects PG&E scenarios] and the GHG emission factor of landfill gases [for scenarios 2-5].

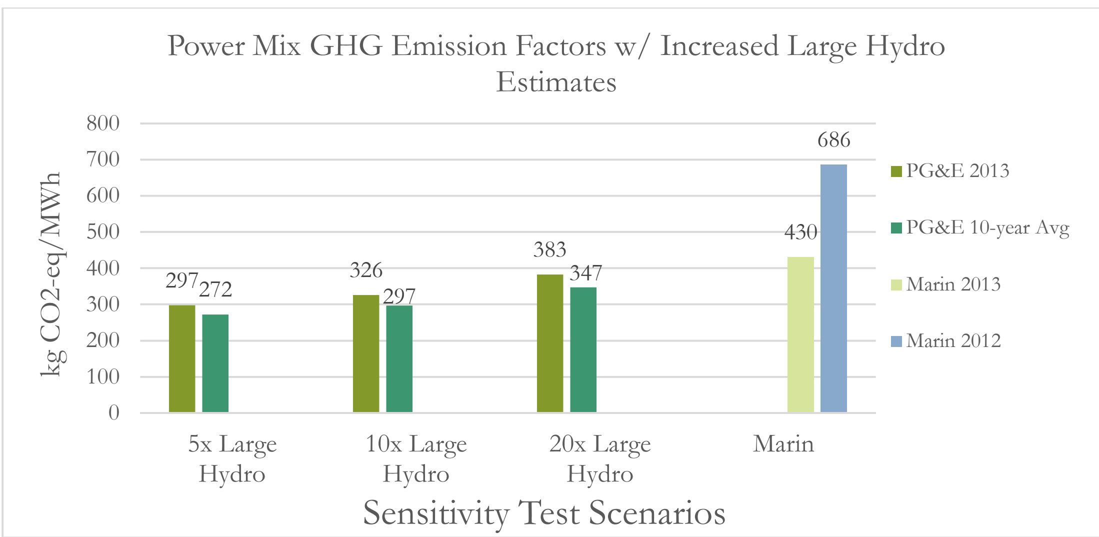


Figure 10 *This graph shows LC GHG emission factors recalculated with 5x, 10x, and 20x the original large hydro GHG estimates.*

To test the effect of the as large hydro uncertainty, GHG emission factor of at 5x (183.5 kg CO_2-eq/MWh), 10x (367 kg CO_2-eq/MWh) and 20x (734 kg CO_2-eq/MWh) its current value will be used in the model and the emission factors of the scenarios will be recalculated for scenarios 4-5 (since there's no electricity from large hydros in MCE's renewable portfolios), assuming the all other emission factors stay the same. The result is shown in **Figure 8**. Even at 20 times the original estimates, the GHG emission of the PG&E power mix portfolio increased only modestly. Only about 10% of PG&E's electricity come from large hydro. This number will likely not be increasing substantially as the availability of suitable sites for large hydros are relatively few and are likely to face serious scrutiny and opposition by local community. [ORNL/RFF, 1994] Therefore, a larger life cycle GHG emission estimates from large hydro will not be likely to change the environmental preference for PG&E's power mix.

Another parameter to be tested is the estimation of life cycle GHG emission from landfill gas. With a higher landfill gas utilization rate and higher efficiency in electricity production, increased electricity production from the plant could offset more GHG emission and lead to a lower emission factor. Landfill gas life cycle GHG emission factors will be evaluated at 30% (1072 kg CO_2-eq/MWh), 50% (1786 kg CO_2-eq/MWh), and 70% (2500 kg CO_2-eq/MWh) of the original estimate from Cherubini, et. al [2009]. LC GHG emission factors will be recalculated for scenarios 2-5. The result is shown in **Figure 9**. MCE's 2012 and 2013 renewable power mix included a 19% and 12% share of the electricity from landfill gas (LG). While not a majority, these portions were significant enough to dominate contribution to LC GHG emission of the whole portfolios. A large reduction in MCE power mix scenarios LC GHG emission is seen when original landfill gas GHG emission factor is reduced. In fact, when landfill gas LC GHG estimates is down to 50% of estimate from Cherubini, et. al [2011], MCE's power mix starts to like a more favorable alternative to PG&E in overall GWP. Because PG&E uses relatively little (<1% total retail) electricity from landfill gas, no substantial changes in LC GHG emission of its power mix is seen. Based on its *Procurement Progress Report* [PG&E, 2014], it has started to buy more power from landfill gas generation, but the amount is still insignificant.

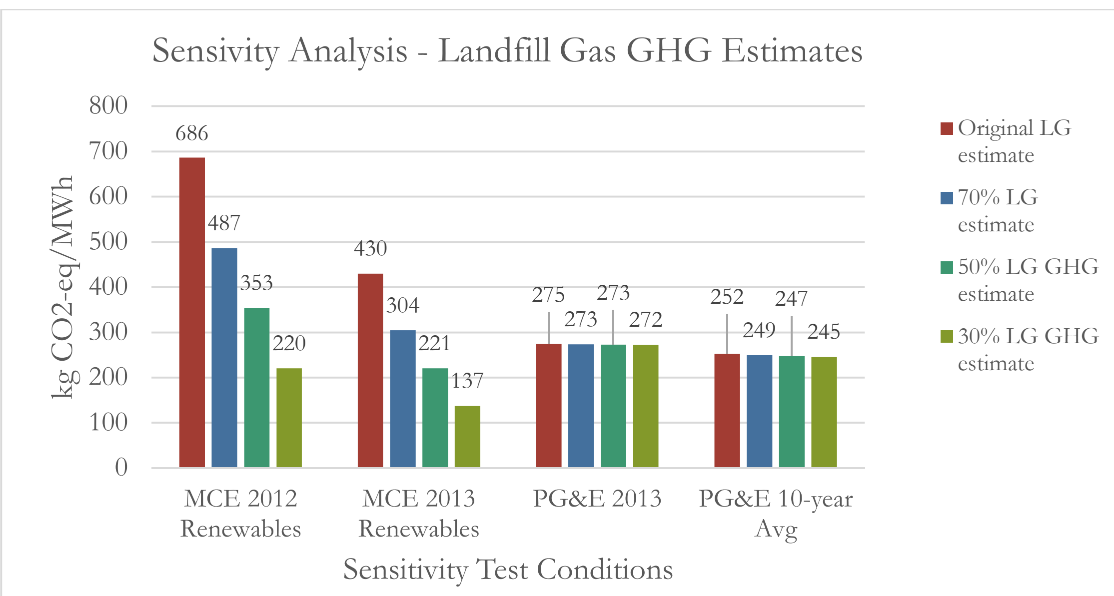


Figure 11 Scenarios *LC GHG emission factors recalculated with 30%, 50x, and 70x the original landfill gas (LG) GHG estimates.*

7. Uncertainty Assessment and Management

Power Mix Data Quality from MCE Renewables and PG&E.

Because of reporting requirement in California in recent years, MCE and PG&E's renewable electricity purchases are very well documented, down to each kWh of electricity. The relative portion of PG&E's non-renewable are based on PG&E's power content labels, while slightly less precise, is still within ±1% of total retail. Because there is an "unspecified" category in PG&E's power mix, its actual power mix is uncertain. The estimated mix in "unspecified" category is based on unqualified claims from CEC [CEC, 2014] introduces more uncertainty into PG&E's power mix data.

LC Emission Factor Data of Each Power Generation Technology

LC emission factor data are based on review of LCA literature. The quality of data collected differ significantly from one technology to another. Fossil fuels-based power plants data (natural gas, coal, unspecified) are generally considered excellent because most of the emissions are from the operation stage of their life cycle and eGRID [USEPA] data has excellent data that accounts for most sources of variability, including fuel quality and emission control technology. LC emission factor data for most renewables have large uncertainty due to the location-specific (climate condition) and plant-specific (fuel provision, technology, capacity factor) nature. In general, renewables LCA results could be considered accurate within a factor of 3. An exception is estimates for GHG emissions from large hydroelectricity power plants and landfill gas, which involve system boundary uncertainty, results could be very different from actual value. Because PG&E's portfolio has a sizable portion of "unspecified" electricity portion, its exact value is unknown. Based on the CEC claim that natural gas help make up major of electricity from both the WECC Northwest and Southwest, more than 50% of unspecified would come from natural gas emissions, which has good estimates. The uncertainty in LC emission factors from the unspecified portion is estimated to be 20%.

To show relevance of collected LC emission factors data, the following criteria are used: geographical relevance, temporal relevance, technological relevance, and representativeness. Specific scoring rubric for each criterion is listed on a scale of 1 to 5, with 1 being the best.

Score/Criteria	Geographical relevance	Temporal relevance	Technological relevance	Source reliability
	LCA/review data that represents	Data from LCA/review published within	Data from LCA/review that are specific to the:	LCA/reviews based on:
1	average of the grid	Last 3 years	known manufacturer of equipment used at power plants and operating condition	Large samples of collected LCI
2	State average	3< Data< 5 years	same manufacturer but unknown operating condition	LCI of a representative power plant
3	National average	5< Data< 10 years	Same technology within finer category (i.e. run-of-river; solar CdTe)	Theoretical model values based on some actual data
4	Based on international data	10<Data<20 years	Technology within broader (i.e. solar)	Purely theoretical values
5	Obscure/Unknown	>20 years	Unknown technology	Unqualified

Table 8 *Data quality scoring criteria.*

Data Quality	Geographical relevance	Temporal relevance	Technological relevance	Representativeness
Natural Gas	1	1	3	3
Nuclear	2	1	3	3
Large Hydro	3	2	3	3
Small Hydro	3	2	3	3
Solar PV	1	3	2	3
Solar Thermal	3	2	3	2
Wind	3	1	3	1
Biomass	3	2	3	3
Landfill Gas	4	3	5	3
Geothermal	3	2	3	3
Coal	1	2	3	3
Unspecified	N/A	N/A	N/A	N/A

Table 9 *Data quality summary for power generation technologies.*

8. Interpretation and Discussion of Results

The environmental impact assessment of different power generating technologies yielded both expected and unexpected results. In general, renewables power sources tend to have lower environmental impacts as expected. Specifically, electricity from small hydro and wind energy have lowest impact because of lowest impact among generation technologies and uncertainty in their GHG emissions are small. A somewhat surprising result is the LC GHG emission from burning landfill gases. Studies from landfill data suggests that for each MWh of electricity from landfill gas more than 3 times as much GHG is generated as getting one MWh from coal-burning power plants, which considers by many as the "dirtiest". One reason may be that landfill biogas is not always captured because of its lower energy content than regular methane. Landfills facilities that burn often are not the most efficient at turning the energy content in the biogas into electricity. This result highlights the fact that while generating electricity from biogas reduces impact of electricity from other non-renewable resources, extracting the useful landfill gas itself may not be very efficient and thus may increase overall life cycle emission. Life cycle emission factor of geothermal plants is also another renewable power source that is "emission free" in the ordinary sense but embodies a large life cycle emission factor. When shopping for environmentally-friendly electricity, small hydro and wind should make up as much of the power mix as possible.

Environmental impacts can change significantly depending on the mixed source of the electricity used. MCE's Deep Green portfolio that delivers only wind power has clear environmental benefits in reduced life cycle GWP, NO_x, and SO_2 emissions. However, this program only serves <3% of its customer's retail electricity [MCE, 2014] and is not certain to be able to scale up when Alameda County decides to offer its CCA option. In fact, UC Berkeley's annual electricity consumption was 211,786,848 kWh [Stoll, 2014], almost the same as the MCE's Deep Green retail of 2,882,663 kWh last year [MCE, 2014]. If Alameda County organizes its own CCA, it will probably procure a mix of electricity from renewables like MCE's. Due to the large variation in MCE's renewable power purchase pattern, overall environmental impacts of its power mix changes significantly from year to year. LC GHG emission is reduced by about 1/3 from 2012 to 2013. This suggests a low comparability between its portfolios and others' at this time. On the other hand, PG&E's power mix portfolio is relatively stable mix and environmental impacts are better defined due to its large size and result of its long-term planning. Patterns of its power purchases within the near future is very well known. However, "unspecified" system power complicates analysis of its portfolio's actual impacts. Comparison between PG&E's 10-year average portfolio and its 2013 portfolio show PG&E's portfolio has improvement over time. This corroborated its large power purchase from Ivanpah solar thermal plant and increased power from solar PV over the next few years. As it's working towards the 33% renewable by 2020 goal, its LC GHG emission factor drops from 275 kg CO_2-eq/MWh in 2013 to 253 kg CO_2-eq/MWh in

2019, or about a 10% reduction. Its LC NO_x and SO_2 emission will see similar improvement as solar power displaces some of the natural gas power generation. However, PM emissions will be elevated with more solar electricity by about 10%.

Sensitivity analysis identified LC GHG emission factor estimate of landfill gas as having largest influence on GHG emissions of all power mix scenarios. Given the relatively low LC GHG emission factor of other renewables, contribution from landfill gas dominates the overall GHG emission factor. At 70% of the original estimate of LC GHG emission, it has already reduced MCE 2013 portfolio GHG emission by almost 200 kg CO_2-eq/MWh. At 30% of the original estimate, both MCE 2012 and MCE 2013 portfolios will outperform PG&E's portfolios. Given the low landfill gas utilization rate and low efficiency of the Italian landfill [Cherubini, et. al, 2009] reaching 50% reduction may be a real possibility by increasing power output through a combination of increasing gas utilization rate and increasing efficiency. But getting to 30% of the original estimate is highly unlikely because that requires the plant to triple its power generation without emitting more GHG. Therefore, MCE's 2012 and 2013 power mix portfolios will be unlikely to be have a substantially lower LC GHG than PG&E's.

Comparison of cost between MCE and PG&E's power mix were done using levelized cost of electricity (LCOE). The interpretation of this value is that if both MCE and PG&E were to build power plants for additional capacity with the same mix going in-service in 2018, these LCOE are the expected value of their cost over the next 20-30 years of power generation. In reality, electricity prices involve many different factors and many players in the market and are very difficult to predict. While MCE's portfolio shows a smaller LCOE, it is not a definite competitive edge in MCE's electricity cost profile over PG&E's.

9. Conclusions and Recommendations

From LCA literature review, life cycle emissions data are compiled for different renewable and non-renewable power generation technologies. Based on the reported procurement records, the life cycle environmental impact for each of the five scenarios were calculated and compared. MCE's Deep Green shows an environmentally-favorable option of using only wind power, but it may not be scalable when UC Berkeley joins Alameda County's CCA. For its larger portfolio of renewables from 2012 and 2013, significant difference is seen in procurement, leading to significant difference in life cycle GHG emission factors from year to year. Although both of MCE's power mix scenarios have higher LC GHG emission factor, the actual amount is highly sensitive to the estimated value of landfill gas electricity emission factor, which is of high data quality. Due to the large uncertainty inherent in the estimated life cycle GHG emissions of different power generation technologies, no definite conclusion about its environmental performance over PG&E's portfolio. NOx, SO_2, and PM life cycle were also compared and reached similar conclusion. Data also suggests that PG&E's mix is less sensitive to landfill gas estimation. It is possible to conclude that PG&E's power mix has improved environmental performance over time due to its work towards the RPS. Cost comparison LCOE showed a noticeably lower LCOE from Marin's portfolios, it is not a large enough difference to conclude that it has more competitive pricing than electricity generated by PG&E. This study is inconclusive about the claimed environmental benefits from using electricity from a renewable source. A more conclusive note could be put on this from a future study when life cycle assessments of landfill gas electricity generation with data specific to the plants in consideration is available and when a power purchase pattern at MCE becomes more apparent.

Recommendations to the UC Berkeley Office of Sustainability

Due to inconclusive results about the possible environmental benefits and the economic cost, no conclusion can be drawn about whether it is beneficial to join CCA. Based on the results presented above, these are my recommendations.

- UC Berkeley should not participate in Community Choice Aggregation (CCA) until the CCA shows a consistent power purchase pattern that leads to lower life cycle emissions of GHG, PM, NOx, and SO_2. Since PG&E has shown improvement on the environmental footprint of its mix over the years, it is best to stay with it in the near future.
- When evaluating future renewable power mix portfolios, preferences should be given to portfolios that have lower life cycle impacts, such as wind, small hydro electricity, and solar power. UC

Berkeley should stay on watch for a better opportunity in the future, whether it is from PG&E or a CCA.

- From a life cycle perspective, there is no such thing as "zero-carbon" electricity. Pursuing such a goal may lead to unintended environmental impacts in hidden embodied emissions of power infrastructure. Currently, a better goal might focus on improving energy efficiency and demand reduction.

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