Feasibility & Life Cycle Assessment of Renewable Energy Generation for UC Berkeley

Opportunities to Evaluate: Large Wind, Small Wind, Solar Thermal, and Photovoltaic Systems

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I. Abstract

The Cal Climate Action Partnership (CalCAP) aims to reduce greenhouse gas emissions from campus operations to 1990 levels by 2014. Even though most of CalCAP's efforts have been focused on improving energy efficiency, net energy demand is still increasing. Adding renewable energy generation capacity will be a key component of the greenhouse gas reduction efforts in the next two years and even more important as the campus aims to reach climate neutrality in the long term.

A useful analysis of each renewable energy option must consider 1) technical feasibility, 2) economics, and 3) environmental impacts. We will focus specifically on four renewable energy technologies: photovoltaic systems, solar hot water, big/traditional wind turbines, and smaller wind turbines. Many renewable energy options have been examined (and mostly dismissed as infeasible) years ago for the main campus. But CalCAP and the Office of Sustainability conjecture that changes in price and improvement in technologies over the past few years might have brought about a "tipping point". UC Berkeley's Office of Sustainability has asked our group to holistically reevaluate these renewable energy options with the most current information.

An economic analysis using the most recent price data for each installation may or may not demonstrate prices competitive with UC Berkeley's current procurement price of $0.11/kWh from Pacific Gas & Electric. All energy generation projects must be compared on a life cycle assessment (LCA) economic and environmental basis to each other and to the current energy procurement (which is through Pacific Gas & Electric for electricity or the natural gas cogeneration steam plant providing hot water and heating to campus).

The goal of the study is to provide the economic and life cycle comparison of renewable and fossil fuel based energy generation to help UC Berkeley decide how to meet increasing energy demands in the short term (2014) after analyzing the lifetime costs and benefits of each option.

II. Executive Summary

During our information-gathering phase, we identified a shortfall in campus' sustainability efforts: they were not utilizing life cycle assessment to evaluate their operations. Therefore, campus emissions were inaccurately represented and even efforts to improve sustainability were underrepresented. For example, an LCA would reveal that electricity purchased from PG&E actually has 60% higher CO_2-eq than PG&E reports (see Section V 3. c). Our first recommendation to campus was to utilize a more holistic and accurate approach to understanding their own emissions and use LCA to understand the true footprint of campus.

A lifecycle GHG emissions comparison of photovoltaic (PV), big wind (rated power > 100kW), smaller wind (>100 kW), and the PG&E electricity mix demonstrates the much smaller environmental footprint of any of the renewable energy generation technologies compared with PG&E. PG&E emits *at least* six times more CO_2-eq than on campus wind or PV would do.

An analysis of land area and upfront costs required to meet the electricity needs of over 35,000 students with PV or wind resulted in completely infeasible and unattainable cost and land requirements. The analysis was then scaled down to instead to see what would be required to just meet the *increase* in electricity demand over the next two years to at least minimize the growth in absolute emissions. Based on historical growth, UC Berkeley would purchase an additional 3,500 MWh in each year for 2013 and again in 2014.

Generating 7,000 MWh over the next two years with PV would require five to six football fields filled with multicrystalline PV panels. Small wind would require between 50 to 500 turbines depending on turbines power output (between 10 to 100 kW) and would be challenging to install on campus roofs without significant retrofits or challenging to fit on the ground in a densely populated urban environment. Large wind (analysis was performed on a 2-MW turbine) would be infeasible in Berkeley due to low wind speeds, obstructions, and land requirement. If UC Berkeley were to install large wind turbines, it would likely be somewhere outside of the main campus boundaries and results show that just two turbines (taking up two football fields of space) located in a more suitable wind area (7 m/s) could meet the electricity demand increase.

Many factors affect the true cost of an energy generation source and certain costs do not fit neatly into power equations and estimated capital or maintenance costs. Given this qualification, our calculations show that an unsubsidized cost per kWh comparison demonstrates that big wind in a high wind area could possibly be even less expensive than PG&E rates. PV and small wind are more expensive than PG&E but with government incentives could get closer to the PG&E rates. If campus prioritized installing generation capacity on campus and chose to install small wind or PV, they should begin by integrating renewables into new buildings when it is most cost effective.

III. Introduction

UC Berkeley (UCB) is struggling with conflicting goals regarding meeting energy demands and achieving sustainability targets. The campus is growing – in both population size and building square footage – which means increasing energy demand. CalCAP and the Office of Sustainability set ambitious environmental goals for campus, including procuring 20% of total energy used from renewable sources and eventually making the university a ‘net zero campus’. Often contrary to environmental goals, budget cuts have understandably made campus administrators extremely price sensitive. Also, administrators and most building managers are naturally risk-averse and weary of compromising the campus land resources, building integrity, or reliability of energy supply in exchange for emissions reductions, especially after UCB’s first photovoltaic installation experience failed.

Campus efforts to reduce emissions have been multi-faceted, including reducing waste, reducing air travel, changing commuting habits, implementing energy efficiency measures, and constructing ‘greener’ buildings. Due to the CalCAP initiatives campus’ emissions decreased by 1.1% from 2008 to 2010. (UC Berkeley Sustainability Office, 2011) Building renewable generation capacity, or at least *not increasing* fossil fuel energy generation directly or indirectly, is a key part of the campus emissions reduction strategy (Stoll, 2012). If the assumption is that net energy demand will increase over time, we must ask the question: how will we meet this increasing demand?

In order to balance the many interests on campus, Kira Stoll, Manager at the Office of Sustainability, requested a life cycle assessment (LCA) to address the different concerns of campus decision-makers. If we take as a given that energy demand will increase over time, we must first determine the physical and technical feasibility of different energy generation options, then compare them on a cost and environmental impact basis. No single factor can be used to determine which path the university should or will choose. UCB’s commitment to being a leader in sustainability (after all, UCB *has* an Office of

Sustainability!) may or may not result in choosing a potentially more expensive renewable energy technology over purchasing from Pacific Gas & Electric (PG&E). Land or other physical constraints could eliminate certain technologies for feasibility reasons despite a potentially lower price. While considerable uncertainty exists around the decision-making process, this analysis should at least serve to inform and assist the decision-makers as they negotiate and weigh their priorities.

IV. Problem Statement

Currently, UCB purchases most of its electricity from PG&E. Campus also buys steam from a natural gas cogeneration steam plant ("steam plant" or "cogeneration plant"). The university utilizes the steam for heating and hot water on campus. UCB then buys nearly all the electricity needed for campus activities from PG&E (at a very low rate of $0.11/kWh).

Despite efforts to curb energy demand, it is still increasing. In order to meet that demand, UCB must decide what energy source or combination of sources they will use for generating the additional electricity demand through one of the following three ways (or a combination of the following):

1) Continue to purchase all additional electricity from PG&E
2) Begin to use electricity from the steam plant
3) Meet the increased demand through one or a combination of renewables such as solar PV, traditional/big wind, or smaller wind systems

Based on a LCA of environmental impacts as well as coarse economic and feasibility analysis, how should UCB meet the increasing in energy demands from 2012 to 2014 on campus?

Scope of Work/Boundaries

This project complements the other two groups working on the campus sustainability office – one group is performing a life cycle assessment of the campus natural gas/steam cogeneration plant, and the other is looking at other mitigation measures, such as energy efficiency and reducing emissions related to travelling. While it is clear that reducing energy demands through efficiency measures and behavioral changes must be prioritized over increasing generation capacity, campus will still need to buy more electricity or own generation capacities in the years to come.

The sustainability office previously had the overly optimistic goal of generating 20% of our energy demands from renewable sources by 2010, but this goal was not even close to being reached (even today). A more realistic goal for the campus is to at least meet the future growth in demand through renewable energy generation. In terms of time frame, the analysis will examine the generation options to meet increase in energy demand (i.e. electricity and heating needs) from 2012 until 2014. A short time frame of two years was chosen because price, relative emissions and other data change are changing so rapidly, analyzing a longer time frame would be less accurate than a shorter time frame.

This report analyzes and compares the economics, environmental impacts and feasibility of six different energy generation options: PV, solar thermal, big wind, small wind, PG&E's generation mix, and the campus steam plant. Based on end-use, solar thermal will be compared with steam for space or water heating and for electricity use we will compare PV, big wind, small wind, and PG&E.

While each of these generation options are not mutually exclusive, we will simplify the presentation of our analysis and determine what would be required in terms of physical, economic, and environmental resources to meet the energy demand increase over two years with each technology. A real-world result may be a combination of the presented options.

V. Background

1. TECHNICAL FEASIBILITY

a) Relevant Existing Projects in Berkeley

Currently, there are three relevant installed projects, with varying states of functionality.

MLK PV Installation (Campus)

In 2003, UC Berkeley installed three 60 kW systems on the roof of the Martin Luther King, Jr. Student Union Building (see figure 1). UC Berkeley's Associated Students of the University of California (ASUC) and Graduate Assembly approved this first photovoltaic system installation on campus by funding it with $100,000 each, and the California Public Utility Commission also provided $270,000. The project cost approximately $470,000 and covered approximately 5,000 square feet of the roof.

Issues: The PV installation also entailed a $120,000 retrofit of the roof. Even at the time of installation, they expected it would take 17 years to pay back. The PV project was expected to be much less economically sensible than purchasing power from PG&E, but it was initiated to be an example of UCB's commitment to environmental sustainability and to set an example for other campuses.

As of today, only one of the three modules generates electricity. According to Tom Spivey, Associate Director of the Associated Students of the University of California and informally titled 'MLK PV historian', the first module is still operating at a 60 kW capacity, the second has a failed inverter, and the third is not working correctly but is apparently under warranty (Spivey, 2012).

Unfortunately, the system has performed so poorly, that building managers and campus administrators are hesitant to invest limited student funds in any new PV projects given the disappointing performance of this installation (Green Building Research Center, 2009) (Powel, 2003).

Martinez / Anna Head (Residence Hall) – solar thermal facility

The newest dormitory for students, housing 430 students, has installed a solar hot water system of 80 panels and one 5,000 gallons storage tank. It has been installed, and just begun operating. While there is not enough data from its nascent operational history, the system is supposed to offset 10,156 therms that would normally come from natural gas and save $11,000 annually (H3O Funding LLC, 2012).

Berkeley Marina (Shorebird Nature Center) - Wind Turbine

While this is not a campus installation, the Berkeley Marina Shorebird Nature Center hosts a 1.8 kW wind turbine donated by Southwest WindPower. The turbine is expected to generate 7,000 kWh annually and was the first municipally owned wind turbine in the nation (Kamlarz, 2006) (City of California, Berkeley, 2012).

Issues: The turbine has not been spinning and generating because the surrounding trees block the wind and the facility has determined that trimming the trees would be prohibitively expensive (Romain, 2012).

Overall: UC Berkeley has experienced a patchy and disappointing history with renewable energy installations. They have generally been more expensive than expected and underperformed in actual generation. Campus administrators are likely skeptical of paying for any type of renewable energy installation and will likely be unwilling to take on all the performance risk of the project. A thorough site analysis must be performed for any installation so that the campus can ensure trees or buildings will not block the sun or wind. Also, the campus must get performance guarantees to not repeat the operating failures of the MLK PV installation.

b) Campus Buildings Currently Considering Renewable Energy Installations

Wurster Hall

The building manager, Eli Persyzk, at Wurster has identified a sufficient amount of roof space and an interest in a solar thermal installation. Wurster Hall hosts the College of Environmental Design and would like to be a leader in renewable energy installation. Eli Persyzk also thought Wurster would be a good candidate for solar thermal because many of the design students work in the building at all hours of the day and night and need heating. In 2006, UCB commissioned a study by EMCORE, which identified Wurster as one of the top three potential buildings to do a PV installation (Persyzk, 2012).

Recreational Sports Facility (RSF)

The same EMCORE study also identified RSF as a good candidate for a photovoltaic system as well. Mike Weinberger, director of Recreational Sports, is enthusiastic but feels a significant amount of pressure to lower the costs of maintaining the building and does not have the resources to fund an installation based on student fees. RSF would be a good candidate for either PV or solar thermal because they have high electricity demands and also have hot water showers in the locker room. Mike Weinberger also thinks that with funding and significant support, he might be able to get around the administration more easily because the RSF operates quasi-independently as a student funded resource (Weinberger, 2012).

EMCOR Report – PV feasibility study in 2006

In November 2006, a feasibility study on reviewing potential and technologies for installing a solar photovoltaic (PV) array on campus was prepared by EMCOR Energy Solutions. Three campus buildings were taken into consideration: Recreational Sports Facility (RSF) Field House, Tolman Hall and Wurster Hall. These buildings were selected by UC Berkeley because of their relatively large, flat roofs in good condition. At that time, the PowerGuard System was already outdated. However, it was included in the study because UC Berkeley was in discussions with DTE, a renewable project implementer, regarding the possible donation of an existing 5-year old PowerGuard array. Thus, the economic information provided assumes that this system is donated. The estimated costs for the PowerGuard system include array equipment, modules, mounting system, inverter, transformer, combiner boxes, data acquisition and costs of dismantling. In the estimate, UC Berkeley is responsible for shipping costs, which is not a relevant comparison to a PV system installed today. Since the SunRoof FS system would have been a new acquisition, the estimated costs are much higher (they do not include costs for any utility or other incentives). In both cases the estimates for constructions costs calculate manuals, vendor quote and the current catalog prices at that time. All expected costs were subjected to a variation by -5% to +10% due to uncertainties in market conditions. Analyzing the installed cost leads to the result that the SunRoof FS system is marginally more expensive than the average cost for a PV systems in 2006 ($7.9/WDC).

Figure 1: Summary of the performance and cost of PowerGuard and SunRoof systems

Building – Array	Module Area [m²] (Proportion of total roof area)	Estimated Annual Energy [kWh/yr]	Prop. of total energy consumption (06/2005 – 06/2006) [%]	Rated Power [kW_{DC}]	Major Equipment Cost [$]	Installation Cost [$]	Total Cost [$]	Installed Cost [$/$W_{DC}$]
RSF – PowerGuard	1410.6 (70.0%)	178,755	11.3	144.675	5,700	248,100	253,800	1.75
RSF – SunRoof FS	1491.7 (74.0%)	192,006	12.2	155.400	900,300	369,500	1,269,800	8.17
Tolman – PowerGuard	1410.6 (43.1%)	178,755	10.3	144.675	5,700	246,600	252,300	1.75
Tolman – SunRoof	1231.2 (37.6%)	163,282	9.4	132.300	767,300	322,800	1,090,100	8.24
Wurster – PowerGuard	522.1 (43.1%)	62,792	4.5	52.900	5,700	140,100	145,800	2.76
Wurster - SunRoof	535.9 (37.6%)	64,759	4.5	54.600	320,000	177,100	497,100	9.10

Source: (Snaith & Staget, 2009)

Study prepared for UCB for application for CREB funding

In 2009, a basic solar potential analysis of three campus-owned buildings – two off the main campus and on campus was performed. The analysis includes Clean Renewable Energy Bonds funding (CREBS) that is no longer available (it expired with no extension in 2009). The study came to the conclusion that the rated cost would be between \$6.5/W_P and \$7.5/W_P depending on the system size.

Figure 2: Summary of feasibility study in 2009 - system size and cost

Location	3300 Regatta Blvd, Richmond	Golden Bears Building, 1995 University Ave, Berkeley	Recreational Sports Facility, main campus
System size [kWp]	1,020	470	260
1 year output [kWh]	1,428,000	658,000	364,000
25 years total output [kWh]	33,637,899	15,499,816	8,574,366
Total project costs [\$]	7,650,000	3,313,500	1,690,000
Rated Cost [\$/W_P]	7.5	7.05	6.5
Energy Cost [\$/kWh]	0.227	0.214	0.197
Proportion of total energy consumption [%]	67	27	23

(Source: EMCOR UC Berkeley feasibility study (Snaith & Staget, 2009))

The feasibility studies that have been prepared for UC Berkeley plan for PV systems of 50 to 500 W_P. PV systems in this size are also called “large-scale building PV systems”. They typically do not exceed 1 MW_P and are placed in large building or complexes as hospitals or universities

c) Feasibility: Land Area

UCB owns 6,651 acres distributed throughout the Bay Area and Northern California (i.e. Richmond Field Station, etc.) but just 178 acres on its main campus. Besides aesthetic considerations in a heavily trafficked area, much of the main campus has buildings and large trees, which could interfere with solar or wind installations.

PHOTOVOLTAICS (PV)

Description

Photovoltaic (PV) uses semiconductors to convert solar radiation into direct current electricity. The panels could be located on flat rooftops or on the ground whichever fits campus needs better. The analysis focuses on one of many PV technologies: multicrystalline PV panels.

Considerations

UCB's first PV installation performed so poorly (with a failed inverter and other parts of the system not working properly), that campus and building managers are hesitant to initiate a new installation and believe quoted payback times. Other issues include roofs that are not flat or host machinery in place of the panels. Constraints or barriers to PV (or solar thermal) installations include fitting arrays in a crowded campus with many unsuitable buildings and tall trees, maintenance concerns, cloud cover/fog, and risk averse building managers uncomfortable with altering or compromising the roofs of buildings.

One benefit of PV systems is that UCB pays PG&E based on Time of Use (TOU) rates. Solar systems produce the most electricity in the afternoon, which corresponds to the highest TOU rate, when demand is the highest. This allows offsetting electricity usage at the time when we would be paying the most for electricity.

Solar Irradiance/Availability

The average insolation, or the power density of solar radiation on a surface at sea level, is dependent on latitude and surface orientation. For south-facing surfaces (which is the optimal orientation for energy collectors) in San Francisco, CA, the average insolation is 246 W/m^2 (da Rosa, 2009).

The average daily energy yield for the Bay Area, averaged over an annual time span, is somewhere in the range of $5 \text{ to } 6 \ \frac{\text{kWh}}{\text{m}^2}/\text{day}$ (NREL - Renweable Resource Data Center, 2009).

Note that these values are strictly the actual energy that falls on the surface--not the energy produced from photovoltaic panels. The energy produced will be significantly lower, since efficiencies for photovoltaic materials tend to be fairly low as shown in figure 3 below from the National Renewable Energy Laboratory (National Renewable Energy Laboratory, 2011).

Figure 3: Commercial Solar PV Module Efficiencies

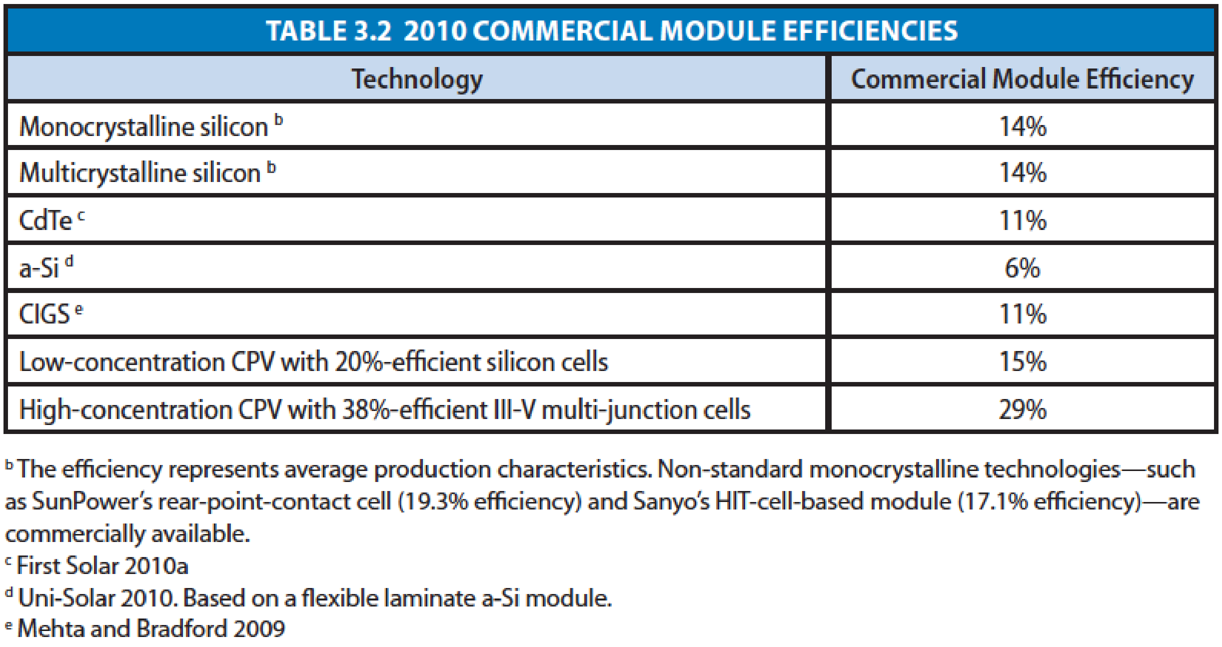


TABLE 3.2 2010 COMMERCIAL MODULE EFFICIENCIES

Technology	Commercial Module Efficiency
Monocrystalline silicon [b]	14%
Multicrystalline silicon [b]	14%
CdTe [c]	11%
a-Si [d]	6%
CIGS [e]	11%
Low-concentration CPV with 20%-efficient silicon cells	15%
High-concentration CPV with 38%-efficient III-V multi-junction cells	29%

[b] The efficiency represents average production characteristics. Non-standard monocrystalline technologies—such as SunPower's rear-point-contact cell (19.3% efficiency) and Sanyo's HIT-cell-based module (17.1% efficiency)—are commercially available.
[c] First Solar 2010a
[d] Uni-Solar 2010. Based on a flexible laminate a-Si module.
[e] Mehta and Bradford 2009

Source: (National Renewable Energy Laboratory, 2011).

Assuming that the daily average energy yield is on the lower end of the scale provided by NREL, and assuming a conversion efficiency of approximately 14%, we get a daily average photovoltaic energy production as follows:

$$\left(5-6\frac{\frac{kWh}{m^2}}{day}\right)\times(0.14) = \ 0.70-0.84\frac{\frac{kWh}{m^2}}{day}$$

This corresponds to an annual production yield of approximately $256-307\frac{kWh}{m^2}/year$.

BIG WIND

Description

The American Wind Energy Association defines big wind systems that have turbines with a rated capacity greater than 100 kW. In 2011, the average rated capacity installed in the U.S. is 1.97 MW, increased from 1.90 MW in 2010. Modern big wind systems can reach a rated power of 7.5 MW and produce 18 GWh of electric energy annually, which is sufficient to cover the demand of 5,000 three-person households in Europe (Odenwald, 2011). In the U.S., the average hub height of a big wind system is 81 m (266 ft) whereas the average rotor diameter measures 89 m (292 ft). Since the 1990s the average hub height has increased by 45%, while the average rotor diameter has increased by 86%. In general, this development is driven by new turbines designed to serve low wind speeds (Wiser & Bolinger, 2011 Wind Technologies Market Report, 2012). Usually the lowest wind speed that is sufficient to spin the blades and to produce electric energy (also known as cut-in wind speed) for big wind systems is 4.0 m/s (8.9 mph) (American Wind Association (AWEA), 2012).

Considerations

In general, the electric energy that is produced by a wind turbine mainly depends on the wind speed, the rotor diameter (swept area) and the turbine efficiency. The most significant contributor is the velocity of the wind since the produced energy increases proportionally to the cube of the wind speed. Thus, big wind systems need high wind speeds with as few wind obstacles as possible. Because of the densely built-up area, many trees. and uneven landscape Berkeley and the surrounding area do not offer appropriate sites to install wind systems. Furthermore, safety concerns and noise pollution are not negligible. For instance, the noise level 10 m above ground caused by Vestas' V90-2.0MW Gridstreamer™ under 7.0 m/s wind speed is 104.5 dB (Vestas Wind Systems A/S, 2012) (Vestas Wind Systems A/S, 2012). In Solano County, CA, 50 miles north east of Berkeley the wind situation changes tremendously. Wind speeds of 7.0 m/s in average and higher are measured (California Energy Commission, 2006). Therefore, we assume this area to be our likely location of big wind systems.

SMALL WIND

Description

The American Wind Energy Association (AWEA) defines wind energy systems as small wind turbines that have a rated energy of less or equal 100 kW (even smaller systems from 20 – 500 W are called micro wind systems (National Renewable Energy Laboratory, 2007)). Small wind systems can be divided into two major technologies: Horizontal Axis Wind Turbines (HAWTs) and Vertical Axis Wind Turbines (VAWTs). HAWTs are propeller based energy systems that have vertically rotating blades spinning around a horizontal axis. In contrast, VAWTs consist of a vertical rotor shaft that is spinning around its own axis and the vertical blades are spinning horizontally around this axis. They are often preferred for urban environments due to improved design for turbulent wind flows and low noise levels (Enhar

Sustainable Energy Solutions, 2011). This report focuses on HAWTs. Most small wind systems feature rotor diameters less than 15 meters (50 feet) and are installed on towers less than 49 meters (160 feet). In contrast to big wind systems there are two basic types of towers: self-supporting (free standing) and guyed (see land use requirements for small wind systems). The national average small wind turbine size installed in 2011 was 2.6 kW (2010: 3.3 kW, 2001 – 2009: 1.3 kW). The minimum wind speed required for a small wind turbine, also known as cut-in speed is in general approximately 3.5 m/s (10 mph). Values below the cut-in speed can lead to rotor spins but are not sufficient to produce energy (Berry, 2010). The primarily use of small wind systems is for on-site generation at homes, farms, public facilities (e.g. schools), telecommunication sites and businesses (Wiser & Bolinger, 2011 Wind Technologies Market Report, 2012).

Considerations

As opposed to large wind turbines, small wind turbines can be placed on top of buildings rather than using land, have a less obtrusive aesthetics, and are less dangerous to both humans and wildlife (Dronawat & Kom, 2012). However, it requires investigation of each specific roof and is not suitable for every roof. The turbine and its supporting structure may have detrimental effects on the roof mainly because of increased imposed loads. Furthermore, it causes vibrations through the dynamic usage of the wind systems that may be transmitted into the building. In California and especially in the San Francisco Bay Area the seismic design and safety of buildings is of special interest. Wind systems on rooftops have to be installed judiciously and should not threaten adjacent buildings in case of a seismic event. Moreover, dense areas contain many obstacles like buildings and trees that cause a reduction in wind speed. In general, when considering roof mounted wind systems one must consider many limitations and risks. This chapter only begins to address the additional considerations.

Summary of points to take into consideration when installing a rooftop small wind system:

- Increased turbulent wind flow (i.e. caused by another building or trees) in urban environment can decrease energy output
- Structural suitability must be confirmed by an structural engineer (creates additional costs that are not considered in the cost calculations of chapter V 2. B) Financial background)
- Suitable rooftop turbine technology must consider seismic safety. The American Wind Energy Association states, due to zoning restrictions and the poorer wind quality in densely built

environments, that less than 1% of all small wind turbines are installed in urban areas. This unsuitability would apply to the main campus (Flowers, FAQ for Small Wind Systems, 2012).

There are only a few examples of small wind installations in the city of Berkeley. One recent installation includes the 1.8kW turbines at the Shorebird Nature Park in the Berkeley Marina. The Sustainability Coordinator at the City of Berkeley, Billi Romain, responded to questions about performance data of the Berkeley Marina turbine by saying "Unfortunately the turbines are not currently producing energy. The trees are currently blocking the airflow and need to be trimmed and the cost is currently prohibitive…[and] there is no past performance data" (Romain, 2012). The performance of the Berkeley Marina turbine implies that even in a consistently windy and relatively undeveloped area of the city, it is difficult to get smaller wind generate effectively. On campus, with a high concentration of buildings and trees, the increased turbulence of the wind would likely result in an even poorer performance of installed wind turbines.

SOLAR THERMAL/SOLAR HOT WATER

Description

Solar thermal systems capture the sun's energy to heat water or air for use in space heating or hot water in buildings. It differs from PV systems because the process of converting solar energy to heat can be more than twice as efficient as converting to electricity.

Considerations

Solar thermal installations face similar constraints as PV systems at UCB. In addition, a restriction for solar thermal systems is that the building must have a regular and considerable need for space heating or hot water. Therefore, it may not be suitable for all campus buildings. For example, a building with classrooms and offices may not need much hot water and heating whereas a lab building may have equipment requiring daily cleaning and more stringent heating or air-conditioning requirements. The energy demand is higher for this type of building. Solar thermal poses challenges in meeting the needs of lab buildings, as it cannot generate heat constantly and reliably. Solar thermal systems may be best suited for campus-owned residential buildings – like the Anna Head dormitory building.

Solar Irradiance/Availability

Solar thermal or solar hot water faces the same solar availability concerns as the photovoltaic systems previously described.

d) Forecasted Energy Demand Increase

Even with mitigation projects, campus will need to increase generation capacity because total campus population, building square footage, and building energy intensity are all increasing. Many models have been built to predict future growth under different mitigation scenarios. We used the Business As Usual model that shows the following growth factors in figure 4.

Figure 4: Projected growth factors

Metric	Purchased electricity [kWh]	Purchased steam [MMBtu]	Natural gas [MMBtu]	Student Population	Building Square Footage
Annual Growth	1.6%	1.6%	2.7%	1.2%	1.2%

Source: Business as Usual Spreadsheet Model (UC Berkeley Sustainability Office, 2011)

According to historical data on purchased electricity, the Campus Sustainability Office has projected a 1.6% growth rate until 2020 in a 'business as usual' model. They predict a similar increase in purchased steam (1.6% increase) and a 2.7% increase in natural gas purchased (UC Berkeley Sustainability Office, 2011).

With proper application energy efficiency measures, the rate of increase could be lower than 1.6% or could potentially even decrease in the short term, as one model from the Sustainability Office models.

The Office of Sustainability provided the following data (assuming growth factors as explained and showed in figure 4).

Figure 5: Electricity demand (kWh) and steam demand (MMBtu) for years 2011-2014

Year	Electricity purchased [kWh]	Steam purchased [MMBtu]	Total building space [sq. ft.]
2011	212,878,439	1,061,668	16,127,722
2012	216,284,494	1,078,655	16,305,127
2013	219,745,046	1,095,913	16,484,483
2014	223,260,967	1,113,448	16,665,813

Note: growth factors calculated based on 1.6% annual growth
Source: Business as Usual Spreadsheet Model. (UC Berkeley Sustainability Office, 2011)

Figure 5 shows the projected demand of electricity (in kWh) and in steam (in MMBtu) for years 2013 and 2014 with growth factors deduced from the historical data. In order to determine the increase in demand for electricity and steam between 2012 and 2014, we calculate this "gap" as stated below:

$$Gap\ to\ be\ filled\ in\ 2013 = Electricity_{2013} - Electricity_{2012}$$

$$Gap\ to\ be\ filled\ in\ 2014 = Electricity_{2014} - Electricity_{2012}$$

Figure 6: Electricity (kWh) and steam (MMBtu) to be produced by renewables to meet demand increase

Year	Gap between 2012 level for the electricity purchased [kWh]	Gap between 2012 level for the steam purchased [MMBtu]	New building space being constructed [sq. ft.]
2012	0	0	0
2013	3,460,552	17,258	179,356
2014	6,976,473	34,793	360,686

We rounded the result in figure 7 so that it is easier to handle in our study keeping only three significant digits:

Figure 7: Rounded numbers for electricity [kWh] and steam [MMBtu] to be produced by renewables to meet demand increase

Year	Gap between 2012 level for the electricity purchased [MWh]	Gap between 2012 level for the steam purchased [MMBtu]	New building space being constructed [sq. ft.]
2013	3,460	17,300	179,000
2014	6,980	34,800	361,000

e) Number of Systems Needed to Fill the Gap

Assuming that the entire electricity gap is filled by either solar PV or conventional wind turbines or small wind turbines leads to an analysis of how many solar panels or how many turbines would be needed to meet our goal.

<u>Solar PV needed to fill the gap:</u>

Given the following calculation of energy production potential from photovoltaic, how much area would we need to match future increase in electricity demand? The projected demand increase of 1.6% corresponds to an extra 6,980,000 kWh needed by 2014. With the annual irradiance values of between 256 and 307 kWh/year/m^2 we find a needed area of:

$$\frac{6{,}980{,}000\ kWh\ needed\ in\ 2014}{307\ kWh/year/m^2} = 22{,}700\ m^2$$

for the high irradiance range. For the low irradiance range,

$$\frac{6{,}980{,}000\ kWh\ needed\ in\ 2014}{256\ kWh/year/m^2} = 27{,}300\ m^2$$

This means that the necessary area to fulfill this demand entirely with solar panels would be $22{,}700 - 27{,}300\ m^2$ for 2014 . In other words, Berkeley would need between **5 and 6 football fields worth of panels for 2014**. We could begin to utilize the available roof space area and meet additional area requirements by installing PV on the ground on some of the UC Berkeley-owned property outside of the main campus. Or we could meet the electricity demand with a combination of PV and wind, which have different land requirements. Rooftop PV will not meet our entire electricity demand increase, but depending on how much actual roof-space is available, rooftop PV could begin to address some of the 'gap'.

Big Wind turbines needed to fill the gap:

The present data is derived from a LCA final report published by Vestas Windsystems A/S (Garret & Rønde, 2011). This report will also serve for our LCA model in chapter VI. Vestas is currently one of the largest manufacturers of wind systems that deliver approximately 15% of the total wind energy installed (MW delivered) (IHS emerging energy research, 2011). For this calculation we are looking at a typical 2.0 MW onshore turbine (V90-2.0 MW Gridstreamer™) that is designed to perform mainly under low wind speed conditions (7.0m/s). The rotor diameter is 90 meter, the hub height 80 m and the cut-in wind speed is 4.0 m/s (8.9 mph). The LCA report assumes a turbine lifetime of 20 years. The electricity output of a wind turbine depends on various variables like wind speed, rotor diameter, and efficiency of the turbine. In the sensitivity analysis we will observe the variation in electricity output when the wind speed varies. But we assume from now on that the wind turbines are installed in a proper area with the determined average wind speed of 7.0 m/s. The average wind speed in Berkeley is 4.5 m/s (10.1 mph), which is close to the cut-in wind speed of the turbine and also provides other challenges. Since installing the wind turbines in more dense areas like Berkeley means dealing with aggravated conditions (higher costs, obstacles, noise pollution etc.) we will leave this scenario for the sensitivity analysis in section VIII. As already mentioned, the wind situation in Solano County, CA is more appropriate for big wind systems. Wind speeds of 7.0 m/s in average are measured (California Energy Commission, 2006; City of California, Berkeley, 2012; U.S. Environmental Protection Agency and the U.S. Department of Energy - Energy Star, 2012). Under these circumstances the V90-2.0MW turbine will produce 6,250 MWh of electricity per year (included losses due to grid distance of 20 km, notably less than the distance from Solano County to Berkeley).

After determining the annual electricity produced, one can calculate the number of turbines needed to fill the electricity increase in 2014. **If the turbines are installed in Solano County, 2 turbines will be necessary to meet the 'gap'.**

$$\frac{Additional\ electric\ energy\ demand\ in\ 2014}{Annual\ electric\ energy\ produced\ by\ 1\ turbine} = \frac{6{,}980\ \frac{MWh}{year}}{6{,}250\ \frac{MWh}{year}} = 2\ turbines$$

In 2009, a report called "Land-Use Requirements of Modern Wind Power Plants in the United States" examined the land use needs of 20 MW or larger capacity wind farms consisting of big wind turbines (Denholm, Hand, Jackson, & Ong, 2012). More than 170 wind projects in the United States were obtained, representing more than 26 GW. The report distinguishes between permanent and temporary land use. Permanent land use covers wind turbine pads, access roads, substations, service buildings, and other infrastructures that physically occupy land area, or create impermeable surfaces whereas temporary land use is associated with temporary construction-access roads, storage, and lay-down. Among these, 93 projects provided information about the permanent land use.

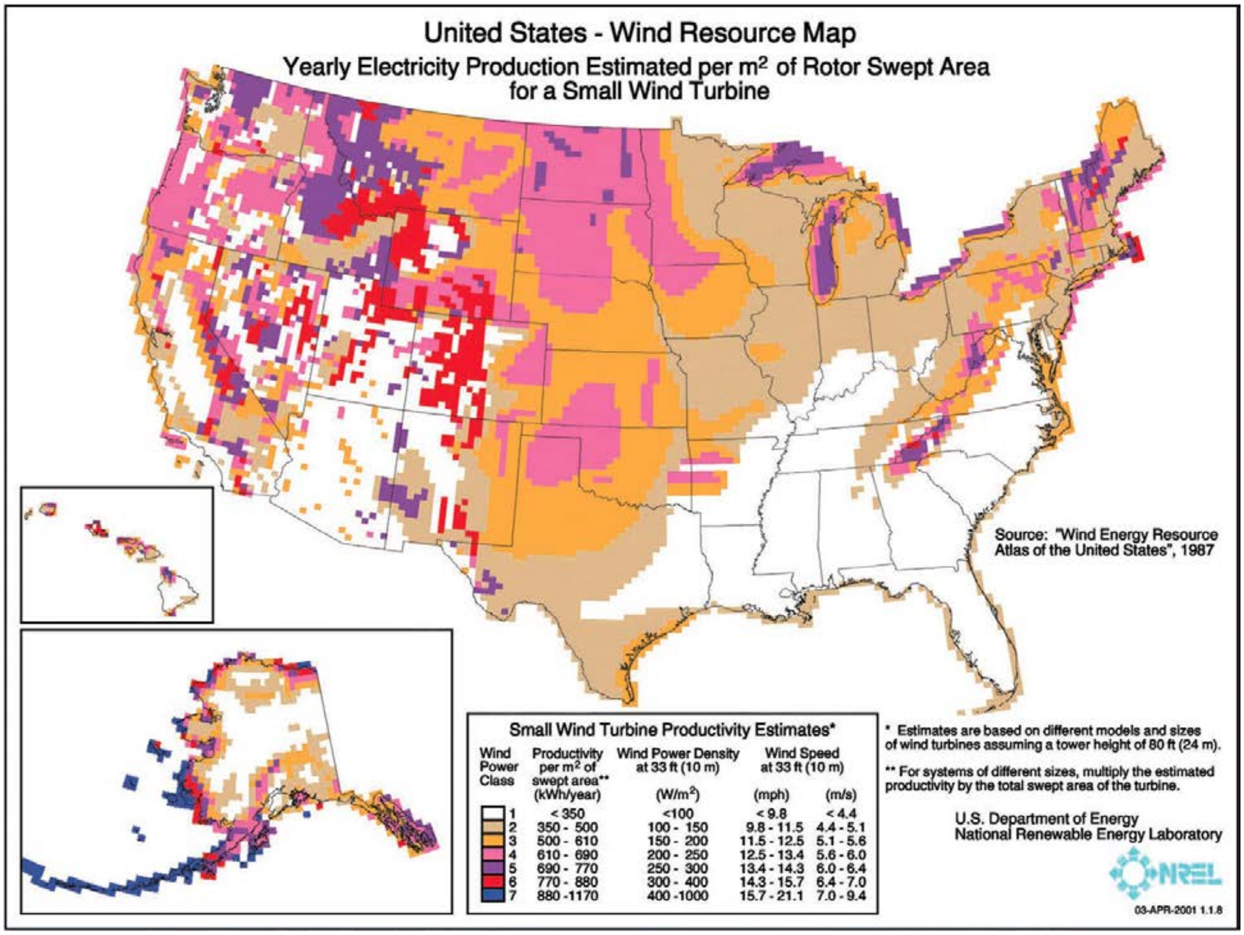
The report comes to the conclusion that the average area required per installed MW is 0.3 ± 0.3 hectares. In order to satisfy the increased energy demand in 2014, 2 big wind turbines if installed in proper wind areas with a rated capacity of 2 MW are needed. If we consider a land use range of 0.3 to 0.6 ha/MW, **2 big wind turbines would require approximately 0.6 to 1.2 hectares of land, respectively 1 to 3 football fields.**

<u>Small *Wind turbines needed to fill the gap:*</u>

To determine the number of small wind turbines (rated power ≤ 100 kW) needed, the variable rotor diameter and wind power density [W/m^2] must be factored. Wind energy systems become more cost effective as the size of the rotor diameter increases. The amount of power a turbine produces is determined primarily by the diameter of its rotor. The diameter of the rotor defines its swept area, or quantity of wind intercepted by the turbine. The longer the rotor blades the more wind power density [W/m^2] can be captured and thus, more electricity can be produced. Note that there are other variables determining the power output of a turbine, e.g. efficiency factor, tower height, wind speed, wind direction, etc.

For simplicity, we only concentrate on rotor diameter and wind power density [W/m^2]. The following map in figure 8 is from a small wind consumer's guide published by U.S. Department of Energy in cooperation with the National Renewable Energy Laboratory (NREL). The map gives information about available wind speeds around the nation. Berkeley and its surroundings are designated as Class 2 wind power (4.4 to 5.1 m/s) areas. Furthermore, values are given for the estimated productivity per m^2 of swept area. For Class 2 wind ares, estimated productivity is 350 – 500 W/m^2. The range of productivity is due to the size of small wind turbines. In figure 9 we assume rotor diameters for different rated powers [kW] of small wind systems. These values comply with current data sheets of small wind manufacturers. In addition, the range of productivity (350 – 500 kWh/year/m^2) correlate to different turbine sizes meaning that the productivity of 350 kWh/year/m^2 is achieved by a small turbine size of 10 kW and the corresponding 100 kW relates to a productivity of 500 kWh/year/m^2. After calculating the swept area and multiplying the result with the productivity of this area, we gain a value for the annual electricity produced [kWh/year]. The calculation of needed turbines to fill the gap in 2014 is analogous to the above-mentioned equation for big wind turbines. Depending on the rotor diameter and the productivity we will need approximately **50 up to 500 small wind turbines.**

Figure 8: United States Wind Resource Map and yearly electricity production for Small Wind Turbines.



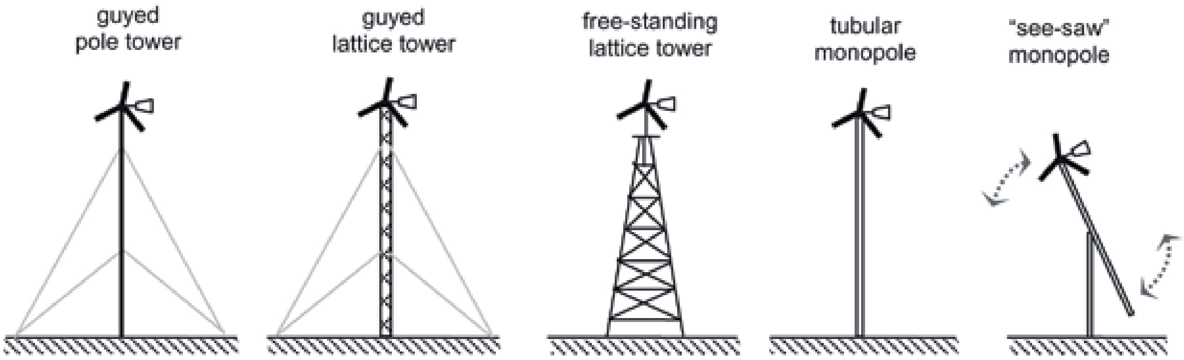
Source: (National Renewable Energy Laboratory, 2007)

Figure 9: Number of turbines needed by using the rotor diameter and the productivity of swept area.

Rated Power	10kW	50kW	100kW
Rotor diameter [m]	7 [1]	15 [2]	20 [3]
Swept Area [m^2]	38.5	176.7	314.2
Productivity of swept area [kWh/year/m^2]	350	450	500
Annual Electricity Produced [kWh/year]	13,475	79,515	157,100
Number of turbines needed	508	88	45

Sources: [1] (Bergey Wind Power, 2012); [2] (eps Engineered Wind Systems, 2012); [3] (The Wind Power, 2012)

Figure 10: Small wind tower designs.



Source: (Enhar Sustainable Energy Solutions, 2011)

The previous figure was derived from an Australian small wind turbine guide that was published in 2011 by the New South Wales Government (Enhar Sustainable Energy Solutions, 2011). In contrast to big wind systems there are many different tower designs for small wind systems with varying land use requirements. The main tower types are shown in figure 10. The monopole tower uses the least footprint area but it is normally more expensive since the tower consists of thicker and heavier steel compared to the other design options. Although the guyed tower is the most filigree construction and lowest cost option, it requires the most land. Usually the guy radius must be one-half to three-quarters of the tower height (U.S. Department of Energy, Energy Efficiency & Renewable Energy, 2012). The minimum radius of one-half of the tower height is based on simple truss element force calculations. The shorter the radius the higher the axial force in the brace will be, whereas if the radius were too long the force to pre-stress the braces would be too high. Guyed towers have the advantage of being hinged at the bottom so that it can be lowered to the ground during maintenance or hand winches can be installed to achieve the same result.

The following land requirement calculation is based on a guyed tower. Choosing the right tower height is crucial for the success of the system and should be appropriately balanced with different requirements. A higher tower ascertains an increased energy yield due to higher wind speeds and less wind obstacles of adjacent buildings. An estimate of the tower economics is provided by an American study (Sagrillo, 1993). The study concludes that two 10 kW wind systems with a tower height of 18 m will produce the same amount of energy as one 10 kW turbine on a 30 m tower. Thus, a 10 % increase of the system costs can double the energy output. However, it has to be kept in mind that taller towers increase the visual impact.

To derive a result for the required land of the estimated small wind turbines we assume a tower height of 30 m (100 ft) for ground mounted towers since the turbines need to be 30 ft above anything within 300 ft (trees, roofs, power cables etc.) and 10 m (32.8 ft) if installed on roofs (U.S. Department of Energy, 2007). Figure 11 presents the results for different tower heights and guyed radiuses. Roof mounted wind systems need less area since the tower height is assumed to be only 10 m. **To present these considerations into a tangible result, roof mounted systems would require an area of 1 to 17 football fields, whereas ground mounted systems would use approximately 17 to 150 football fields of land.**

Figure 11: Results for Land Use Requirements of Small Wind Turbines.

	Number of turbines	Tower height [m]	Guyed radius [m] (½ of height)	Land use [ha]	Guyed radius [m] (¾ of height)	Land use [ha]
Ground mounted	50	30	15	3.5	22.5	8.0
	500	30	15	35.3	22.5	79.5
Roof mounted	50	10	5	0.4	7.5	0.9
	500	10	5	3.9	7.5	8.8

Solar thermal needed to heat, cool and provide hot water to new buildings in 2014:

Presently, campus utilizes steam to provide heat to buildings. Despite the method UC Berkeley uses to account for its GHG emissions, steam is still associated with some GHG emissions - even if steam is a byproduct of a natural gas cogeneration plant (utilizing the exhaust gases to boil water and to produce the steam). Solar thermal heating systems provide low-carbon source of heat and hot water to buildings. Because heat is not easily transportable – **each new building would need its own solar thermal system** to prevent significant heat losses in transportation**.**

For a direct replacement to the steam from the campus cogeneration plant, UCB could build a solar heater farm that heats water and boils it. The steam will then be transported through the existing distribution infrastructure inside campus.

While there is very little useful performance data currently, the recently built Anna Head/Martinez Residence Hall solar thermal heating system will provide valuable feedback to help understand geographically specific and other performance factors to consider for future solar thermal installations.

Technical and physical feasibility are first order analysis of campus energy generation options. A logical second order analysis in a budget constrained world is an economic analysis of each option.

2. ECONOMIC / FINANCIAL BACKGROUND

a) PG&E Rates

The relative prices of installed systems or technologies often determine which projects actually get implemented. UC Berkeley currently pays an average rate of \$0.11/kWh for electricity from PG&E and campus-operated transmission and distribution. Thus, this study will consider this rate as an important benchmark. The rate is significantly less than residential rates. Figure 12 shows an exact list of the current PG&E account that covers 96.2% (as of October 2012) of the total electricity costs. Since there are different rates for 'Peak' and 'Off-Peak' hours, main campus electricity rates account varies slightly from month to month and per season as shown in the table.

Figure 12: PG&E rate "E20T" for 96.2% of buildings on UC Berkeley campus

Season	Time-of-use Period	Demand Charges [\$/kW]	Energy Charges [\$/kWh]	"Average Total Rate" [\$/kWh]
Summer[1]	Max-peak[3]	\$ 12.11	\$ 0.08907	\$ 0.09431
	Part-Peak[4]	\$ 2.62	\$ 0.07516	
	Off-Peak[5]	-	\$0.06351	
	Maximum	\$ 4.06	-	
Winter[2]	Part-Peak[6]	\$ 0.00	\$ 0.07620	
	Off-Peak[7]	-	\$ 0.06655	
	Maximum	\$ 4.06	-	

1 Summer Season (May - October)

2 Winter Season (November – April)

3 Peak Hours: 12:00 noon to 6:00 pm, Mon-Fri (except holidays)

4 Partial-Peak Hours: 8:30 am to 12:00 noon AND 6:00 pm to 9:30 pm, Mon-Fri (except holidays)

5 off-Peak Hours: 9:30 pm to 8:30 am, Mon-Fri (except holidays); All Saturday, Sunday and holidays

Source: UCB Utilities Engineering Services (Escobar & Ng, 2012)

The weighted average electricity cost across times and seasons results in a rate close to \$0.10/kWh paid to PG&E. In addition, \$0.01/kWh is customarily added for the UCB owned and operated distribution system including the campus Hill Area substation. While the table provides a valuable Time of Use cost breakdown to compare wind and solar technologies producing at specific times of day, the university's simplified levelized annual cost of electricity is \$0.11/kWh.

Cost per kWh Comparisons

For comparison purposes, we must use a range of costs based on time of use, transmission costs, and potential increases to 2014. We have determined that \$0.06 - \$0.13 should be the range of cost/kWh comparisons based on balancing uncertainty in the above factors, historical PG&E bills, and conversations with a variety of campus energy administrators such as Gilbert L. Escobar, Utilities Engineering and Kevin Ng, Energy Analyst in the Physical Plant - Campus Services Department. (Escobar & Ng, 2012)

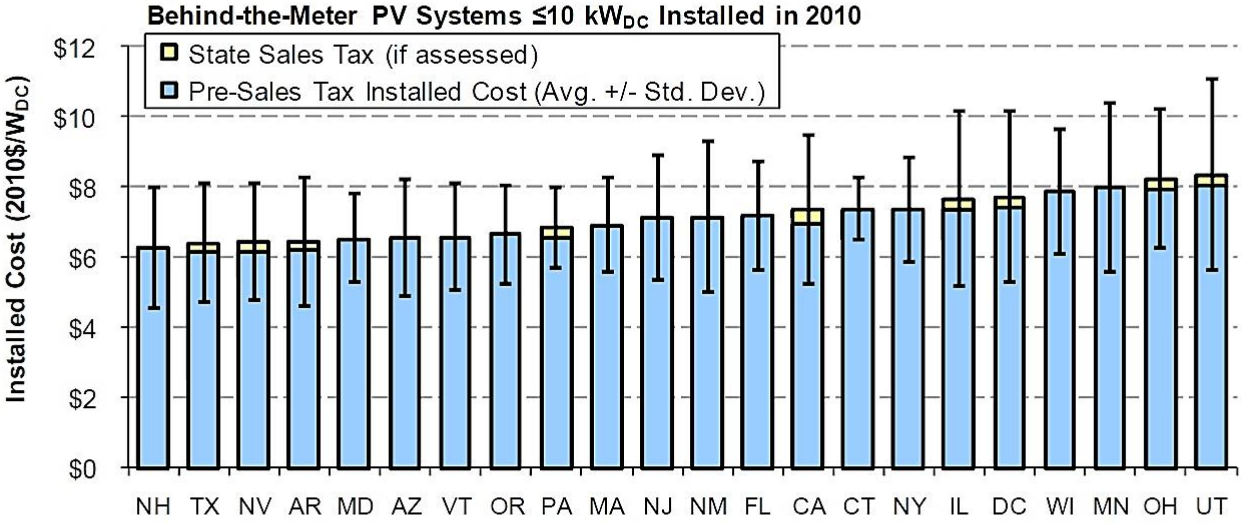
b) Cost Trends

Photovoltaic (PV)

Various units can be used to describe the cost related to PV systems. It is common to use either $\$/W_{DC}$ or $\$/W_P$ and \$/kWh/yr. W_{DC} is a value for the nominal or rated power that gives the number of Watts output when it is illuminated under standard conditions such as illumination of 1,000W/m² and 25°C temperature of the cells (NPD Company, 2012). Since PV systems have many variables that influence the total cost, it is important to be explicit about them. Nominal power and size of the array, location and sales tax treatment are some of the most important price factors. For instance a conventional c-Si PV module is generally much more expensive than CIGS modules because of its higher efficiency (International Renewable Energy Agency (IRENA), 2012).

In addition, non-module costs such as inverters, mounting hardware, labor, permitting and fees, shipping, overhead, taxes, and installer profit have an effect on the total price. "Large PV installations may benefit from economies of scale through price reductions on volume purchases of materials and the ability to spread fixed costs and transaction costs over a larger number of installed watts" (Barbose, Darghouth, Wiser, & Seel, 2011). It is also not surprising that the costs for an installed PV system vary considerably from state to state in the U.S. The United States is clearly not a homogenous PV market, as evidenced by figure 13, which shows the variation in installed cost for PV system ≤ $10kW_{DC}$ among several states. The cost for an installed PV array in California in 2010 is approximately $\$7.5/W_{DC}$ and that is among the highest third of relative PV costs by state.

Figure 13: Variation in installed costs of Behind-the-Meter PV Systems <10 kW among U.S. States

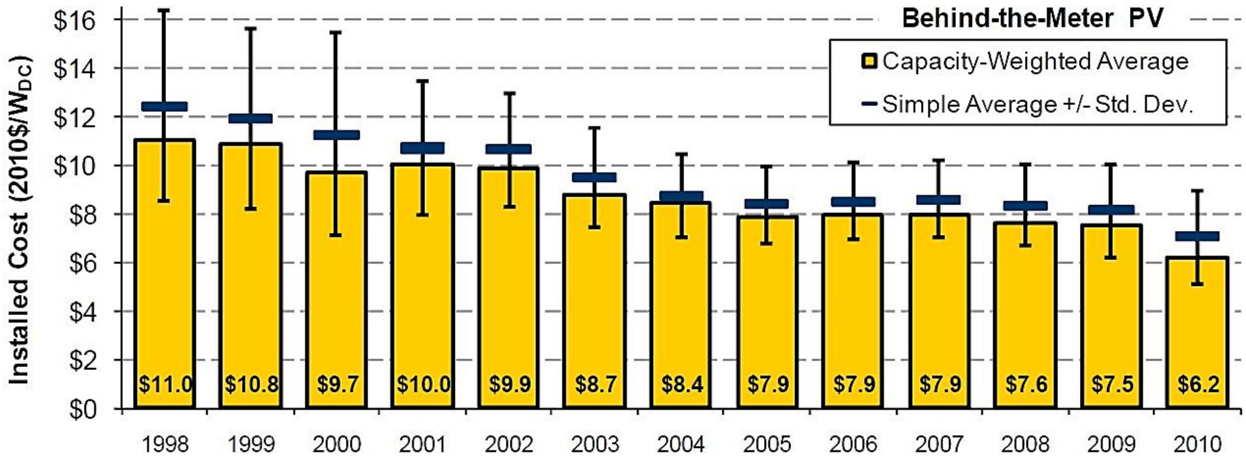


Source: (Barbose, Darghouth, Wiser, & Seel, 2011)

Figures 13 and 14 use the term “Behind-the-Meter” PV systems. It is typically a net metering arrangement that stands for PV systems connected to the customer-side of the electricity meter (as opposed to “utility sector” PV systems). Figures 13 and 14 report the results of a dataset that consists of more than 116,500 behind-the-meter PV systems (totaling 1,400MW) and utility-sector PV systems (totaling 285MW). Both represent 79% of all grid-connected PV systems in the United States through 2010.

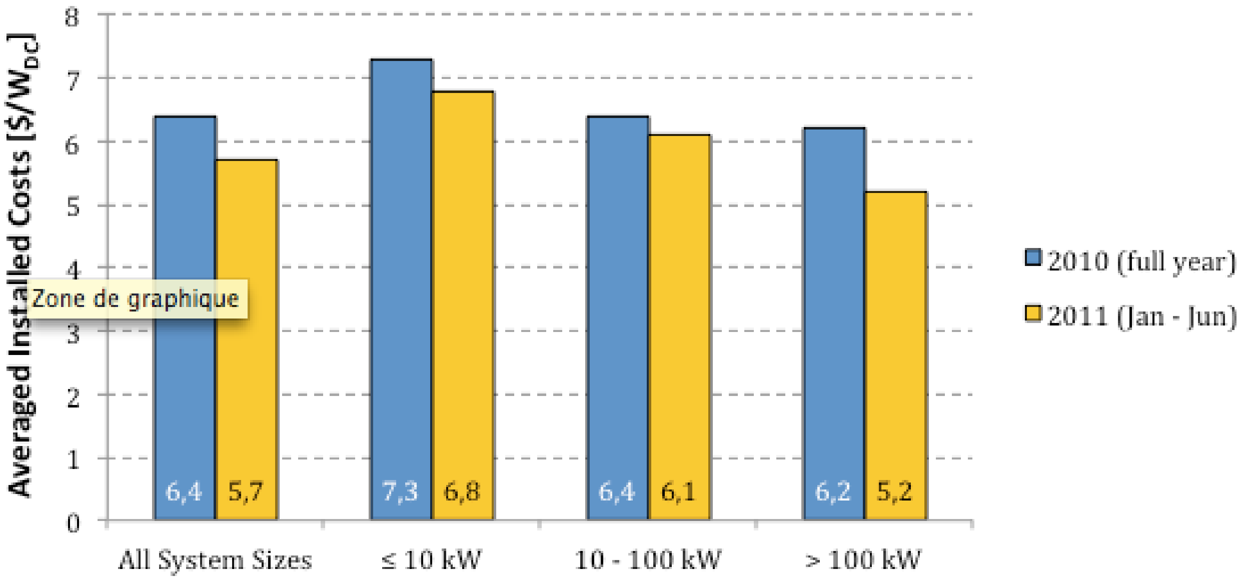
The figure 14 shows the decline in costs from 1998 to 2010. An average installation cost of \$6.2/kW$_{DC}$ represents a decrease of 43% since 1998. The average cost of PV systems in the U.S. has also declined significantly since the beginning of 2010 and costs continue to decline today. The average installed of a PV system declined by 17% between 2009 and 2010, and an additional 11% in the first six months of 2011. It is worth noting that the price for larger systems (> 100 kW) has declined the most since 2010 as shown in figure 15.

Figure 14: Average Installed cost over time for Behind-the-Meter PV



Source: (Barbose, Darghouth, Wiser, & Seel, 2011).

Figure 15: Average installed costs in the CSI Program: 2010 vs. the first-half of 2011



Source: (Barbose, Darghouth, Wiser, & Seel, 2011).

One should note that current data on average PV cost is difficult to find. Projecting the cost into the future is also complicated and unreliable due to the rapidly growing and changing PV market (International Renewable Energy Agency (IRENA), 2012).]

UC Berkeley wants to reduce greenhouse gas emissions from campus operations to 1990 levels by 2014, so campus conducted several feasibility studies on renewable energy installations on campus in the last few years. Most of these studies deal with the costs and feasibility of PV and solar thermal systems on facilities of UC Berkeley. Some of them are referenced below in order to be able to classify the size and costs of potential projects and to compare them to the cost development.

Solar Thermal

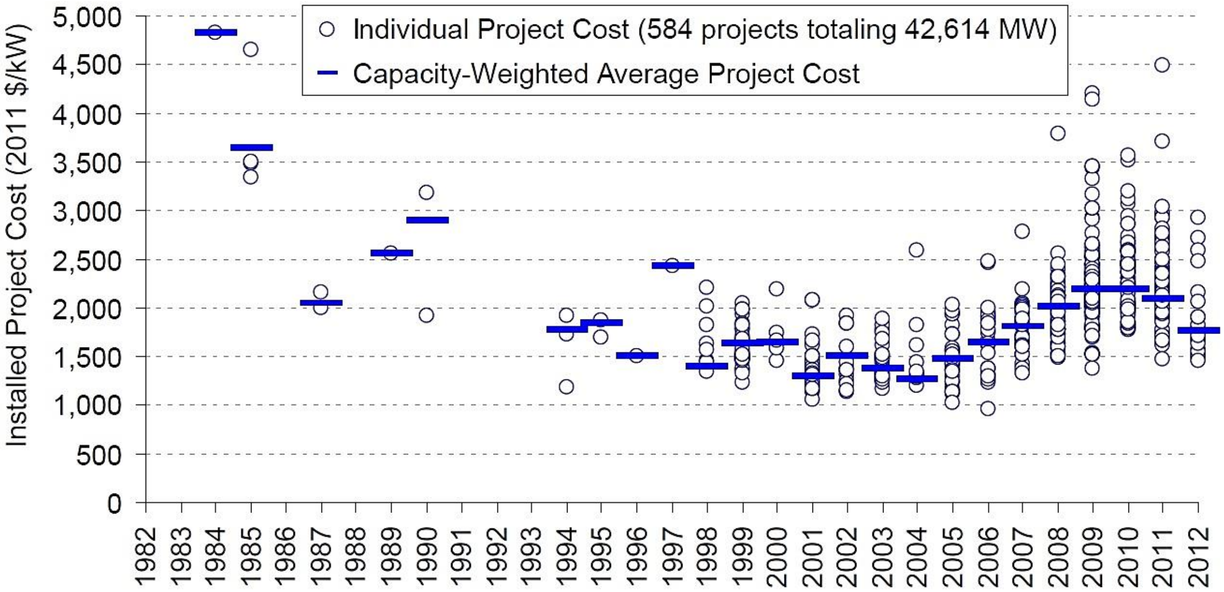
Currently the data relating to solar water heaters, especially for the commercial market is sparse. Our team was unable to find reliable data for pricing of solar water heaters for larger installations that would be appropriate for buildings on UC Berkeley's campus. There is some data for turnkey systems; for example, a 26 collectors system for a cafeteria would cost approximately $100,000 (NC Public Power, 2012). However, prices are highly variable based upon the qualities of the building the panels are to be installed on, especially roof geometry. Anna Head, which has been operating for only a month at the time of writing, can provide very little performance data. Until better-documented estimates are researched, our team is of the opinion that we would need a quote from a contractor for reliable cost predictions for the buildings on campus.

Big Wind

Lawrence Berkeley National Laboratory gathered price data for 584 U.S. wind turbine transactions. It covers installed wind systems totaling 42,614 MW announced from 1982 through 2011. The most recent data from 2011 includes 12 wind systems of 2,630 MW that only represents 38.6 % of the total installed wind systems in 2011 (6,810 MW) (American Wind Energy Association (AWEA), 2012; Andrews, 2012). This data is formatted and summarized by U.S Department of Energy in their “2011 Wind Technologies Market Report” (Wiser & Bolinger, 2011 Wind Technologies Market Report, 2012).

Figure 16 presents data on the development of installed project cost from 1982 to 2012. The few data records from 1982 to 1995 show that there was a tremendous decline in the installed project cost, which reached its nadir in the early 2000’s. After that a steady increase of the cost can be recognized over a time period of 6 years. This increase is due to several variables such that increased labor cost, higher warranty provisions, increased turbine size and profitability of the manufacturers, a decline in the value of the U.S. dollar relative to the Euro, and increased raw material and energy prices (Wiser & Bolinger, Understanding Trends in Wind Turbine Prices Over the Past Decade, 2011). After hitting a peak in 2009/2010 the installed project cost declined again and now has returned to 2006 price levels.

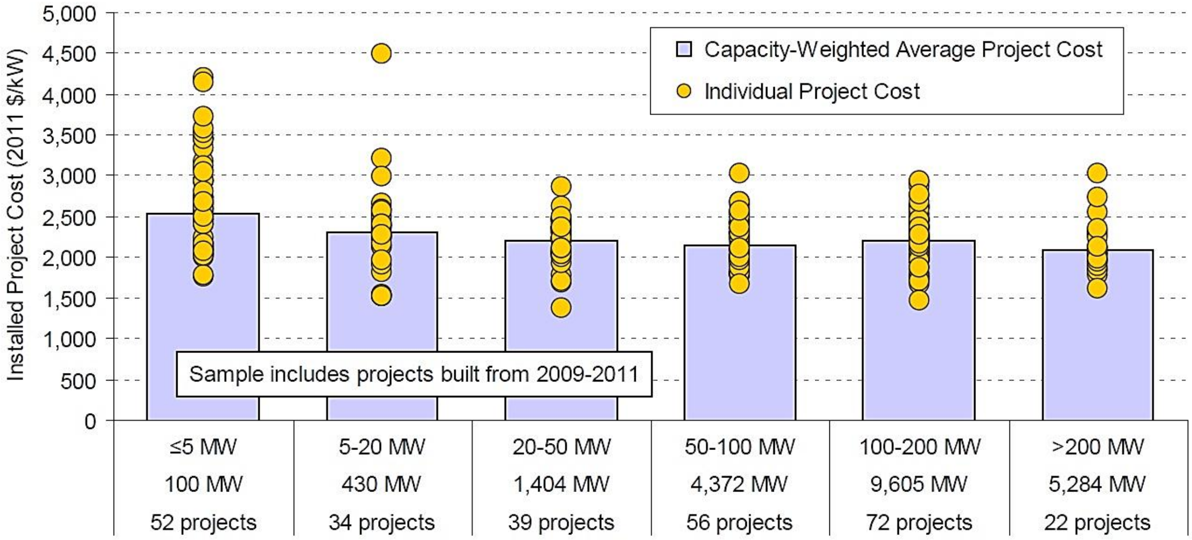
Figure 16: Installed wind power project cost from 1982 to 2012



Source: (Wiser & Bolinger, 2011 Wind Technologies Market Report, 2012)

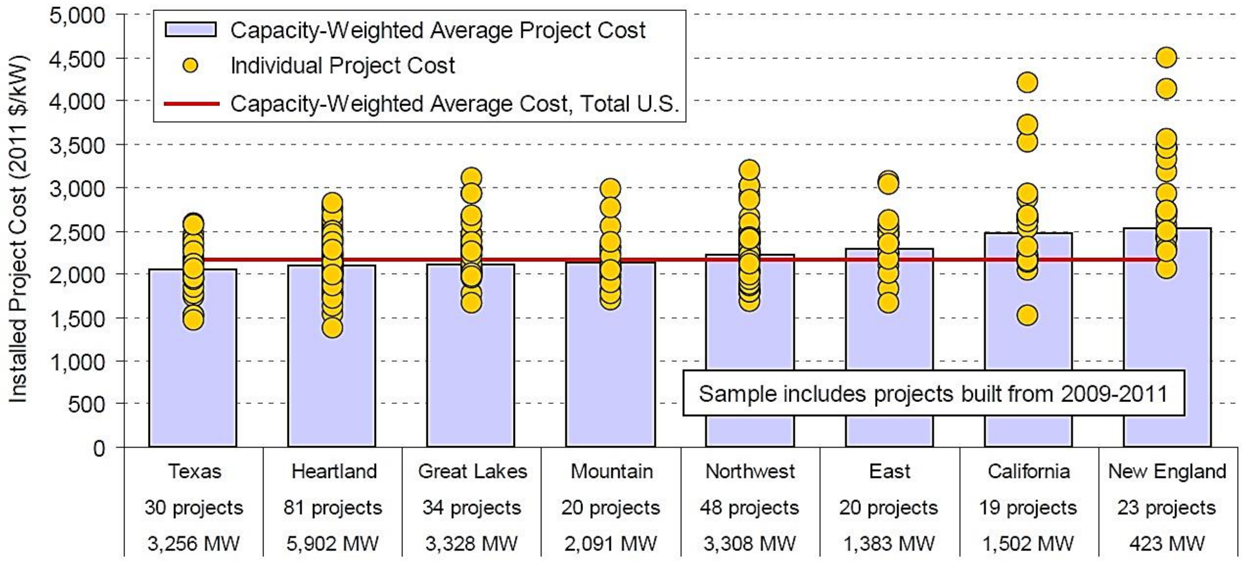
Figures 17 and 18 present information about the most recent projects cost and distinguish between the capacity of wind turbines and their location. Wind systems show the same location dependence of the price, as it is common for PV systems. It is attributed to differences in transportation cost, timeframes, permitting requirements and constructions and development cost (Wiser & Bolinger, 2011 Wind Technologies Market Report, 2012). Installed project costs of approximately $2,500/kW in California are above the national average. Furthermore, figure 17 shows that smaller wind systems tend to be more cost-intensive than larger projects. This data reveals that big wind power installations require an investment of at least $1,500 per kW capacity. Here we want to use the range of **$1,500 to $3,000 per kW installed** since figure 18 reveals that this range applied for most of the projects in California in 2009 – 2011.

Figure 17: Average and individual installed project cost for wind power by project size form 2009-2011



Source: (Wiser & Bolinger, 2011 Wind Technologies Market Report, 2012)

Figure 18: Average and individual project cost for wind power by region from 2009-2011



Source: (Wiser & Bolinger, 2011 Wind Technologies Market Report, 2012)

Small Wind

The American Wind Energy Association (AWEA) yearly publishes a "Small Wind Turbine Market Report". The following information is derived from the latest report in 2011 (Flowers, 2011 U.S. Small Wind Turbine Market Report, 2011).

In 2011, the average costs for a small wind system in the U.S. increased by 11% compared to 2010 to $6,040/kW (2010: $5,376/kW). This report derives the number by evaluating 27 small wind turbine manufacturers from North America, Europe and South Africa. These numbers account for worldwide sales of $397 million, totaling more than 21,000 units and 64 MW. In 2011, the U.S. market for small wind systems installed 19 MW of new sales capacity, representing 7,303 turbines and $115 million in installed system revenue. Domestic sales accounted for 80 percent of the total U.S. market in 2011 in terms of installed kW. These numbers can be compared to price lists of small wind manufacturers. Bergey Windpower Co. (Oklahoma) is one of the few companies that publish a retail price list on their web site. In 2011, the retail price of a 10 kW small wind grid-intertie model was $45,915. This offer includes the turbine, a 30 m (100 ft) tall standard guyed-lattice tower, an inverter and the assembly equipment but does not consider installation costs (Bergey Wind Power Co., 2011; Bergey Wind Power, 2012). Under the assumption that a quarter of the total costs are due to installation, the small wind system would fall into the range of $6,000/kW. Other papers and consumer guides provide a range for small wind costs that range from $4,000/kW to $8,000/kW depending on the size of the turbine, the height of the tower, local zoning, and utility interconnection costs (U.S. Department of Energy - EERE Information Center, 2010).

We summarize our cost computations in the figure 19 below:

Figure 19: Total costs to fill the energy gap with a single renewable technology

	PV	**Big Wind**	**Small Wind**
$/kW	3,800-7,500	1,500 – 3,000	4,000 – 8,000
Needed amount	23,136 m^2	2 turbines	45 – 508 turbines
Total Costs in $	12M - 24 M	6 M – 12 M	18 M - 41 M

c) Steam Economics

Campus steam costs approximately $8.93 per thousand pounds of steam according to the Office of Sustainability (Stoll, 2012). The heat content in 1000 lbs. of steam is 11.94 Therms (U.S. Environmental Protection Agency and the U.S. Department of Energy - Energy Star, 2012; Escobar & Ng, 2012). The heat value reflects an assumed system delivery at 150 psi saturated with steam with a Btu value of 1194 Btu/lb, a value provided to EPA by the International District Energy Association (IDEA). The cost per Therm is therefore $0.75/Therm for the steam on campus. This price is very low because it does not include maintenance of the steam tunnel and does not include the price of the infrastructure, which was built and amortized a long time ago. The existing and fully paid off infrastructure explains why steam is inordinately inexpensive on campus.

d) Incentives in California

There are several government incentive programs intended to encourage the development of renewable energy in California. Due to the current statewide budget crisis, many incentive programs have already ended or will not be extended. For instance the above-mentioned CREBS funding, California’s Emerging Renewable Program for wind systems and the federal Production Tax Credit have been or will soon be curtailed. UC Berkeley is eligible for the following incentives based on geography and status.

Photovoltaic (PV)

California Solar Initiative Program (CSI)

The California Solar Initiative provides financial incentives to qualifying existing residential and commercial entities for installing photovoltaic capacity at home or at the business. Over the next decade, the California Public Utilities Commission plans to disburse more than $2.1 billion to support solar capacity installations on existing buildings (Pacific Gas and Electric Company, 2012). There is also the NSHP (New Solar Homes Partnership) a program designed to provide incentives for the inclusion of solar panels in new home construction. Together, these financial incentives aim to encourage 3 GW of newly installed solar capacity in the state of California by the year 2017. These initiatives will make solar energy more economically feasible for the owner and serve as a government subsidy to California's young solar industry.

Solar thermal

California Solar Initiative Thermal Program

A solar water heating system can offset up to 75% of water heating costs at an average residential building in California. The CSI thermal program incentivizes consumers to add solar thermal water heaters on their roofs. This program was put in place in early 2010 to directly incentivize retail customers to purchase solar water heating devices. In addition, the program subsidized low-cost training programs for contractors and building inspectors, as well as marketing both the environmental and economic benefits of solar water heaters in California. California's climate and year-round sun exposure are well suited to the deployment of passive solar water heaters. More than $350 million was earmarked for this program, with incentives for single-family SWH systems covering up to $1,875. This represents more than one-third the cost for a typical solar water heater setup. Solar water heaters are a low-tech, highly effective way to save energy costs in the American Southwest and this program aims to speed their adoption (Pacific Gas & Electric Company, 2012).

Wind

Self-Generation Incentive Program (SGIP)

The Self Generation Incentive Program (SGIP) offered by PG&E provides incentives for the installation of new wind or fuel cell self-generation equipment. Only commercially available and factory new equipment of a minimum size of 30kW are eligible to receive incentives. Wind turbines are currently supported with $1.25/W (incentive capped at a total of 30 MW installed) (Pacific Gas and Electric Company, 2012; Powel, 2003).

e) Other Financial Resources

Power Purchase Agreements (PPAs)

Power Purchase Agreements (PPAs) allow the university to purchase the electricity output from the PV system for a period of time rather than purchasing the system itself. A third party would build and maintain the system because payments would correspond to kWh produced, UCB would not be penalized if the system underperformed. Ongoing administrative costs of paying several separate electricity invoices should be kept in mind. Some PPAs also prohibit making changes to property that could affect energy production. Due to the disappointing performance of the MLK Building PV modules, Campus administrators have indicated a strong preference for PPAs to minimize risk of underperformance, permitting issues, and avoiding high upfront costs relative to paying for or financing a PV system upfront (Stoll, 2012). A PPA could mean a higher (or potentially lower in the case of underperformance) cost than owning and operating the system. Benefits and challenges of PPAs are summarized in figure 20.

Figure 20: Benefits and challenges of PPAs for UCB

Benefits for UCB	***Challenges for UCB***
• No upfront capital cost. • Predictable energy pricing. • No system performance or operating risk. • Visibly demonstrable environmental commitment. • Potential to make claims about being solar/wind powered (if associated RECs are retained). • Potential reduction in carbon footprint (if associated RECs are retained). • Support for local economy and job creation.	• More complex negotiations and potentially higher transaction costs than buying PV system outright. • Administrative cost of paying two separate electricity bills because system does not meet 100 percent of site's electric load. • Site lease may limit ability to make changes to property that would affect PV system performance or access to the system. • Understand tradeoffs related to REC ownership/sale.

Renewable Energy Credits (RECs)

A Renewable Energy Credit (REC) representing the environmental and other benefits of renewable energy can be sold separately from the actual energy a renewable generation source produces. The CalCAP office maintains an interest in purchasing RECs (as opposed to installing renewable generation capacity) if the physical constraints of UCB's land or wind/solar suitability become the main barrier to renewable generation.

f) Cost per kWh Calculations and Comparisons

For each renewable installation, we must calculate the cost/kWh to make a useful comparison with how campus pays PG&E for electricity: on a per kWh basis. Because government financial incentives (i.e. Production Tax Credit and Investment Tax Credits) vary from year to year, none of the calculations include any financial incentives. Yet, campus should factor in incentives at the time of purchase, which will likely reduce the cost of renewable energy (and possibly make some technologies more competitive with PG&E rates).

Assumptions

Because campus will likely pursue long term financing for any renewable energy installation or pay through a PPA, we annualized the costs of each installation over its lifetime and divided it by the kWh each would produce each year without factoring degradation of electricity production over time. To annualize the costs of the installation, a 7% discount rate was assumed for the life of each installation (either 20 years for wind or 25 years for PV).

PV

In order to calculate the high and low range of costs/kWh of PV, we utilized the high and low $/Watt installed costs and then incorporated the Berkeley-specific insolation and average efficiency of multicrystalline solar panels (the most common) to determine the electricity that would be produced if the panels were installed on the roofs of our own campus buildings. We found that **electricity from photovoltaic panels installed on campus would range between $0.15 - $0.30 /kWh** without any government incentives.

Calculations:

For the high cost calculations, we utilized the $7.5/Watt installed from the 2009 campus PV feasibility study and averaged cost from the 'Tracking the Sun' study ((Barbose, Darghouth, Wiser, & Seel, 2011). For the low cost, we utilized the best-case $3.80/Watt installed from the 2012 US Department of Energy SunShot report (U.S. Department of Energy, 2012).

To calculate the kWh produced per m^2 of panels per year, First, we use Berkeley's average insolation of 246 W/m^2 (to calculate the average insolation in kWh/m^2/year (da Rosa, 2009). Insolation already takes into account the average number of hours the sun shines each day and the cloudiness of a geographical area:

$$\frac{246\,W}{m^2} \times \frac{8760\,hours}{year} \times \frac{1\,kW}{1000\,W} = \frac{2{,}154\,\frac{kWh}{m^2}}{year}$$

We then multiply the insolation by the 14% efficiency to get the electricity actually produced:

$$\frac{2{,}154\,\frac{kWh}{m^2}}{year} \times 0.14 = \frac{301\,\frac{kWh}{m^2}}{year}\ electricity\ produced$$

This is in the range of 256 to 307 kWh/m^2/year we found in chapter V 1. C) PV.

To calculate the annualized cost of system per m^2 installed, we must first understand that PV modules are rated to receive 1kW/m^2 of solar radiation and costs are given per Watt-peak produced. To calculate the Watt-peak of 1 m$^{2:}$

$$\frac{1\,kW}{m^2} \times 1\,m^2 \times \frac{0.14\,kW_{elec}}{1\,kW_{solar\ radiation}} = .14\ \frac{kW - peak}{m^2}\, or\ 140\ \frac{Watt - peak}{m^2}$$

The cost per m^2 is then either:

LOW COST: $\frac{\$7.5}{W\text{−}peak} \times \frac{140\ W\text{−}peak}{m^2} = \frac{\$1{,}050}{m^2}$ OR HIGH COST: $\frac{\$3.8}{W\text{−}peak} \times \frac{140\ W\text{−}peak}{m^2} = \frac{\$532}{m^2}$

We can use the annuity equation to solve for the levelized cost of the system (U = the annualized cost, P= upfront present value of the cost, n=useful lifetime, r=discount rate):

$$U = P\left[\frac{r}{1-(1+r)^{-n}}\right]$$

$$With\ n = 25\ years, r = 0.07, and\ P = either\ \$1{,}050\ or\ \$532\ per\ m^2$$

Or, the high-annualized cost can be calculated:

$$U = annualized\ cost = \big(140\ Watt\ peak \times (\$1{,}050)\big)\left[\frac{0.07}{1-(1+0.07)^{-25}}\right] = \frac{\$90.10}{m^2}$$

The low cost:

$$U = annualized\ cost = \left(140\ Watt\ peak \times (\$532)\right)\left[\frac{0.07}{1-(1+0.07)^{-25}}\right] = \frac{\$45.65}{m^2}$$

Finally, in order to calculate the cost/kWh, we divide the annualized cost by number of kWh produced:

$$\frac{annualized\ cost\ of\ system\ per\ m^2}{kWh\ produced\ per\ \ m^2 each\ year} = \frac{\$90.10}{301\frac{kWh}{year}} = \$\mathbf{0.30}\ \boldsymbol{per\ kWh}\ (\boldsymbol{HIGH\ levelized\ cost\ of\ electricity})$$

$$\frac{annualized\ cost\ of\ system\ per\ m^2}{kWh\ produced\ per\ \ m^2 each\ year} = \frac{\$45.65}{301\frac{kWh}{year}} = \$\mathbf{0.15}\ \boldsymbol{per\ kWh}\ (\boldsymbol{LOW\ levelized\ cost\ of\ electricity})$$

Therefore, **the range of cost for PV panels installed on campus would be $0.15 - $0.30 / kWh electricity.**

Big Wind

Wind production and production costs are heavily influenced by the quality of wind at the installation site. In order to compare it fairly with small wind and PV, we could perform a calculation based on the wind resources in Berkeley, which is 4.5 m/s average wind speed. But, since campus is not likely to install towering 2 MW turbines right next to campus, we will show the calculations based on a better wind resource in northern California, such as Solano County, which blows at 7 m/s on average. Regarding transmission from a place like Solano County, campus could either feed the wind into the existing electricity grid or sell the electricity locally, accounting for it as a reduction in campus emissions by ensuring it displaces dirtier energy generation sources. Overall, this poses some accounting intricacies, but the relatively higher wind resources and therefore lower cost should make the more complex energy accounting worthwhile. Overall, we assume the density of air is 1.225 kg/m^3, the lifetime of turbines is 20 years and we were using standard 2 MW wind turbines corresponding to the Vestas V90-2.0 MW Gridstreamer™ model with a 90m-rotor diameter and 40% efficiency. For installed costs, Wiser and Bollinger indicated a range of $1,500 - $3,000 per kW installed cost. To calculate the $/kWh, we first calculate the cost per 2MW turbine by multiplying the high and low costs by the capacity:

LOW COST: $\frac{\$1500}{kW} \times \frac{1000\ kW}{1\ MW} \times \frac{2\ MW}{turbine} = \$3{,}000{,}000\ per\ 2MW\ turbine$

HIGH COST: $\frac{\$3000}{kW} \times \frac{1000\ kW}{1\ MW} \times \frac{2\ MW}{turbine} = \$6{,}000{,}000\ per\ 2MW\ turbine$

In order to annualize the cost, we use the same formula as we used for PV:

We can use the annuity equation to solve for the levelized cost of the system (U = the annualized cost, P= upfront present value of the cost, n=useful lifetime, r=discount rate):

$$U = P\left[\frac{r}{1-(1+r)^{-n}}\right]$$

With n=20 years, r=0.07,and P=either \$3 million or \$6 million per 2MW turbine:

HIGH COST: $U = (\$3{,}000{,}000)\left[\frac{0.07}{1-(1+0.07)^{-20}}\right] = \$283{,}179$ per 2MW turbine, annualized cost

LOW COST: $U = (\$6{,}000{,}000)\left[\frac{0.07}{1-(1+0.07)^{-20}}\right] = \$566{,}357$ per 2MW turbine, annualized cost

We calculate the swept area of our 90m-rotor diameter by using the area of a circle:

$$swept\ area = \pi r^2 = \pi \times \left(\frac{90\ m}{2}\right)^2 = 6359\ m^2\ swept\ area$$

To calculate the electricity production each year, we must understand how the rotor diameter and wind speed affect the production. In order to calculate the power output of the wind turbine in relationship to the average wind speed, we use the wind power equation incorporating the Rayleigh distribution associated with using *average* wind speed:

$$P_{average\ output,Watts} = (1.91) \times (\tfrac{1}{2}\ \rho\, A\, v_{avg}^3\ ) \times efficiency\ of\ turbine$$

where ρ = air density = 1.225 kg/m^3 at 15°C and 1 atm, A = swept area [m^2] and v_{avg} = average velocity of wind [m/s].

Therefore, if the wind farm were located somewhere off campus, in a place like Solano country with average wind speeds of 7 m/s, the economic are:

$$P_{average\ output,Watts} = (1.91) \times \left(\tfrac{1}{2}\ \rho\, A\, v_{avg}^3\right) \times\ efficiency\ of\ turbine$$

$$= (1.91)\left(\tfrac{1}{2} \times\ 1.225\ kg/m^3 \times 6359\ m^2 \times\ (7\ m/s)^3\right) \times\ 0.40 = 1{,}020{,}583\ W = 1{,}021\ kW$$

And:

$$1{,}021\ kW \times \frac{8760\ hours}{year} = 8{,}940{,}305\frac{kWh}{year}$$

Finally, we can calculate the cost/kWh by dividing the annualized cost by the annual production (LCOE):

$$\frac{\frac{\$283{,}178}{year}}{8{,}940{,}305\frac{kWh}{year}} = \frac{\$0.03}{kWh}\ (LOW\ Levelized\ Cost\ of\ Electricity)$$

$$\frac{\frac{\$566{,}358}{year}}{8{,}940{,}305\frac{kWh}{year}} = \frac{\$0.06}{kWh}\ (HIGH\ Levelized\ Cost\ of\ Electrici\ \square)$$

This $0.03 – 0.06 range is actually lower than PG&E costs.

Small Wind Costs / kWh

For small wind, we utilized the same process to calculate the LCOE as we did for big wind, except we utilized three different sized turbines with different rotor diameters and different costs/kW installed. The costs per kW decrease, as the nameplate capacity of each turbine gets bigger. UC Berkeley would only install small wind turbines rather than big wind turbines because of an interest in putting wind on top of buildings on campus, so only the 4.5 m/s average wind velocity was used to calculate the LCOE for small wind.

The assumptions were based on the descriptions in the 'small wind' section and the calculated LCOE associated with each size turbine were as shown in figure 21 below:

Figure 21: Assumptions for calculating the levelized cost of electricity

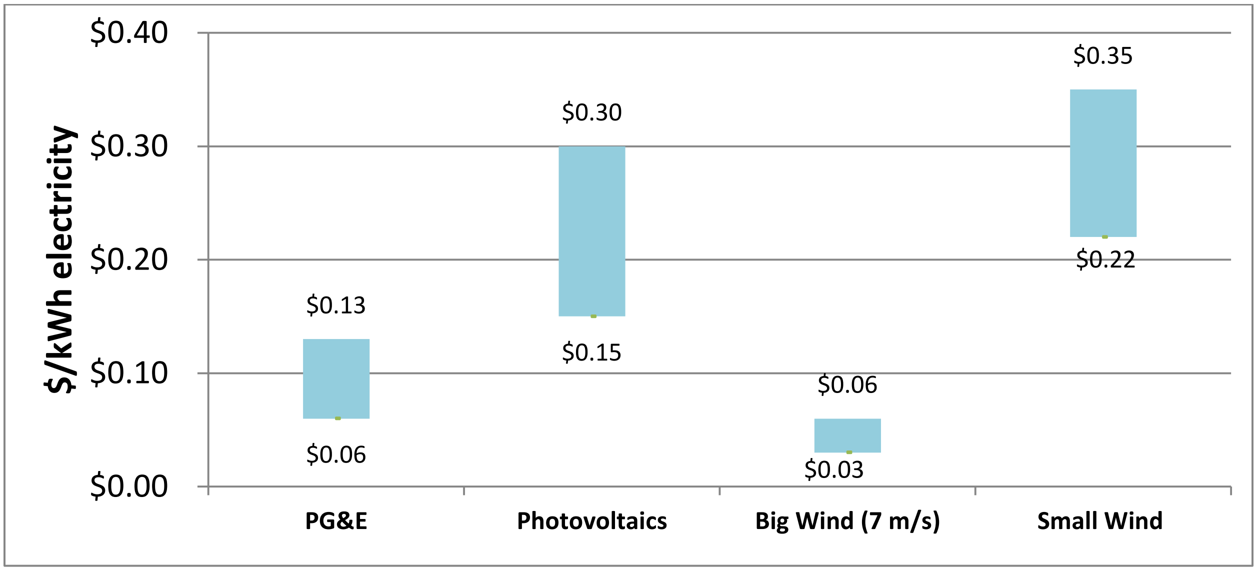
Size of Turbine	**Cost/kW Installed**	**Rotor Diameter**	**LCOE**
10 kW	$8,000 / kW	7 m	$0.35 / kWh
50 kW	$6,000 / kW	15 m	$0.29 /kWh
100 kW	$4,000 /kW	20 m	$0.22 /kWh

Therefore, **the range for small wind was $0.22 - $0.35, or one of the highest cost generation options!**

Electricity Cost Comparisons

In figure 22 below, we can compare the costs of each generation option. The renewable energy calculations do not include subsidies, transmission costs, or ongoing operations and maintenance costs. Our calculations show big wind at 7 m/s is the only one that is less expensive than PG&E if unsubsidized. Likely, with the government solar ITC or another incentive, PV could possibly be cost competitive with PG&E's high cost range.

Figure 22: Levelized cost of electricity for different generation option

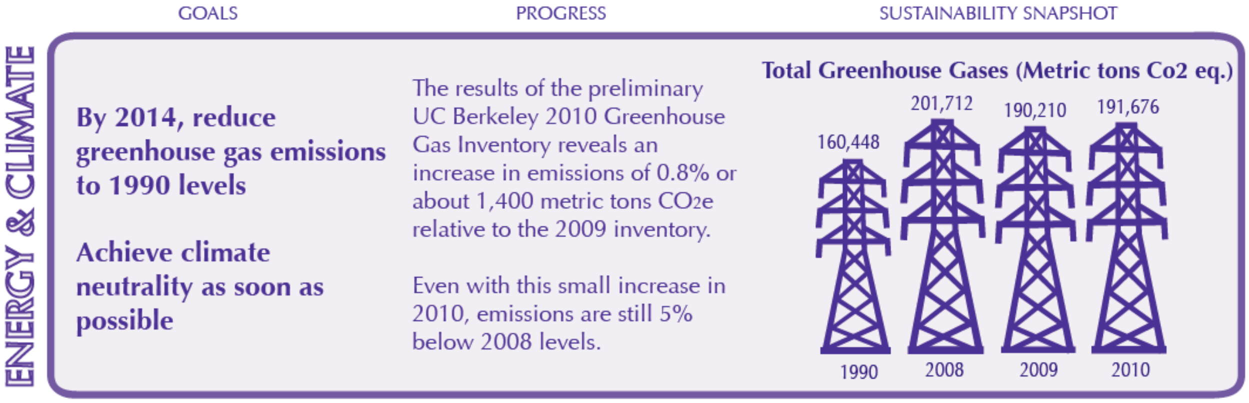


3. ENVIRONMENTAL BACKGROUND

a) Campus Goals

The Cal Climate Action Partnership (CalCAP), formed in 2006, is a collaboration of faculty, administration, staff, and students working to reduce greenhouse gas (GHG) emissions at UC Berkeley. In 2007, the campus committed to its first greenhouse gas emissions reduction target: to reduce GHG emissions to 1990 levels by the year 2014. This goal is six years earlier than State of California and the UC Policy on Sustainability Practices requires. (Berkeley Sustainability Office, 2011; National Renewable Energy Laboratory, 2011; Wiser & Bolinger, 2011 Wind Technologies Market Report, 2012)

Figure 23: Description of UC Berkeley's goals



GOALS

By 2014, reduce greenhouse gas emissions to 1990 levels

Achieve climate neutrality as soon as possible

PROGRESS

The results of the preliminary UC Berkeley 2010 Greenhouse Gas Inventory reveals an increase in emissions of 0.8% or about 1,400 metric tons CO2e relative to the 2009 inventory.

Even with this small increase in 2010, emissions are still 5% below 2008 levels.

SUSTAINABILITY SNAPSHOT

Source: Office of Sustainability (Stoll, 2012)

Key Strategies to achieve these goals as stated in the Campus Sustainability Report (Campus Sustainability Report, 2011):

1. Reduce system wide growth-adjusted energy consumption by 10% or more by 2014 from the year 2000 base consumption level.

2. Work on UC system goal to provide up to ten megawatts of local renewable power by 2014.

3. Develop a campus standard for sustainable design specific to our site, climate, and today. facility inven

4. Update the *Campus Design Standards* and set a campus-wide energy policy.

5. Implement strategies and actions identified in the UC Berkeley *2009 Climate Action Plan* and future climate action plans.

6. Set next interim greenhouse gas emissions reduction target for 2020 or 2025.

7. Define climate neutrality and a target date for reaching neutrality.

b) Renewable Energy Fits into Matrix of Sustainability Goals

Adding renewables to existing buildings or integrating renewables in new buildings design can help achieve at least some of the energy and climate goals discussed above. The trend is to aim towards a net zero campus, which means that the campus produces as much energy from renewable energy as it consumes, even while maintaining connection to the grid.

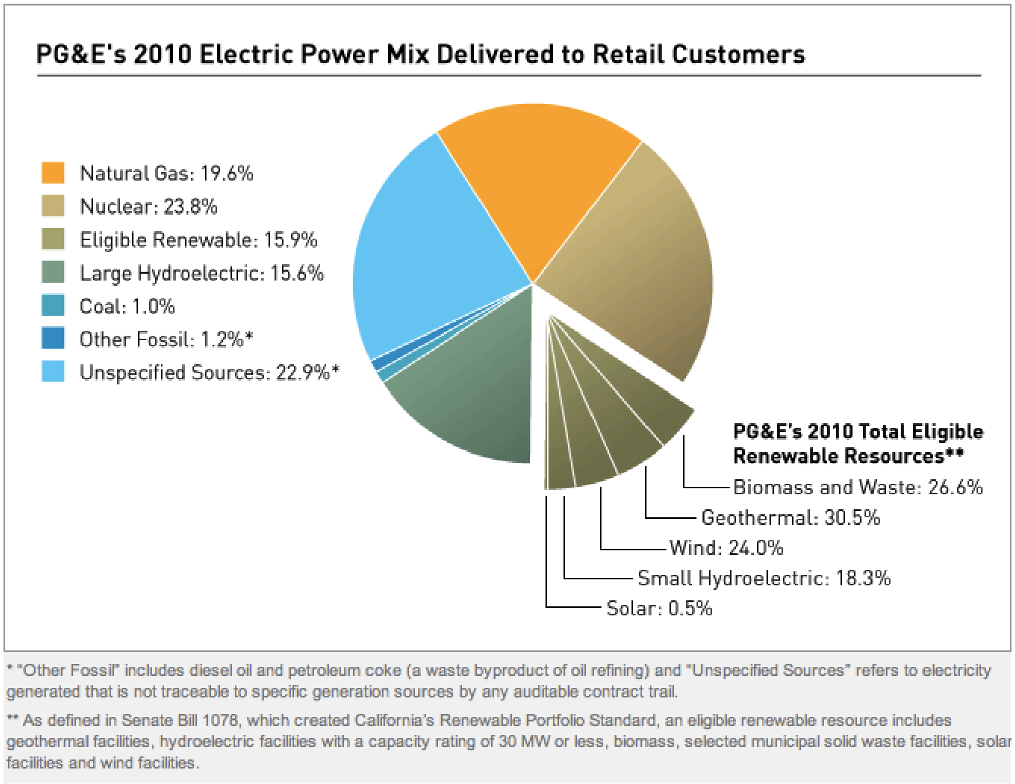
Renewable energy projects fit into the matrix some current initiatives carried out by various organizations. The Green Initiative Fund (TGIF), for example, plans to use funds raised from students for sustainability projects such as to increase the number of recycling bins, reducing packaging at Berkeley's cafes, etc. Claudia Covello of TGIF has expressed a willingness to help fund and promote campus renewable energy projects with part of TGIF's $300,000/year budget (Covello, 2012).

CalCAP divides its mitigation actions into three categories: 1) infrastructure projects, 2) behavioral Projects, and 3) other (which are mainly increasing renewable generation capability). The Sustainability Office has published a detailed matrix of infrastructure projects, of which the last is on-site PV and solar thermal. All initiatives, including our project can be considered as 'wedges' to accomplish the campus sustainability goals.

c) Carbon Intensity of Current and Future PG&E Generation Mix

Berkeley and UC Berkeley campus are powered through PG&E utility. The GHG emissions from campus energy use are closely tied to the carbon intensity of the current PG&E mix. Fortunately for UC Berkeley, PG&E's emissions rate is relatively low compared to California average (PG&E rate is 35% below California rate average) and only about one-third as carbon intensive as the national utility average. In fact, more than half of PG&E's power came from a combination of non-greenhouse gas emitting and renewable sources in 2010. The mix consisted of nuclear (23.8%), large hydroelectric facilities (15.6%), and renewable resources (15.9%). The remaining portion came from natural gas (19.6%), coal (1.0%), other fossil (1.2%), and unspecified sources purchased through the wholesale power market (22.9%) as shown in the figure 24 below (Pacific Gas & Electric Company, 2011). 16% of PG&E's power mix comes from renewable resources.

Figure 24: PG&E's 2010 Electric Power Mix Delivered to Retail Customers



* "Other Fossil" includes diesel oil and petroleum coke (a waste byproduct of oil refining) and "Unspecified Sources" refers to electricity generated that is not traceable to specific generation sources by any auditable contract trail.

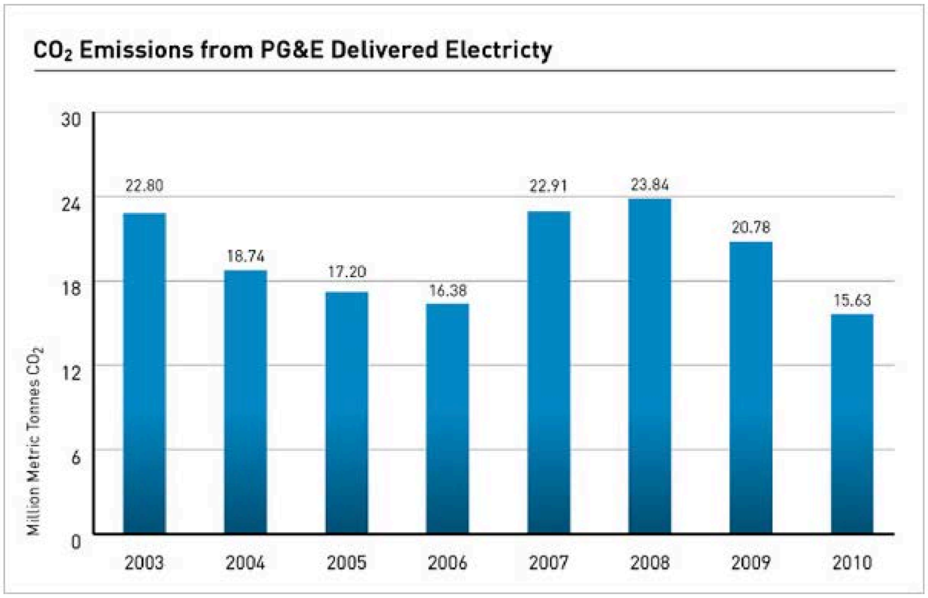
** As defined in Senate Bill 1078, which created California's Renewable Portfolio Standard, an eligible renewable resource includes geothermal facilities, hydroelectric facilities with a capacity rating of 30 MW or less, biomass, selected municipal solid waste facilities, solar facilities and wind facilities.

Source: (Pacific Gas & Electric Company, 2012)

From year to year, several factors affect PG&E's power mix and emissions including demand growth and the availability of hydropower as shown in the figure 25 below. At least one underlying trend is strongly favorable, however. In 2012, PG&E expects to source 20% of its electricity from renewable generation, and 33% by 2020.

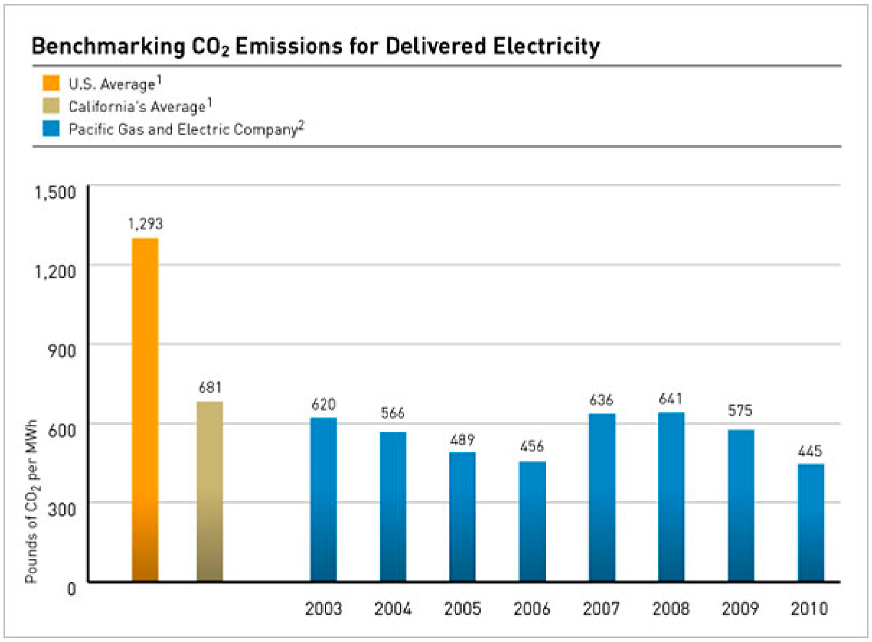
PG&E reports the GHG emissions from the electricity it provides (electricity emission factors) and from gas (natural gas emission factors) to the public (see figure 26 below). These factors are third-party verified and emissions intensity has been forecasted to 2020. (Balachandran, 2012)

Figure 25: CO_2 emissions from PG&E delivered electricity



Source: (Marshall, 2012)

Figure 26: CO_2 emissions per MWh of electricity delivered



[1] Source: U.S. Environmental Protection Agency eGRID2010 Version 1.1, which contains year 2007 information configured to reflect the electric power industry's current structure as of December 31, 2010.

[2] Because PG&E purchases a portion of its electricity from the wholesale market, we are not able to track some of our delivered electricity back to a specific generator. Therefore, there is some unavoidable uncertainty in PG&E's total emissions and emissions rate for delivered electricity.

Source: (Marshall, 2012)

The official 2010 emission factor from PG&E (Figure 26) is 202 g CO_2/kWh (using the conversion 1 pound equals 454g).

PG&E only reports CO_2 emissions from electricity generation whereas many other harmful greenhouse gases are being emitted during electricity generation (methane, NOx, etc.). In order to accurately compare the renewable options from an environmental perspective, we must calculate emission factors for PG&E mix in CO_2-equivalents.

For our study, we analyze the campus-provided 'Business as Usual' scenario that does not take into account any energy savings and thus GHG emissions reductions from mitigation projects implemented at Berkeley. This scenario does not use PG&E's predicted emissions factors for 2020 but rather assume that PG&E's emissions factors decrease by 2% annually in line with the current trend.

In addition, PG&E's official reporting and both of the graphs above do not consider the full lifecycle impacts of electricity generation. In order to calculate a more accurate emissions estimate, we used the electricity generation sources analysis from the "Life-cycle Energy Assessment of Alternative Water Supply Systems in California" report prepared for the California Energy Commission. (Horvath, 2011).

The figure 27 below shows the life cycle emissions factors for each major type of generation technology:

Figure 27: Life-cycle emission factors for different generation technology

Energy sources	**Life-cycle emission factors (GHG in g CO_2-eq/kWh)**	**% of this energy source in PG&E mix from 2010**
Coal	1059	1
Oil	957	0
Gas	696	19.6
Nuclear	17	23.8
Other Fossil Fuel	417	1.2
Hydro	55	18.5

Biomass	56	4.2
Wind	31	3.8
Solar	64	0.08
Geothermal	28	4.8
Unspecified source	?	22.9

Source: (Horvath, 2011; Kamlarz, 2006; Lenzen & Munksgaar, 2002) and (Pacific Gas & Electric Company, 2012)

From Figure 27, we can calculate a new PG&E LCA emission factor. We have to make an assumption though on the LCA emission factor for the ‘Unspecified Source’ category. We will assume here that this ‘unspecified source’ is mostly natural gas with an emissions factor of 696 g CO_2-eq because natural gas plants can respond quickly to the hour-ahead market and in an interview with a PG&E Executive; PG&E formerly used this assumption (Friedman, 2012).

Figure 27 above gives an LCA emission factor for PG&E of 331 g CO_2-eq/kWh.

The calculated LCA emission factor is 60% higher than PG&E official number:

PG&E official emission factor for 2010	**PG&E LCA emission factor for 2010**
202 g CO_2-eq/kWh	331 g CO_2-eq/kWh

So we can calculate the different GHG emissions from the added electricity generation needed in 2013 and 2014 to fill the gap (see figure 28).

Figure 28: Calculated GHG emissions

Year	2013	2014
Gap from 2012 level for the electricity purchased (kWh)	3,460,000	6,980,000
GHG emitted with PG&E mix (tons CO_2-eq)	1,144	2,307
GHG emitted with PG&E mix using PG&E – non LCA – numbers (tons CO_2)	657	1,300
GHG emitted when all the additional electricity is produced by 'big wind' only (tons CO_2-eq)	1.1	2.2
GHG emitted when all the additional electricity is produced by solar only (tons CO_2-eq)	2.2	4.5
GHG emitted when all the additional electricity is produced by half by 'big wind' and half by solar (tons CO_2-eq)	1.6	3.3

d) Carbon Intensity of Purchasing Electricity from Campus Cogeneration Plant

The natural gas fired cogeneration plant on campus produces both electricity and steam. Currently, campus outsources its operations and sells all the electricity to PG&E. Campus has the option of directly purchasing or using the electricity from the plant itself. At first glance, the above analysis shows that natural gas has an average emissions factor of 696 g CO2-eq/kWh and PG&E's mix has an overall emissions factor of 331 g CO2-eq/kWh. This makes it seem like campus would be environmentally better off purchasing from PG&E. Yet, in order to do an accurate comparison, one must observe that campus already utilizes the steam from the cogeneration plant (and there is no option to sell the steam to anyone else due to difficulties of transporting steam). If campus purchased both electricity and steam from the plant, the accounting issue would be simplified and the CO_2-eq from the plant would be accounted for just once and for a single customer.

Overall, any type of renewable generation would outperform purchasing electricity from the cogeneration plant, but comparing a direct purchase from the steam plant (that will likely continue operations in any case) compared to an indirect purchase through PG&E is difficult. Currently, the emissions from the cogeneration plant and the costs are somewhat arbitrarily split between electricity generation and steam production and the infrastructure for the cogeneration plant already exists, making it tricky to determine the exact comparison for this option.

VI. Model

1. Discussion of Method (data sources, assumptions, models and methods)

In order to do a Life-Cycle Assessment four activities are required according to ISO 14040 (ISO, International Organisation for Standardisation, 2006):

- Define the LCA goals and its scope
- Collect life-cycle inventory data
- Conduct the life-cycle impact study that characterizes the impact of constituent process
- Interpret results and make sensibility and uncertainty analysis

In order to make the most informed environmental choice for our campus, we must compare different renewable technologies throughout their entire life cycle. We then compare these renewable technologies to the current PG&E mix to understand how the renewable options really compare to PG&E's mix. Nevertheless, we are well aware that PG&E already has its entire infrastructure in place, which is not the case for the renewable technologies discussed for future installations on UC Berkeley campus.

The scope is not as precise as it would be if the exact technology chosen for implementation were identified. Instead, we used an average of the different technologies inside one renewable technology.

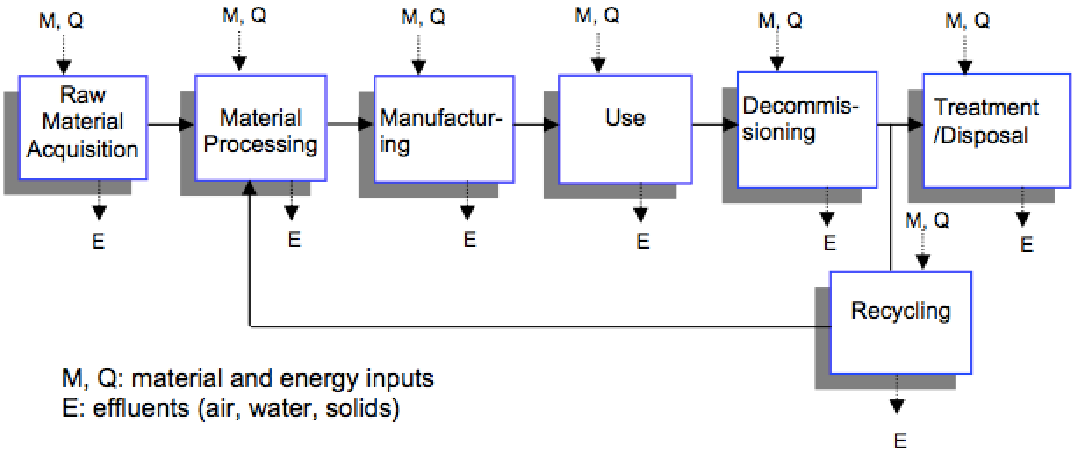
For example, we are studying the life cycle impact of different solar PV technologies like crystalline solar cells as well as thin-film solar cells. Using the averages can at least provide an order of magnitude estimate for the impact of installing PV.

2. Renewable Electricity Generation Life Cycle Assessments

a) Photovoltaics Life Cycle Assessment

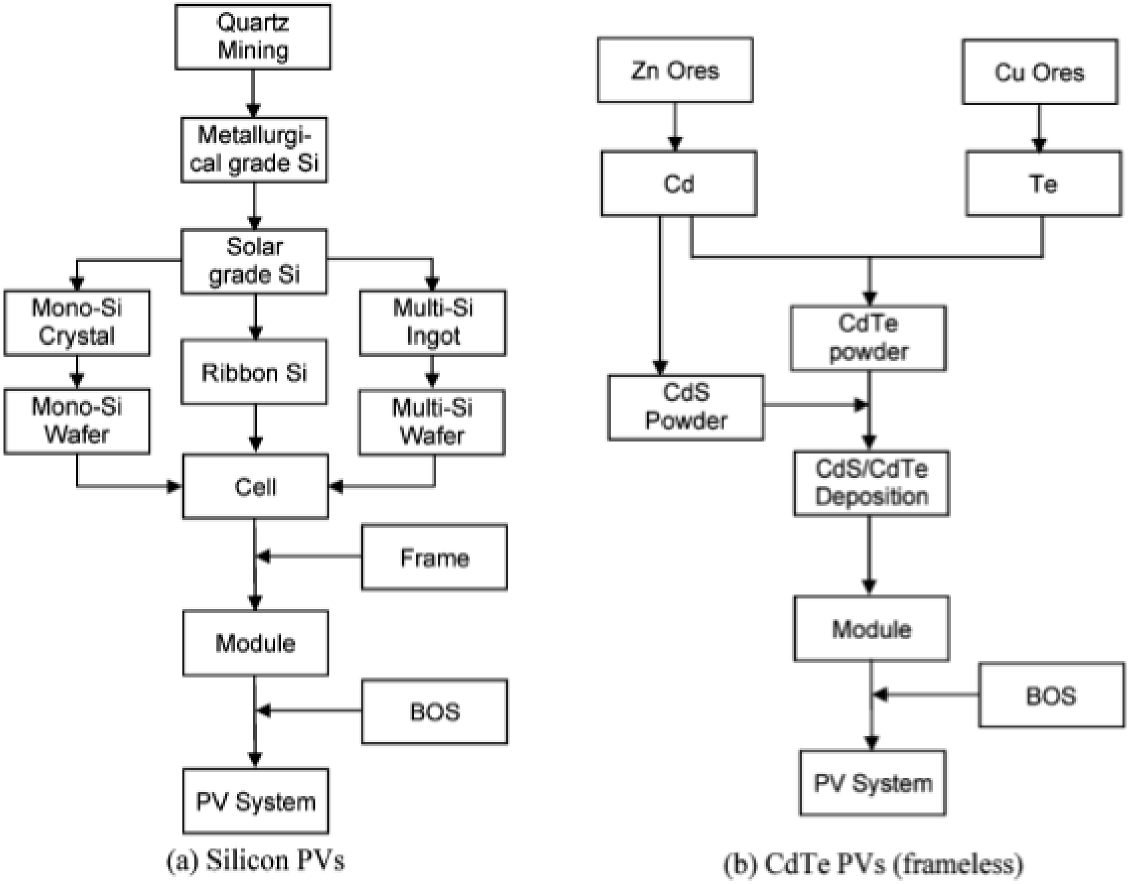
For PV life cycle assessment, we are studying the stages from raw material extraction and acquisition, to the disposal of the solar modules as shown in figure 29. Our study relies on two LCA reports done by V. Fthenakis: "Photovoltaic: Life-Cycle Analyses" from 2009 and "Emissions from Photovoltaic Life Cycles from 2008"; (Fthenakis V. K., 2009) and (Vasilis M. Fthenakis, 2008). We are studying in particular mono--, ribbon-, and multi-Si PVs as well as thin film Cadmium Telluride PV. For these technologies the stages from mining to system manufacturing (three first steps of figure 29) are described in figure 30.

Figure 29: Flow of the life-cycle stages, energy, materials, and wastes for PV systems



Source: 'Photovoltaics: Life-cycle analyses' (Vasilis M. Fthenakis, 2008)

Figure 30: Simplified process-flow diagrams from mining to system manufacturing stages for (a) mono-, ribbon-, and multi-Si PVs, and (b) thin film CdTe PVs



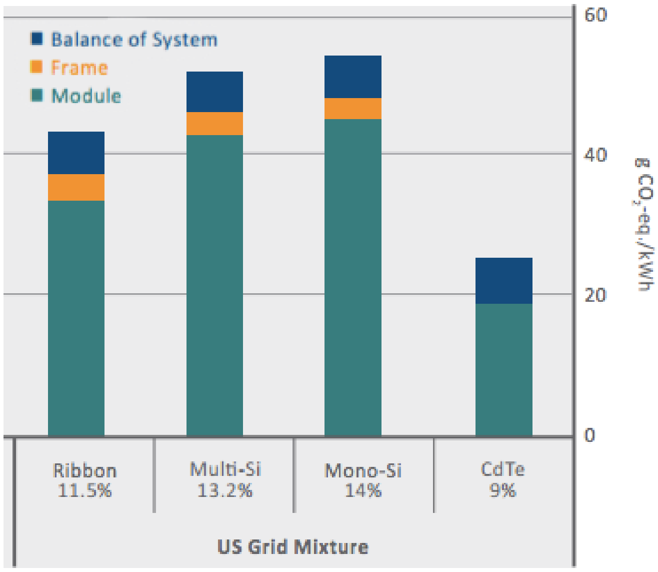
(a) Silicon PVs (b) CdTe PVs (frameless)

Source: “Emissions from Photovoltaic Life Cycles” (Vasilis M. Fthenakis, 2008)

We focus on the US market for our study because we assume UC Berkeley is going to buy solar modules from US companies, which manufacture their systems in the US. This is important regarding to the electricity needed in the manufacturing process. Different electricity mixes give completely different results (see the PV sensitivity analysis for more details). U.S. average grid mixture data come from the Franklin database (USA LCI Database Documentation; Franklin Associates: Prairie Village, KS, 1998). The GHG emissions from these different solar PV technologies are separated into three distinct categories: the module itself, the frame, and the Balance Of System (BOS) – which includes module supports, cabling, and power conditioning. The computation is done under the following conditions: round-mounted PV systems, Southern European insolation of 1700 kWh/m^2/yr, performance ratio of 0.8, and lifetime of 30 years. The average solar irradiance conditions for the Bay area and Berkeley in particular are higher (between 5 to 6 kWh/m^2/day or between 1820 and 2200 kWh/m2/yr). Nevertheless, we consider this study relevant and use its results. Below in the sensitivity analysis we will study how the difference in terms of solar irradiance impacts the results.

The results (in g CO_2eq/kWh) appear in figure 31 below with a total of 48 g CO_2-eq/kWh for multicrystalline silicon solar cells. Unlike fossil fuel systems, most of the GHG emission occur upstream of the life cycle with the majority of the emissions arising during the production of the module (between 50-80%). Other significant GHG releases in the upstream relate to the balance-of-plant (BOS) and the inverter. Operation, end-of-life and associated transport activities do not result in meaningful cumulative GHG emissions.

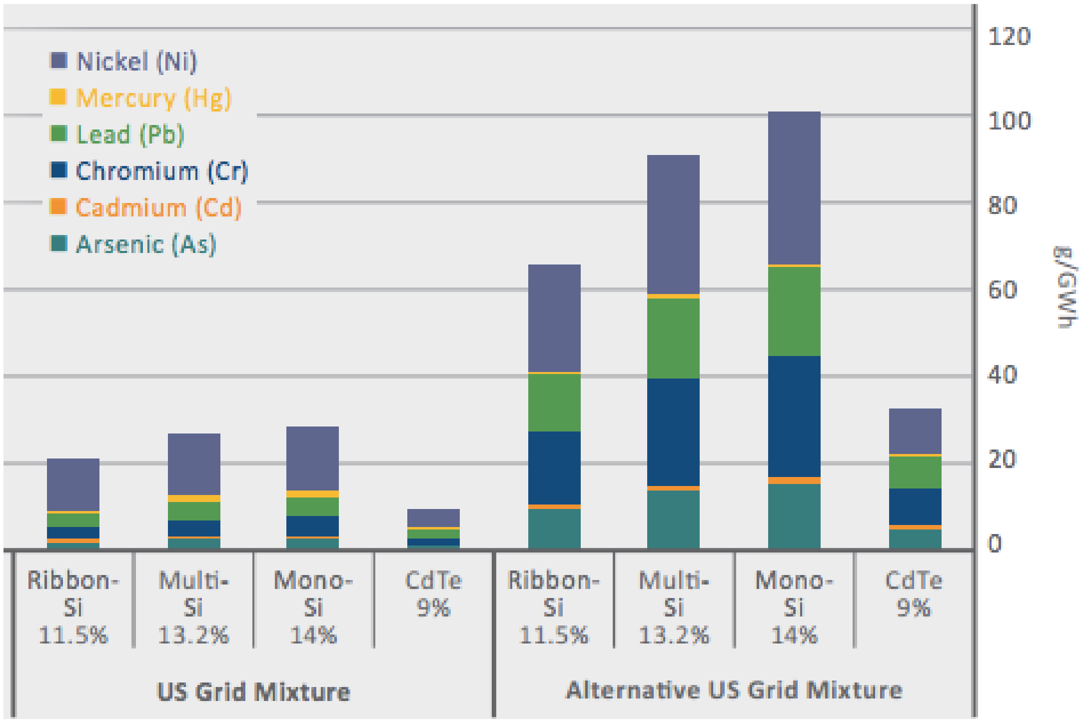
Figure 31: GHG from different solar PV technologies (g CO_2-eq/kWh)



Source: "Emissions from Photovoltaic Life Cycles" (Vasilis M. Fthenakis, 2008)

This study also provides the life cycle atmospheric heavy-metal emissions for these PV systems as shown in figure 32. The conditions are the same as in figure 31: normalized for Southern European average insolation of 1700 kWh/m2/yr, performance ratio of 0.8, and lifetime of 30 years. Furthermore, each PV system is assumed to include ground-mounted balance of systems. These conditions are specified because as explained in the Sensitivity Analysis (Section VIII) the results vary largely depending on the assumptions made.

Figure 32: Life cycle atmospheric heavy-metal emissions for PV systems



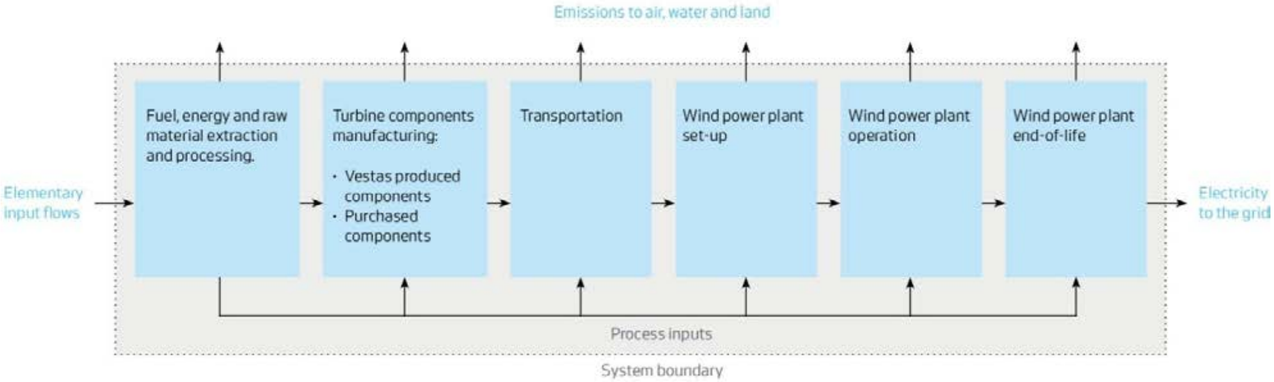
Source: “Emissions from Photovoltaic Life Cycles” (Vasilis M. Fthenakis, 2008)

The heavy-metal atmospheric emissions analysis has been done for two different U.S. grid mixtures. The U.S. grid mixture from Franklin database for the U.S. average grid mixture (USA LCI Database Documentation; Franklin Associates: Prairie Village, KS, 1998). An alternative grid mixture from a recent study by Kim and Dale has also been considered for the U.S. grid mixture (Kim, S.; Dale, B. E. Life Cycle Inventory Information of the United States Electricity System Int. J. LCA 2005 10 294 310). The results can be three times higher depending on the two different data for the US electricity mix used, indicating that a sensitivity analysis should account for the grid mixture in the parameters.

b) Big Wind Life Cycle Assessment

The present data is derived from a LCA final report published by Vestas Windsystems A/S (Garret & Rønde, 2011). Vestas is currently one of the largest manufacturers of wind systems that delivers approximately 15% of the total wind energy installed (MW delivered) (IHS emerging energy research, 2011). For our LCA we are looking at a 2.0 MW onshore turbine (V90-2.0 MW) that is designed to perform mainly under low wind speed conditions (7.0m/s or 15.7 mph). The rotor diameter is 90 meter and the hub height 80 m. The LCA assumes a turbine lifetime of 20 years. Under the assumption of low wind speeds, the V90 wind turbine is able to return 21 times more energy than it consumes over the plant life cycle. This relates to a breakeven time of 11 months. The LCA reports for the electricity produced from a 50 MW onshore wind power plant composed of 25 V90 turbines.

Figure 33: Scope of LCA for a 50MW wind power plant of V90-2.0MW.



Source: (Garret & Rønde, 2011)

This LCA considers the following steps:

- Production of all parts of the wind plant - The observed data covers 99.5% of the turbine weight and is derived from bills of materials, design drawings and supplier data.
- Manufacturing processes at Vestas' sites - Includes information about 100 Vestas sites all over the world.
- Transport - There are several transportation steps due to the manufacturing, maintenance and end-of-life. This LCA assumes transport associated with incoming raw materials, incoming large components, moving wind plant components, end-of-life recycling or disposal, and the transportation of the maintenance crew.
- Installation and erection - Includes usage of cranes, onsite vehicles, diggers and generators.
- Site servicing and operations (including transport) - Due to wear and tear of moving parts, there are several parts that need to be replaced regularly such as oil and filers.
- Use phase power production - End-of-life treatment (of the entire power plant)

All large metal components are assumed to be 98% recycled, cables 95% and all other parts of the turbine are recycled according to realistic European recycling rates (steel, aluminum, copper

90% recycled, polymers 50% recycled, concrete 100% landfilled and lubricants 100% incinerated).

At first look, there are two major assumptions in this LCA that do not totally match our problem: the number of turbines and the geographical coverage of the virtual 50 MW wind plant primarily relates to a European scenario. The LCA assumes 25 V90-2.0MW turbines that are installed onshore to a wind power plant. Since the LCA calculates the GHG emissions per kWh produced, we are not concerned about considering only 2 turbines. It is reasonable because on the one hand we assume that every turbine produces the same amount of energy and on the other hand, every turbine will be manufactured similarly, will have the same transportation distance to the site and will undergo the same end-of-life treatment. Thus, 25 turbines will emit 25-times more emissions but will also produce 25-times more electric energy that leads to the same carbon footprint.

Furthermore, this LCA assumes a European scenario that differs from American scenarios since transportation, manufacturing process and recycling rates are not the same. The Vestas approach to delivering green energy to the people is “be in the region for the region” meaning that the wind systems are produced as close to the site as possible. Nevertheless, the sensitivity analysis in this LCA reports assumes the scenario that the power plant is erected in a continent where Vestas does not have full production capacities such as Australia. Thus, longer transportation distances are used for this scenario. To derive reasonable values for the carbon footprint of a similar turbine installed in the U.S. we assume the turbine to be manufactured in the European Union and then shipped to Northern California (a reasonable assumption because many wind turbine manufacturing facilities are scattered throughout the country). The baseline for the turbines carbon footprint is **9.7 g CO_2-eq/kWh**. Because of longer transportation distances within the U.S., we increase the footprint by 10 % to **10.7 g CO_2-eq/kWh**. We utilize both values in our range of environmental impact calculations because we have to deal with the above-mentioned uncertainties. Note that these data can only be an approximation for the situation in California. Nevertheless, this LCA was used is made because of its comprehensiveness and accuracy that cannot be found in other big wind systems LCAs.

c) Small Wind Life Cycle Assessment

From a life cycle analysis perspective, generally, the smaller the wind turbine, the higher the GHG emissions per kWh electricity generated. Bigger wind turbines are unequivocally better than smaller wind turbines from a cost and environmental standpoint, yet it is worthwhile to consider smaller wind turbines on a campus with space restrictions because they can be installed on roof tops rather than use up valuable real estate with just wind turbines. James Andrew, an engineer in charge of renewable energy generation at the San Francisco Public Utilities Commission, said that the maximum size of building integrated wind turbines are between 30 – 50 kW turbines. The Moscone Center in San Francisco has 1.2 kW vertical-axis turbines installed on the roof, but unfortunately they have not generated much electricity (Andrews, 2012).

Any small wind turbine installed will be between the 0.5 – 50 kW range. The Lenzen report performed an LCA of 15 different installations with wind turbines in the 0.5 – 50 kW power range and found that **the CO_2 intensity was between 29 and 52 g CO_2 per kWh electricity produced for small wind**. The LCA assumed a 20-year lifetime for most models and wind speeds of 9 – 13 m/s. The study looked at a variety of models produced, a wide variety of load factors, different shaped turbines, and in different locations. This provides a level of comfort in the range because we do not have the technical information to understand which small wind turbine would be most technically suitable for UC Berkeley. (Lenzen, 2002)

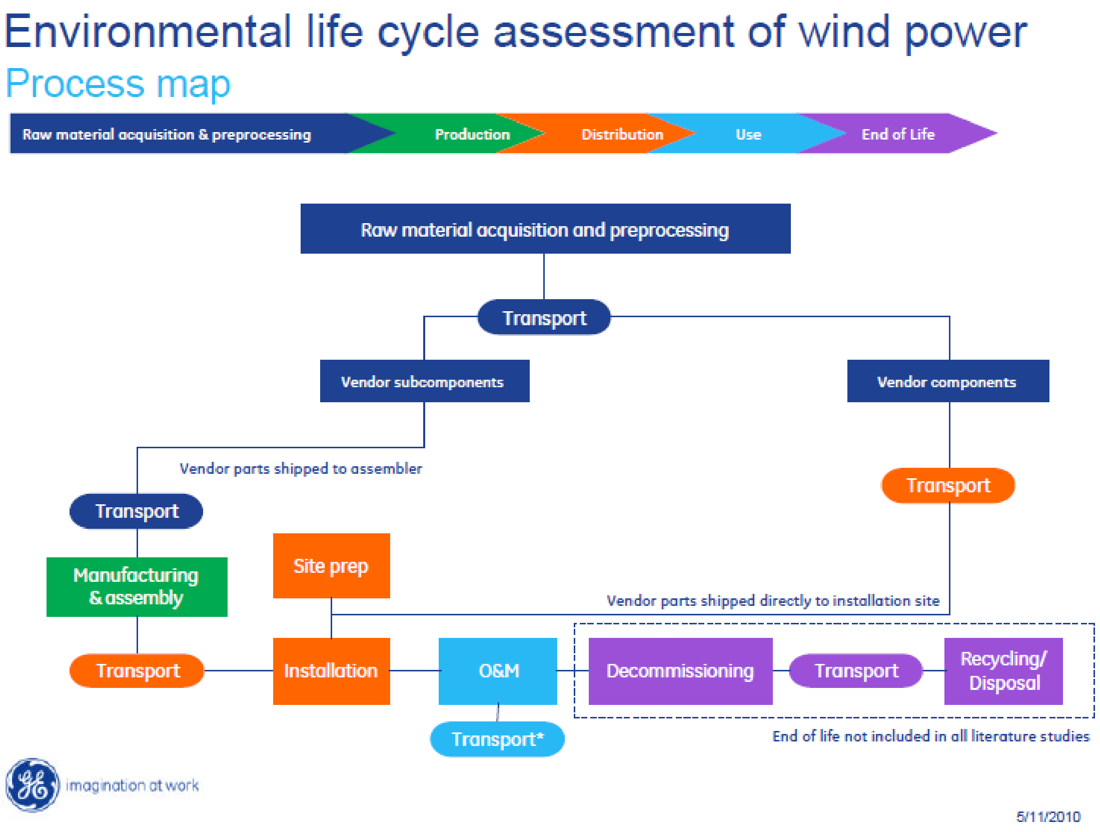
Each building and geographical area has a unique set of physical factors that determine the most appropriate small wind turbine for their building, as we learned from a conversation with James Andrews from SFPUC. (Andrews, 2012) For some buildings, vertical axis turbines are better. For others, horizontal axis turbines are better. Older buildings may only have the capacity to host a very small turbine without damaging the roof (and many buildings on campus are much older than the 26-year old roof on the Moscone Center). Birds also congregate on top of buildings and campus might need to choose a type of turbine that is more bird-friendly than horizontal axis turbines with blade tips moving at dangerous speeds. The wind speed on top of each building (which is affected by the buildings next to them) is also an important factor in determining which turbine is most appropriate. If the turbine is too big, then it will never spin at a low wind speed. If it is too small, then it will not capture a significant amount of the energy in the wind. The wind speed, building-specific suitability, costs, and aesthetics will weigh more into the selection process of a small wind turbine than the relative environmental impacts.

In all cases, small wind will be better for the environment than buying electricity from PG&E, yet it is still worthwhile to discuss how to minimize the life cycle emissions of small wind turbines based on certain selection criteria.

General comments on lifecycle analysis emissions

When looking at the entire life cycle of a wind turbine, from manufacturing to disposal, there is a wide range of emissions intensities. CO_2 intensities range between 8 and 124 g CO_2/kWh for unit power ratings between 0.3 and 3000 kW wind turbines (Lenzen & Munksgaar, 2002). The enormous range is due to the increasing electricity output associated with increasing the size of the wind blade as well as specific variations in the process (see figure 34 below) – due to differences in the components, the distance transported, the percentage of recycled materials, etc.

Figure 34: Process Map of the Environmental Life-Cycle Assessment of wind power



Source: An Environmental Life Cycle Perspective on Wind Power" (Flanagan, 2010)

Rather than recommend a specific turbine model and complete a full life cycle assessment, below is discussion on how to minimize the environmental impacts when choosing a model:

- Choose a suitable wind area with steady, strong winds to maximize the electricity extracted from the produced turbine (Tremeac & Meunier, 2009)
- Purchase a turbine made locally, in the US, hopefully in a place like CA with a relatively clean electricity mix
- Pick a turbine with a high percentage of recycled materials and refurbish or recycle all the materials at the end of life
- Minimize the tower height (the tower often constitutes half of the life cycle emissions) and making towers out of concrete rather than steel minimizes the environmental impact
- The bigger the turbine, the lower the GHG emissions/kWh electricity produced

To illustrate the correlation between bigger turbines and decreased emissions/energy embedded per kWh electricity produced, figure 35 plots the amount of embedded energy per produced energy, which mostly tracks the CO_2 emitted/kWh electricity produced and shows a clear trend. The bigger the turbine, the lower the embedded energy per kWh produced. Some of the small turbines could only produce 6 or 7 times more electricity over its lifetime than was used to manufacture and install it!

Figure 35: Embedded energy per produced energy (kWh_{in}/kWh_{out})

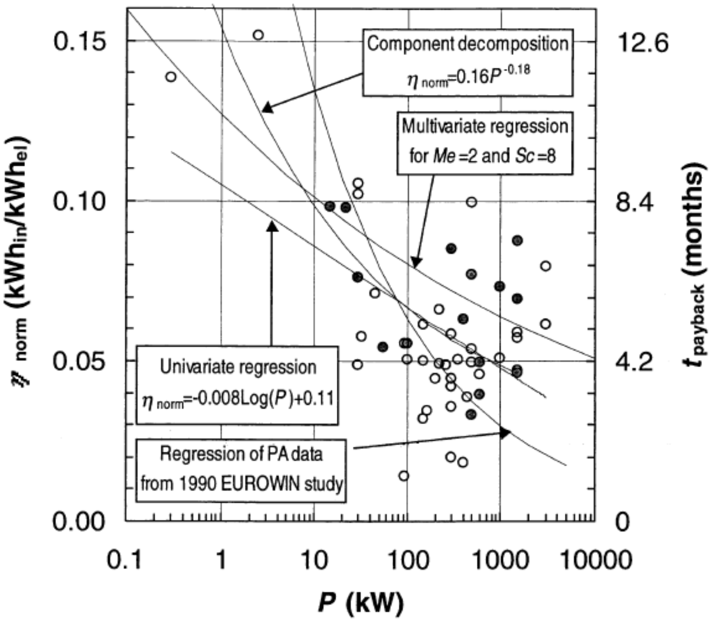


Fig. 1. Energy intensities normalised according to Eq. (2) as a function of power rating for the case studies listed in Table 1. Open circles: process analyses; filled circles: input–output analyses. The trend-lines mark (1) a univariate regression, (2) an approximation based on detailed examinations on component level ([21,22,30,35]; see Section 2.2), (3) a regression of process analysis data of about 100 WT contained in the EUROWIN study [22], and (4) a multivariate regression for maximum analysis breadth and depth (see Section 2.4).

Source: (Lenzen & Munksgaar, 2002)

Small Wind Environmental Impact Conclusion

While better than the PG&E mix, small wind has a strictly worse environmental impact than bigger wind. Campus may consider building integrated smaller wind turbines if procuring land or permitting for large wind turbines proves impossible. Like building integrated photovoltaic, small wind would be most easily and economically installed on new buildings where the additional load and vibrations of small wind turbines could be integrated into the roof and building structure.

3. Heat: Solar Thermal vs. Steam/Cogen plant

Performing an LCA of steam through the cogeneration plant entails an entire study of its own. The steam group was dedicated to this particular analysis and found the following:

As explained in Steam economics section, the price of steam is low due to the already existing infrastructure. It is then difficult to compete against steam from either an economic point of view or from an environmental point of view – any other solution, and solar thermal in particular, will have to make up for a whole life cycle of CO_2 emissions. Furthermore, solar thermal has the disadvantage of being intermittent and therefore has to be backed up with natural gas heating. This means replacing steam, generated form a cogeneration plant with natural gas, a non-environmentally sustainable solution at a larger scale. Campus laboratories need heat and hot water at all times and therefore the back-up system will be used more than in a residential building where hot water needs are concentrated during certain times of the day. Due to campus' constant demand for heating laboratory equipment and solar thermal's intermittent generation capacity solar thermal is not an adequate replacement for steam.

Steam proves to be the most efficient way to heat our campus provided the fact that the infrastructure is already there. For this for reason, we did not pursue a further study of solar thermal as a viable option for campus. Nevertheless, once additional information from the new Anna Head facility will be known, we should evaluate the results for potential on other residence halls located outside of main campus.

VII. Findings and Results

1. Renewables generating electricity vs. PG&E

The environmental impact of having renewables on campus compared to the option of buying electricity from PG&E to fill the gap between now and 2014 is shown in figure 36.

Figure 36: Tons of CO_2-eq emitted by each technology/choice

Technologies	**Solar PV (multicrystalline)**	**Big wind in Berkeley**	**Big wind in a windier location**	**Small wind**	**PG&E mix**
g CO_2-eq/kWh	25-55	8-12		29-52	331-421
Tons of CO_2-eq for 2014 target	175-384	52-78	4-7	202-393	2310-2939

In figure 36, the ranges represent the low and high values for each category based on different assumptions. In the Sensitivity Analysis section (section VIII) we explain how each range was calculated for each technology. Yet, for the assumptions stated in each LCA a single number has been found based on the most likely assumptions of the technology implementation on campus. In the graph below (figure 37) we then represent this single number as being the value for our analysis based on the assumptions stated and by varying these assumptions regarding different parameters (see the sensitivity analysis for more details) we derive a range shown as error bars in this graph.

Big wind (in Berkeley and in a windier location) results in such a tiny range that on the figures 37 and 38 we do not see their range and the values appear as single values. Solar PV and small wind, on the other hand, have ranges that can vary from a factor of two (see figure 38).

We see on figure 37 that meeting the campus 2014 demand gap with PG&E electricity, i.e. pursuing the status quo will result in at least 5 times more GHG emissions (in tons of CO_2-eq) than filling the electricity gap with renewables. From an environmental impact perspective, renewables would outperform PG&E and help campus to meet its emissions goals by 2014.

Figure 37: Environmental impact of filling the 2014 gap with renewables vs. with PG&E electricity

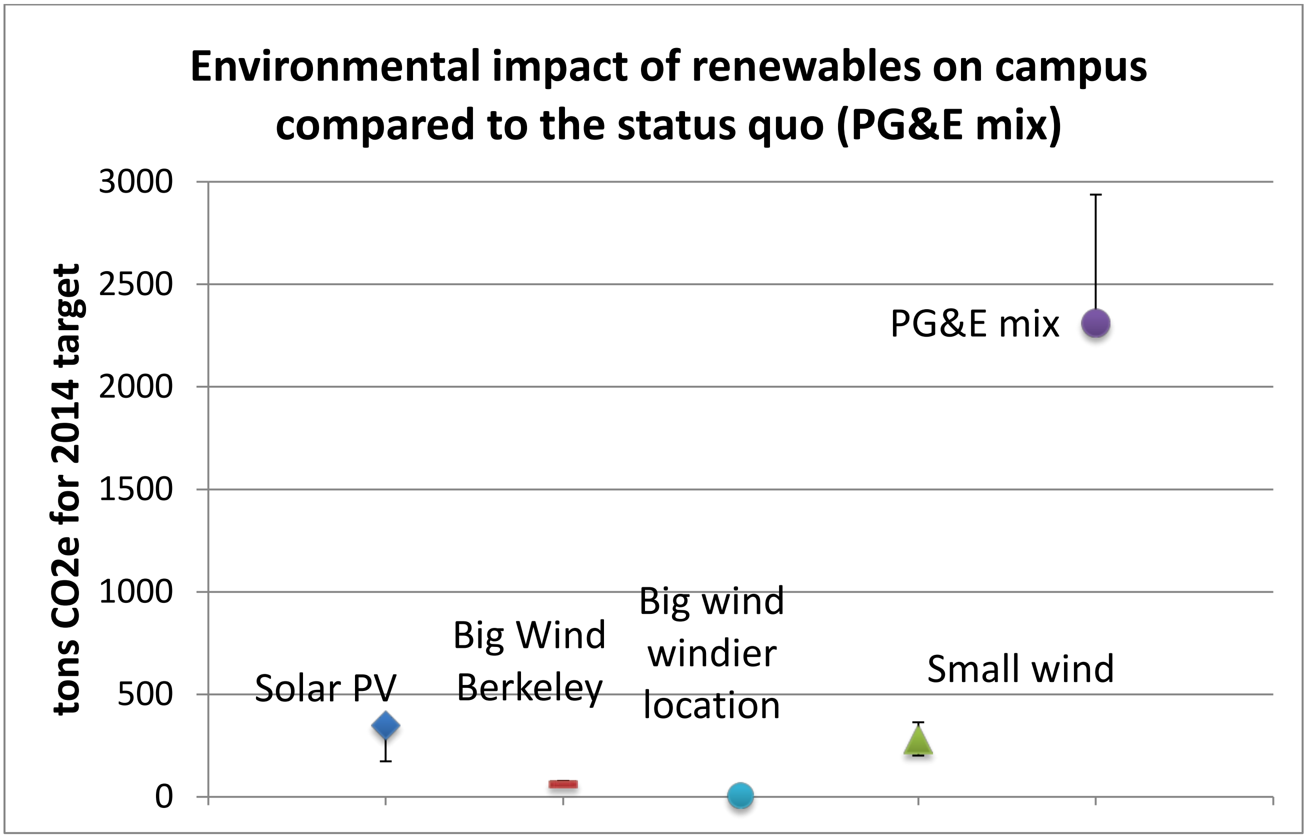
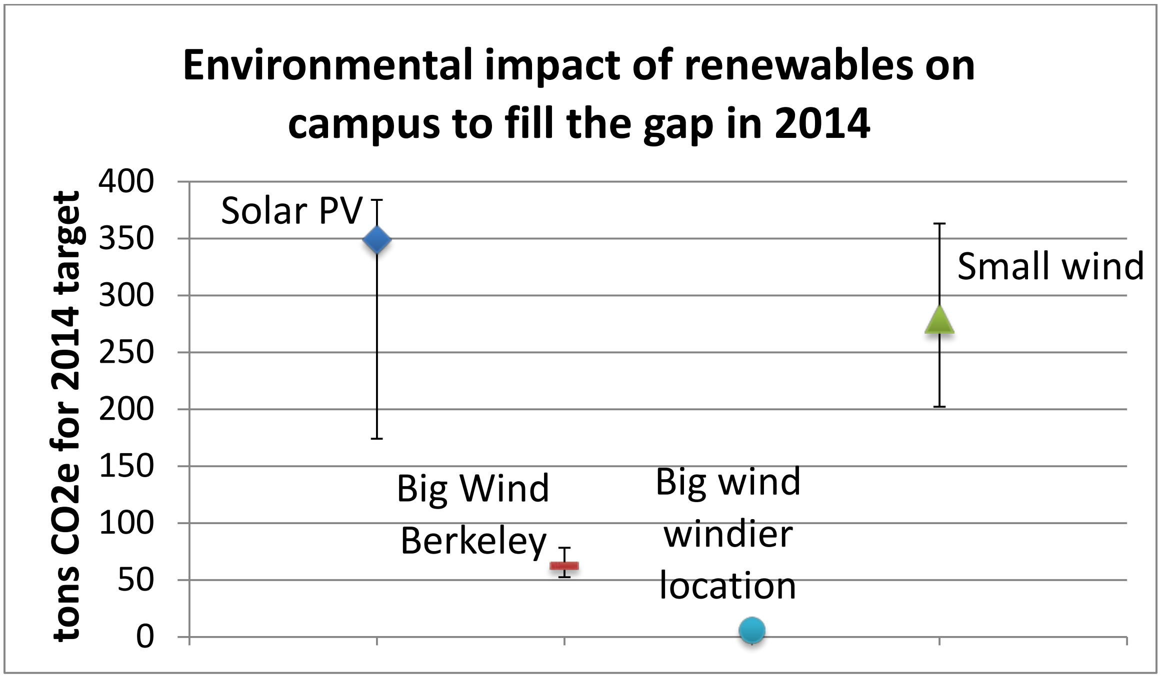


Figure 38: Environmental impact of renewables on campus – bigger scale



2. Solar thermal vs. Steam

As explained in section VI 3 steam proves to be the most efficient way to heat our campus provided the fact that the infrastructure is already there. For this for reason, we did not pursue a further study of solar thermal as a viable option for campus.

IX. Sensitivity Analysis

A sensitivity analysis provides a more thorough evaluation of the underlying assumptions, methodologies and parameters. This report has focused on three renewable energy sources: PV, big wind and small wind. Costs and GHG emission-dependent variables are varied in this sensitivity analysis to gain a better understanding of how costs and emissions results vary with changed assumptions.

1. Photovoltaics Sensitivity Analysis

For PV systems, variations in the results can be for a range of factors, such as module efficiency and lifetime, as well as irradiation. Differences in installation, such as integrated and non-integrated systems, as well as facade, flat roof and solar roof tiles, or the efficiency of the peripheral equipment, such as the balance-of-system (BOS), also significantly affect lifecycle GHG emissions.

We chose to concentrate on the following parameters, which can have a big impact if they vary:

- The electricity grid mixture from the country where the panels are manufactured

The LCA study has been performed using an average U.S. grid mixture for the manufacturing of the panels. But within the U.S., grid mixtures vary across regions leading to differences in the results. The best example is figure 32 showing the heavy-metal atmospheric emissions for PV systems life cycle for two different U.S. grid mixtures. The difference is significant as it goes from a total of 25g/kWh to more than 95g/kWh of heavy-metal emissions. This means more than 3 times higher results in one case compared to the other. Our LCA study was done using U.S. average grid mixture data from the Franklin database (Franklin Associates, 1998). An alternative grid mixture such as the one from a recent study by Kim and Dale will give completely different results. Finally, using the California grid mixture instead of the U.S. one – relevant as many solar cells manufacturers are in California – will also change the results (Kim & Dale, 2005). Solar panels manufactured in California have an even smaller environmental impact due to a cleaner energy mix than the national average.

- The solar irradiance where the panels are used:

In the range we gave for PV (between 25 and 55 g CO_2-eq/kWh) we took into account the range we have for the Bay area solar irradiance (between 5 and 6 kWh/m^2/day or between 1825 and 2190 kWh/m^2/yr before any efficiency has been taken into account).

- The life expectancy of the modules:

The lifetime in the Fthenakis study is 30 years (Fthenakis V. K., 2009). However, if the lifetime of the PV systems is either shorter or longer it has a significant effect on the GHG emitted per kWh of the PV system. Indeed, a panel that produces electricity for 35 years will produce more kWh than expected and therefore this will lower the GHG impact of the PV systems. On the contrary, if a panel breaks before its lifetime expectancy of 30 years, it would not produce the expected electricity and this would increase the CO_2-eq emitted per kWh. In the different studies we looked at, we found a lifetime between 25 and 35 years. The "Methodology Guidelines on Life-Cycle Assessment of Photovoltaic Electricity" from November 2011 by the *International Energy Agency Photovoltaic Power Systems Programme* recommend using a 30 years lifetime for the modules, a 15 years lifetime only for the residential PV inverters, and 30 years lifetime for the utility-scale inverters (Fthenakis, et al., 2011). Therefore, the LCA we used agrees with the industry guidelines form the International Energy Agency Photovoltaic Systems Programme.

2. Big Wind Sensitivity Analysis

As discussed in the feasibility section, installing big wind turbines in the area around the campus is not a realistic scenario. However, as UCB might consider nearby locations with different wind speeds, one applicable sensitivity analysis involves varying wind speeds to observe the correlation between energy costs per kWh and the wind speed.

Since Vestas' LCA distributes the transportation emissions over the different manufacturing processes we are not able to calculate numbers for different transportation distances. The only information that can be derived from this report mentioned in the sensitivity analysis. It assumes longer transportation distances that we intend to use for our LCA numbers. Thus, it is not possible to set up the sensitivity analysis for transportation distances.

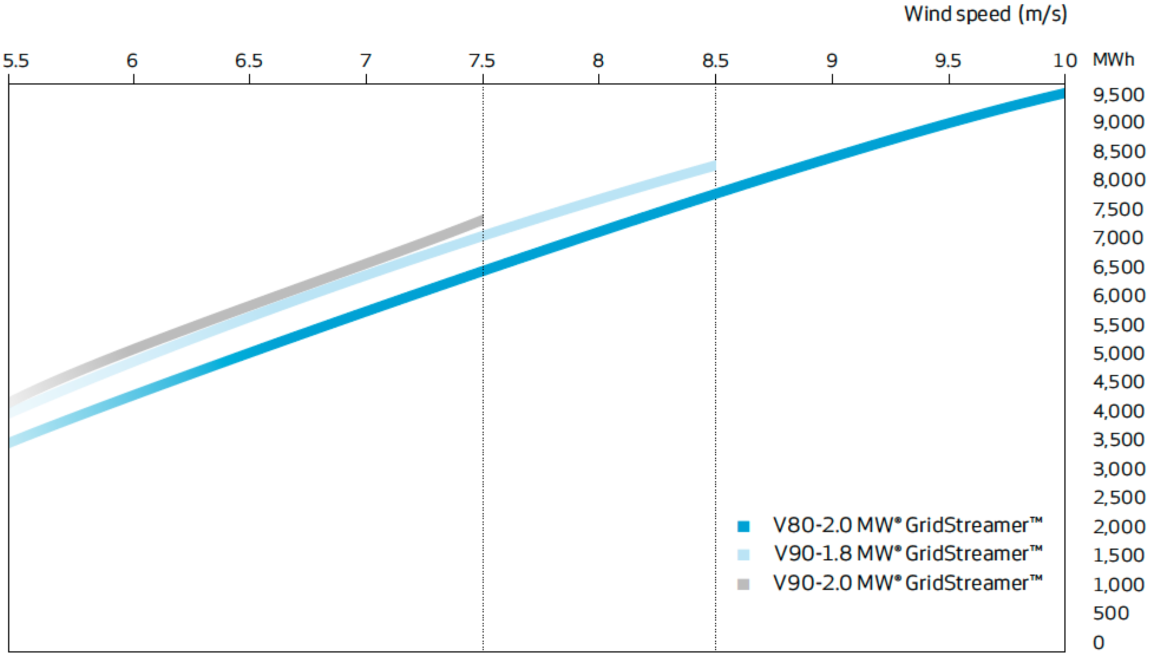
The big wind sensitivity analysis assesses the following scenarios:

- Variation in wind speed (focus only on energy costs)
- Variation in turbine lifetime of ± 4 years

As already mentioned the power output of a wind turbine is dependent on many factors. One important input of the wind system is the wind speed. In order demonstrate the importance of choosing an appropriate site for the wind turbines with high enough wind speeds the calculations compare the output based on different velocities. The two bounding values are the average wind speed in Berkeley, 4.5 m/s (10.1 mph), and a high wind speed of 9.25 m/s (or 20.7 mph). The V90 turbine is designed for a wind speed of 7.0 m/s and under these circumstances it can produce approximately 6,250 MWh annually. However, the next generation of this turbine contains minor changes that allow operating in medium (8.0 m/s) and high wind classes (9.25 m/s). Under improved conditions the upgraded turbine will be able to produce 7,632 MWh to 9,131 MWh of electric energy annually. In both cases only one wind turbine would be sufficient to meet the increased demand in 2014.

Instead, if we assume lower wind speeds that are likely to occur because of the geographical variation, the energy output will decrease significantly. Figure 39 shows the annual electricity production based on different wind speeds (Vestas Wind Systems A/S, 2012). In case of an average wind speed of 6.0 m/s the annual energy output is approximately 4,600 MWh. Since the figure 39 does not show values for wind speeds under 5.5 m/s we are extrapolating the values for 4.5 and 5.0 m/s linearly. The function that enables to derive values by extrapolating is: f (x) = 1,657 + x * (-5342) [MWh/year]. Thus, we derive an annual electricity output that is 2,940 MWh for a wind speed of 5.0 m/s and 2,110 MWh respectively for a wind speed of 4.5 m/s. Furthermore, another column is added to figure 40 containing the number of turbines needed to meet the increased energy demand in 2014 (calculations analogous to chapter V-1 “Technical Feasibility”).

Figure 39: Annual Energy Production (AEP) for V90-2.0MW turbine (grey curve).



Source: (Vestas Wind Systems A/S, 2012)

Figure 40: Electricity production for different wind speeds.

Turbine	Wind class	Wind speed [m/s]	Annual Electricity Produced per turbine [MWh]	Number of turbines
V90-2.0MW (mk9)	High	9.25	9,131	1
V90-2.0MW (mk9)	Medium	8.0	7,632	1
V90-2.0MW (mk8)	Low	7.0	6,257	2
V90-2.0MW (mk8)	--	6.0	4,600	2
V90-2.0MW (mk8)	--	5.0	2,940	3
V90-2.0MW (mk8)	Cut-in	4.5	2,110	3

Source: (Garret & Rønde, 2011) and (Vestas Wind Systems A/S, 2012)

Based on these results and the findings of the average costs of big wind systems (1,500 – 3,000 $/kW) we are now able to calculate the costs per unit electric energy [$/kWh] according to chapter V-2 “Economic Background”. We make use of the annualized cost and the above-mentioned Annual Electricity Produced-values. The results are summarized in figure 41.

Figure 41: Cost per unit electric energy generated for different wind speeds.

Wind Speed [m/s]	Number of turbines	Total Costs [$]	Cost per unit electric energy [$/kWh]
9.25	1	3 M – 6 M	0.03 – 0.06
8.0	1	3 M – 6 M	0.04 – 0.07
7.0	2	6 M – 12 M	0.05 – 0.09
6.0	2	6 M – 12 M	0.06 – 0.12
5.0	3	9 M – 18 M	0.10 – 0.19
4.5	3	9 M – 18 M	0.13 - 0.27

The available LCA about the Vestas V90-2.0MW Gridstreamer™ wind turbine assumes a lifetime of 20 years (Garret & Rønde, 2011). However, it is possible to extend the lifetime of wind systems depending on specific conditions of operation. The lifetime of a wind system has a substantial overall impact on the carbon footprint because the impacts are amortized over the years. By varying the lifetime (± 4 years) the GHG emissions differ from 8.1 to 12.2 g CO_2-eq / kWh in which an increased lifetime lowers the overall GHG emissions (20 years baseline: 9.7 g CO_2-eq / kWh). Due to longer transportation distances considerations, we want to increase these numbers by 10 percent as explained in chapter V-2 “Big Wind LCA”. **Thus, we conclude having a GWP for different life times of 8.1 to 13.4 g CO_2-eq.**

3. Small Wind Sensitivity Analysis

For small wind, both costs and emissions vary depending on the exact design, model, and size of the turbine. Whereas scaling up large wind is fairly uniform and involves increasing blade sizes, land area, and material proportionally, scaling up small wind may mean a different design altogether (i.e. vertical v. horizontal axis), roof retrofits (disproportionate to size of turbine), as well as more material. Also, campus would only consider small wind if there was a strong interest in rooftop installations. Berkeley’s wind speed is 4.5 m/s and that is really the only wind speed that is relevant when it comes to small wind for UC Berkeley. Therefore, it is difficult and futile to perform a graphical sensitivity analysis on small wind to base on direct dependencies on size, wind speed, or cost factors.

4. PG&E Sensitivity Analysis

Figure 37 illustrates that emissions associated with PG&E electricity also have a range: filling the gap with PG&E electricity – with the assumptions for PG&E mix exposed in Section V 3. c) – can represent from 2,310 up to 2,940 tons of GHG (in CO_2-eq) emitted in the atmosphere. This range is due to the way we calculate PG&E LCA emission factor. With our assumption that the 22% of “Unspecified Source” was equivalent to the emissions intensity of natural gas we found a LCA emission factor of 331 g CO_2-eq/kWh. If we take a harsher assumption and assume that the Unspecified Source is coal, then we find a LCA emission factor for PG&E mix 21% higher: 421 g CO_2-eq/kWh. Taking coal instead of natural gas and not renewables or nuclear makes sense because this “Unspecified Source” is neither produced by PG&E power plants nor procured through long-term contracted electricity. Indeed, PG&E purchases this electricity on the hour-ahead spot market. Then, this electricity comes from somewhere in the Western Electricity Coordinating Council (WECC) network, which contains coal plants that can be ramped up easily and quickly, which is not the case for nuclear or renewables. Whether coal or natural gas, likely this ‘Unspecified Source’ comes from fossil fuels.

Nevertheless, one would doubt that PG&E’s would purchase 22% of its electricity in the hour-ahead market. This electricity demand is not alone responsible for ramping up coal or natural gas power plants. Another reasonable assumption then is to take for this Unspecified Source the WECC average electricity mix. Factoring in the WECC average into the 22% ‘Unspecified Source’ resulted in an LCA emission factor of 331 g CO_2-eq/kWh – the same as using 100% natural gas assumption for this Unspecified Source. Of course, this is purely by chance that the two numbers appear to be the same!

With these three assumptions regarding PG&E Unspecified Source, which accounts for 22% of PG&E mix we have a good insight of what PG&E real LCA emission factor can be. We are then equipped to calculate the total range for 2014 PG&E emissions (in tons of CO_2-eq). This results in a range between 2,310 up to 2,940 tons of CO_2-eq emitted by campus if they decide to fill the 2014 electricity gap with PG&E electricity.

X. Uncertainty Assessment and Management

Throughout our analysis, we found a number of uncertainties about both present values (such as costs) as well as difficulties in predicting the future and analyzing the timeframe that campus may have preferred. We classify our uncertainties as follows:

1. Cost Uncertainties

Because renewable energy technologies are undergoing technology and process improvements, they are still rapidly changing in price. Also, PG&E prices are subject to changing prices of fossil fuels. For example, the 20% of PG&E's electricity mix coming from natural gas is highly influenced by the price of natural gas and very few analysts could have guessed five or ten years ago how natural gas prices would fall. While campus would have preferred an analysis predicting all the way to 2020 or even 2050 to help analyze long term goals, the uncertainties with regards to how prices would change led us to contain our analysis to just 2014 because it required much less 'looking into the crystal ball' to figure out how prices would change.

2. Emissions Uncertainties

Uncertainty about how PG&E's electricity mix would change over time as well as the renewables manufacturing process changes further supported limiting the analysis and forecasting to just two years.

3. Government Incentives / Campus Funding

The United States has notoriously uneven and ephemeral government support policies for renewable energy (i.e. the 'lumpiness' of the wind industry due to the vacillations in the production tax credit). Therefore, we could not reasonably factor in government support into our cost calculations. Rather, we intend for camps/readers to factor in current government incentives into the calculations in order to make a current and applicable cost comparison.

Campus' ability to fund any type of project is complex and dependent on many different factors – the state budget, internal bureaucracy, student opinions, etc. The analysis left the funding sources and intricacies unaddressed.

4. Resource and Cost Uncertainties

Actual production based on wind speeds and insolation is uncertain, especially on a campus with many buildings, which shade panels and block the wind. Installed costs of each type of system are variable depending on retrofits necessary, contractor, and exact specifications. Cost ranges were provided for the cost/kWh calculation to account for the variation.

5. Steam vs. Solar Thermal

The cogeneration plant produces both electricity and steam and it is a matter of arbitrary (and often inaccurate) protocols for attributing costs or emissions to the steam portion of the output. Costs and emissions associated with steam are extremely difficult to pinpoint. Due to these uncertainties, we performed only a rudimentary analysis of steam and solar thermal for heat and hot water.

6. Process Uncertainties

Our process has inherent uncertainties in data quality. To mitigate this effect, we rate the data we used based on a self-estimation. Of course, this is a subjective rating and does not have the power of qualitative uncertainty assessments. Nevertheless, we think that because we have dealt deeply and thoroughly with the data we were able to correctly estimate their strengths and weaknesses. We chose to rate the source of the data: is it a governmental source or a more biased source, its completeness – whether or not the data address the entire issue or just consider some components of it, its correlation to our own study: geographical and technological. For example, we look at questions such as: is the study in accordance with our study geographical location? Is the study assessing the same technology?, and at last the data age – is it still relevant for us or is it too old? Some technologies and fields change rapidly and some other may not change as fast, making the quality of data age depend on the field. For example, a study from 2 years ago may be relevant for wind technology but is not at all relevant for the PV industry as this one is continuously changing – in terms of cost and technology.

Figure 42: Data quality

	Source of data	Completeness	Geographical Correlation	Technological Correlation	Data age
PV LCA	5	4	5	5	3
PVA Cost	5	5	5	4	4
Big Wind LCA	5	5	2	5	5
Big Wind Cost	5	4	5	4	5
Small Wind LCA	4	5	4	2	3
Small Wind Cost	4	4	5	3	5

Ranking System: 5 Very Confident, 4 Confident, 3 Acceptable, 2 Less Confident, 1 Least Confident

XI. Conclusions and Recommendations

Current campus protocols only involve looking at direct emissions of operations. Yet because campus is sincerely interested in reducing their environmental impact, one of the most important takeaways from this report is to have highlighted that life cycle assessments are a more accurate and holistic way for campus to evaluate past and future operations. Campus purchases nearly all of its electricity from PG&E. Our analysis reveals that PG&E lifecycle emissions are at least 60% higher than reported direct emissions. This leads us to two conclusions: 1) Campus emissions are overall higher than previous records indicate and 2) replacing any of the energy demand with renewable energy would result in an even higher CO_2-eq reduction potential under LCA accounting methods.

Campus has a variety of renewable energy technologies to choose from: geothermal, wind, PV, etc. This report provided a limited analysis of only electricity generation technologies that could physically be installed on campus property (initially disregarding aesthetics, permitting, and other logistics) and researched PV, big wind, and smaller wind. Any of the three technologies have the ability to reduce emissions down to between just 0.1% to 17% of current PG&E emissions on a per kWh basis depending on the exact technology and resource factors. From any perspective, the renewable technologies are environmentally superior than the PG&E generation mix and we encourage campus to consider beginning the transition away from fossil fuels to not only reduce campus' environmental footprint, but also to set an example to other universities and communities.

Yet, we also realize that campus faces real-world constraints in terms of budget, land, safety, aesthetic, and permitting limitations. If campus prioritized installations on the main campus, PV makes the most sense. PV does not make noise, kill birds, or detract from the physical beauty of UC Berkeley's campus. PV is also less expensive than small wind, and is beginning to approach grid parity with government incentives and cost reductions. If locating on campus itself is not a primary goal then big wind located in a high-wind area off campus performs best in our analysis. Our levelized cost of electricity calculations show that it could potentially be less expensive than electricity purchased from PG&E. Big wind off campus may pose a more complex accounting problem or transmission issues, but the low costs calculated may just be worth it.

UC Berkeley has genuine concern for the environment. They could reduce electricity demand altogether, change travel behavior of faculty and students, generate electricity from renewable sources, or take a number of other actions to reduce their environmental footprint. Our analysis focused on electricity and heat generation. We believe that energy generation is just one small part in a host of measures that campus must take in order to meet their sustainability goals. We encourage them to pursue renewables, in parallel with other progressive and positive changes on campus in order to educate students how to be global citizens in our classrooms and also through example.

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