Climate Neutrality Report
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I. Introduction

The University of California, Berkeley has a goal of reducing its greenhouse gas emissions to 1990 levels by 2014 and achieving climate neutrality "as soon as possible thereafter." [ACUPCC] The goal of this report is to provide some guidance in setting a more detailed target and timeline for carbon neutrality.

Berkeley has a responsibility to take its goal of carbon neutrality seriously and to pursue this goal aggressively. The state of California has committed to emissions reductions of 80% by 2050; this is in line with current estimates by scientists of what developed nations need to achieve in order to prevent dangerous climate change. Not only does Berkeley have a responsibility, as an emitter in the developed world, to abide by this target, but it has a stronger responsibility due to its role as an educational institution. Berkeley must consider the values that it wants to pass along to the students who study here and who will go on to become leaders in business, academia, and civil society. Buildings that are obviously green, that generate their own electricity, and that advertise their energy efficiency will continually remind students of the importance of working towards carbon neutrality. Berkeley is a national leader in environmental and energy research, and a truly green campus would emphasize that Berkeley practices what it preaches.

Our analysis looks at potential emissions reductions over the next several decades. Any forecast that looks at a 20-40 year time-horizon contains numerous large uncertainties. What will future fuel prices be? What policies will the U.S. and California set that will influence Berkeley? What future technologies will become available? Thus, we have attempted to make our scenarios as simple and transparent as possible, with the understanding that they should only be seen as rough guides to what Berkeley could achieve.

According to our analysis, Berkeley could reduce emissions 30-50% relative to 1990 levels by 2030 through energy efficiency measures alone. A further 10% emissions reduction can be achieved by switching to renewable steam and electricity generation. Thus, we suggest a target of 50% by 2030, which may require the purchase of offsets.

The remainder of this report explains how we arrived at these targets. In the next section we discuss Berkeley's projected emissions and how those are tied to existing California policies. We then discuss potential emissions reductions from efficiency and renewable energy generation in two key areas: building electricity and steam. Finally, we discuss Berkeley's options for reducing emissions in transportation, an area over which it has limited control.

Figure 1: UC Berkeley Emissions by Source, 2007

Emissions Sources	CO_2 equivalent (metric tons)	Percentage Contribution
Steam (co-generation)	85,436	41%
Purchased Electricity	61,443	30%
Air Travel	20,991	10%
Faculty & Staff Auto Commute	17,433	8%
Natural Gas	10,470	5%
Student Commute	3,736	2%
Fugitive Emissions – Refrigeration	3,517	2%
Water Consumption	1,955	1%
Solid Waste	981	<1%
Campus Fleet	1,253	<1%
TOTAL EMISSIONS	**207,215**	100%

II. Business as Usual Projections

Figure 1 shows the breakdown of greenhouse gas emissions at Berkeley in 2007, as reported in the 2006-2007 Feasibility Study (Ahmed, 2007). The greenhouse gas emissions inventory in that study included all central campus buildings, all student housing, and the Richmond Field Station. It included the following sources of emissions: purchased electricity, steam generation, natural gas use, fugitive refrigerants, campus fleet, staff and student commutes, air travel emissions, solid waste disposal, and embodied emissions in water use. According to this analysis, total greenhouse gas emissions were 209,000 metric tons in 2006. An estimate of lifecycle greenhouse gas emissions from electricity generation, university procurement, and construction activities were also estimated in the feasibility study as 273,000 metric tons in 2007 of carbon dioxide equivalent. However, because of the high uncertainty in this figure and the limited control that Berkeley has over these emissions, we do not consider them in this report.

Figure 1. Breakdown of 2007 emissions (2008 Sustainability Assessment)

Steam, purchased electricity, commuting, air travel, and natural gas account for the bulk of emissions. Commuting and air travel are not directly within the university's control; although the university can encourage fuel-efficient transport and videoconferencing, it cannot directly limit emissions from transport. Thus, in this report we focus mainly on reducing emissions from heating and electricity in buildings (outdoor lighting accounts for only 1% of purchased electricity according to Borgeson et al, 2007).

Although we take the breakdown of emissions by source shown in Figure 1 as the baseline in this report, two caveats are worth mentioning. First, it is likely that air travel is underestimated in the Feasibility Study because the California Climate Action Registry emissions factor for air travel does not account for the increased warming effect caused by airplanes emitting carbon dioxide higher in the atmosphere on long-distance flights. We are also unsure whether all flights associated with the University were captured in the inventory because many employees do not book airfare through the Universities travel agent. Second, as noted in the 2007 CalCap report, emissions from the steam cogeneration plant may be overestimated.[1]

Figure 2 shows two scenarios of "business-as-usual" emissions out to 2030. The "no policy" scenario is generated using the same assumptions as in the Feasibility Study. That is, we assume that emissions from electricity, steam, gas, waste, water supply, and refrigerants are constant per square foot and emissions from commuting and air travel (22.2% of the total) are constant per capita (Ahmed, 2007). We make the same assumptions about long-term growth as the Feasibility Study, i.e. we assume an annual increase of campus square footage of 1.14% per year and an annual population increase of 0.61% per year (Ahmed, 2007). We start with a baseline of 210,000 metric tons of carbon dioxide equivalent emissions in 2007 (Office of Sustainability, 2008). Under this scenario, Berkeley's emissions will increase 27% over 2007 levels by 2030.

The "state policy" scenario in Figure 2 includes the impacts of existing California policies on campus emissions. In particular, we model the impact of California's Low Carbon Fuel Standard and Assembly Bill 32. The Low Carbon Fuel Standard requires the emissions intensity from transport to reduce 10% by 2020, a rate of emissions reduction of 0.8% per year from 2007-2020. We assume that this annual rate will continue out to 2030. AB32 requires California to reduce emissions 80% below 1990 levels by 2050. This is equivalent to a reduction of 83% from current emissions (CARB, 2008). We assume that the electricity sector will also reduce its emissions by the same amount so that the carbon intensity of electricity purchased by the university will be reduced 83% from current levels by 2050. (In fact, it is likely that the carbon intensity of electricity will have to decrease even more if AB32's target is to be met because electricity generation is arguably the easiest source of emissions to decarbonize). We assume that the carbon intensity of electricity decreases at a rate of 4.4% per year starting in 2010 to

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[1] The steam plant is a co-generation plant that burns natural gas to produce electricity and steam. As such, it is unclear what percentage of the carbon emissions from burning natural gas should be assigned to the electricity and what percentage to steam. The Feasibility Study followed the California Climate Action Registry's General Reporting Protocol in assigning emissions to steam based on the BTU content of the heat relative to the cogeneration plant's total output. This ignores the fact that much of the heat would have otherwise been wasted if electricity was generated without cogeneration; as a result, steam is credited with generating more CO2 per BTU than steam produced in Berkeley's less efficient auxiliary boiler system. (Borgeson et al, 2007)

reach an 83% reduction by 2050. We further assume an initial carbon intensity of electricity of 0.000301 tons CO2e per kWh (Ahmed, 2007).

Under the "state policy" scenario, Berkeley's emissions will be roughly the same as 2007 emissions. Roughly 16% of the 2030 emissions will be from purchased electricity. When evaluating the emissions reduction potential of energy efficiency and renewables in the next several sections, we use this "state policy" scenario as our baseline.

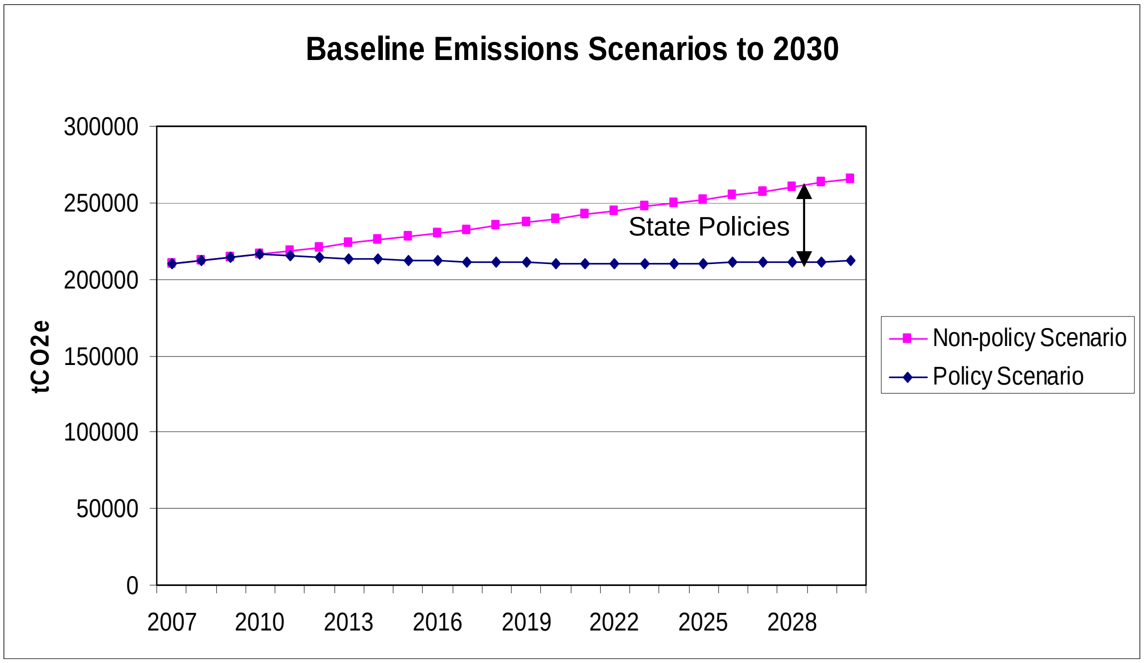

Figure 2. Berkeley emissions trajectories to 2030, with and without state-level policies

III. Potential Savings from Energy Efficiency

In this section, we estimate the potential to reduce campus emissions from heat and electricity use in new and existing buildings by 2030. We chose 2030 as our time horizon because most of the studies of energy efficiency potential in the literature do not look beyond 2030, and indeed it is increasingly difficult to project what technologies might become available after this point. We also provide some suggestions for specific efficiency projects that could be implemented.

A. Long-term energy efficiency scenarios

Our analysis of the long-term potential for energy efficiency is based entirely on published literature on this subject. As such, it does not reflect the specific circumstances of Berkeley's campus, but we felt that this approach was more justifiable than attempting to estimate the savings from the many different energy efficiency options that Berkeley might choose to pursue, given the uncertain costs and savings of many emerging technologies and the limited detailed data available on energy consumption in Berkeley's buildings.

A lowest order conservative estimate of the potential for energy efficiency can be obtained from numbers produced by McKinsey & Company on the energy efficiency potential of the U.S. commercial building sector to 2030. This estimate is conservative because McKinsey admits that this scenario will not be sufficient to put the U.S. on a path to achieve the emissions reductions goals of bills currently before Congress (McKinsey's full scenario includes improvements in other areas aside from the commercial building sector). Table 1 shows the potential for energy efficiency improvements in different categories estimated by McKinsey. McKinsey assumes that square footage in the U.S. building sector grows by 48% by 2030, whereas Berkeley is only projected to grow by 30%. Adjusting for this difference in growth rates leads to the third column in Table 1.[2] McKinsey estimated the cost of conserved carbon for each abatement opportunity by looking at upfront capital costs, operation and maintenance costs, and energy savings levelized over the lifetime of the improvement using a 7% discount rate. (McKinsey, 2007)

Technology	Cost in commercial building sector (2005$/t CO2e)	Potential in commercial buildings (MT CO2e)	Potential under revised growth scenario (MT CO2e)
Lighting	-80	110	99
Electronic Equipment	-93	70	63
HVAC Equipment	40	45	40
Building shell improvements (new buildings)	-55	30	20

Table 1. Cost and potential of energy efficiency improvements in the U.S. commercial buildings sector (McKinsey, 2007).

By considering the projected 2030 square footage of Berkeley's buildings as a fraction of the square footage of the total U.S. commercial building sector, we used the above table to estimate potential emissions reductions for Berkeley. We find a total emissions reduction of 37,000 tons CO2e, or a reduction of 18% relative to the 2030 emissions in the "policy scenario" presented in the previous chapter. The cost per ton of conserved carbon is -$60.

We tried to improve on this estimate by considering other studies in the literature. For this estimate we broke down the University's emissions from buildings into three categories: emissions from existing laboratories, emissions from existing non-laboratory buildings, and emissions from new buildings. (Emissions from labs are much higher than from non-labs because of the increased airflow needed for many labs and the power-hungry equipment used in many labs). We then reviewed the literature for potential energy efficiency improvements in each of these three categories. For existing buildings (both lab and non-lab), estimates of potential savings from efficiency were generally in the range of 30-50%. Thus we consider both a "low efficiency" and a "high efficiency" scenario. In the low efficiency scenario, energy in existing buildings is reduced 30% by 2030, and in the high efficiency scenario it is reduced 50% by 2030. Table 2 shows our assumed emissions reductions in both scenarios for new and existing buildings. The sources for these assumptions are detailed in Appendix A.

	Low Efficiency	High Efficiency
Potential savings in existing labs by 2030	30%	50%

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[2] We multiplied the stated emissions potential in the McKinsey report by the ratio of projected square footage in 2030 assuming a 30% growth rate versus projected square footage assuming a 48% growth rate.

Potential savings in existing non-labs by 2030	30%	50%
Potential savings in new buildings today	30%	50%
Potential savings in new buildings by 2020	55%	75%
Potential savings in new buildings by 2030	80%	100%

Table 2. Summary of efficiency scenarios. See Appendix A for more details.

We then apply these savings potentials to Berkeley's projected 2030 energy consumption in new and existing buildings. For new buildings, under the low efficiency scenario we assume that the growth in energy consumption due to new square footage added from 2007-2015 reduced 30%; growth from new square footage in 2016-2025 is reduced 55%; and growth from new square footage in 2025-2030 is reduced 80%. The high efficiency case is treated in the same fashion. Not surprisingly, the result is a reduction in emissions of 30-50% by 2030 relative to the "policy scenario" presented in the previous section. The emissions reduction is calculated from assuming that 64% of building energy use in 2030 is in steam and the remainder is in electricity (same fraction as in 2007). The emissions factors in 2030 are 0.000122 t CO2e/kWh for electricity and 0.00746 tCO2e/th for natural gas-based steam.[3]

Estimating the net present value cost per ton of conserved carbon is more speculative. For laboratory buildings, we note that the majority of retrofits have payback times less than 10 years (most are significantly less), according to Woolliams et al (no date) and Hoenmans and van Geet (2008). Therefore, we estimate a lower bound on the savings from lab retrofits by assuming a 10-year payback time on all retrofits of existing labs and assuming that 40% of energy use in existing buildings can be attributed to labs.[4] Assuming a 15-year lifetime for retrofits, the lifetime savings come from the discounted electricity savings from the second ten-year period of the retrofit.

For existing non-laboratory buildings we use levelized up-front costs from Brown et al (2008) of $0.027/kWh for electricity improvements and $1.9/MBTU for heating improvements. We add these costs to the discounted savings over the assumed 15-year lifetime of the efficiency improvements.[5] Note that this may underestimate the cost because the Brown et al paper only considers retrofits that save 30% of building energy use, not 50% as we consider in one of our scenarios.

For new buildings, we assume that building energy efficiency new buildings costs $3-$5 more per square foot than building conventional buildings. This is the average cost premium for silver/gold LEED rated buildings (Kats, 2003). Again, we add these costs to the discounted savings over the assumed 20-year lifetime of the efficiency improvements.

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[3] This figure for the carbon intensity of steam is derived from the total emissions from steam and natural gas (95,000 tCO2e in 2006 according to Ahmed, 2007) and the 2006 purchase of 1,260,000 MMBTU of steam and natural gas (Office of Sustainability, 2008).

[4] According to Borgeson et al (2007), 24% of electricity is used for lab ventilation and 13% for lab plug loads. Roughly 20% of Berkeley's square footage is in laboratory buildings, and assuming that lighting demand (which accounts for 30% of all electricity use) is the same in labs and non-labs, a total of 43% of electricity will be used in labs. We assume that the heating demand for labs is disproportionately high as well, due to the extra demand for heating induced by fume hoods.

[5] This assumption is based on Lawrence Berkeley National Lab data that indicates that the average lifetime for heating efficiency improvements is 15-20 years, whereas electric efficiency improvements (e.g. appliances) have a lifetime of 10-20 years (Wenzel et al, 1997). These data are from the residential sector, but we assume that the commercial sector should not be dramatically different.

Because all of the costs in these studies are current costs (not projected costs in 2030) and because of the high degree of uncertainty in these estimates, we do not bother trying to guess what electricity and gas prices will be when these retrofits are implemented. Instead, we simply use the current electricity price of $0.10/kWh and steam price of $0.80/th. We further assume that the existing incentives of $0.24/kWh saved and $1/th saved will continue until 2030. We justify this assumption by noting that, even though the PG&E incentives are only scheduled to last through 2014, it is likely that they will be replaced by some other form of incentive, such as a price on carbon. A discount rate of 7% is assumed.

After making all of these assumptions, we find that the net present value cost per ton of conserved carbon is roughly -$300 in both scenarios. Without the PG&E incentives, the net present value cost per ton of conserved carbon is roughly -$80, similar to the McKinsey scenario. These numbers should not be taken too literally, but the point is that significant savings through energy efficiency do exist, especially if the University is willing to tolerate a longer payback period.

In short, we estimate that energy efficiency in new and existing buildings can reduce emissions 30-50% relative to the business as usual trajectory by 2030 at net negative cost. This implicitly assumes that we could retrofit all of the buildings on campus in the next 20 years. The current rate of lighting renovations is roughly 12 buildings per year; at this rate it will take 17 years to cover the 200 major buildings on campus (Abesamis, 2008; Borgeson et al, 2007). Thus our assumption is not unreasonable although it would almost certainly require hiring additional staff (or external consultants) to make the comprehensive energy efficiency improvements that this report advocates.

Our cost estimates, although very approximate, do suggest that energy efficiency should be pursued aggressively. Unlike renewable energy (which is likely to have a positive lifecycle cost) or the purchase of offsets (which will definitely have a positive lifecycle cost), energy efficiency upgrades are likely to save money overall. As discussed by David Goldstein, one of California's leading energy efficiency experts, this fact makes aggressive pursuit of energy efficiency the most conservative option. He notes that, in the context of binding emissions reductions, "the consequences of assuming the efficiency potential is less than it really could be is that less policy attention is paid to efficiency, which means that more attention and money are devoted to other solutions that are more expensive than efficiency in terms of cost per ton of emissions abatement." (Goldstein, 2008)

It may well be that the potential for energy efficiency is even higher than what we have discussed above. According to Goldstein (2008), "almost all [energy efficiency] potentials studies address uncertainty by intentionally biasing the assumptions (lowering energy savings projections and/or raising cost projections) to the point that there is little technical doubt that the predicted cost of saved energy for each measure in the supply curve will not be lower than what is subsequently found in the real world." He estimates that, if we really needed to, we could reduce energy use in existing buildings by 80-90% within the next two decades. But he further points out that "the path to 80+% savings goes through realizing 35%-50%. Continuation and refinement of the policies that got us the first 35% will allow us to discover and acquire the remaining potential." (Goldstein, 2008)

Implementing an aggressive energy efficiency program will require some policy changes. In particular, it will require the university to accept a simple payback period of longer than 3 years for efficiency projects (Abesamis, 2008). Considering that Berkeley is not a business and is not planning to disappear in the foreseeable future, insisting on a short payback period, although it is the industry standard, does not make much sense for a university. In addition, as alluded to above, implementing an efficiency program will likely require hiring more staff. Such staff could be hired with the requirement that they generate enough savings to fund their position. Alternatively, Berkeley could hire external consultants for the retrofit work. As discussed in greater detail in the 2007 CalCap report, the University of British Columbia pursued this approach and reduced emissions from academic and administration buildings by 26% after a 3-year renovation process (Borgeson et al, 2007).

In the next section, we discuss some possible energy efficiency projects (some of which are already underway) that could lead to significant savings.

B. Sample energy efficiency projects

(i). Lighting

In this section, we discuss the potential savings from two lighting projects: converting all indoor lighting to T8 fluorescent lightbulbs with electronic ballasts and using wireless controls in 50% of campus buildings.

The University is in the midst of switching all lighting to T8s, and currently about 40% of lights on campus are T8 (Abesamis, 2008). T8's reduce electricity consumption 20% relative to the existing T12 lightbulbs. The installed cost is estimated at $36 for ballasts and lamps (ACEEE, 2004). We assume that lights are used 10 hours per day and the average lifetime is 10,000 hours. With these assumptions, we calculate a simple payback time of 2.4 years and a (non-discounted) cost per ton of CO2e of -$130. Total emissions reduction is 2200 tons CO2e per year, or 3.5% of building electricity emissions.

The University has implemented two pilot projects of wireless control technology. Specifically, wireless control technology that was partially developed at Berkeley and is now being commercialized by Adura Tech has been installed in Doe and Moffitt libraries. In this system, a microprocessor (called a mote) is attached to the lighting fixture's ballast. The mote can relay information between remote locations without wiring and can communicate with light and motion sensors. (Borgeson et al, 2007) The savings from the two pilot projects are summarized in Table 3.

	Moffitt	Doe
Savings (kWh/year)	100000	70000
Savings (kWh/sq ft/year)	3	5
Upfront cost	$23,000	$5,100
Upfront cost per sq ft	$0.69	$0.36

Table 3. Cost and savings from wireless controls pilot projects. (Huizenga et al, 2008)

We assume that wireless controls could be applied to 50% of buildings on the rest of the campus and conservatively estimate savings at 1 kWh per square foot per year and upfront costs of $0.7 per square foot. Applying these savings to current building electricity use yields a total savings of 1900 tons of CO2e per year at a payback of 2 year.

Assuming the controls last 5 years gives a cost per ton of conserved carbon of -$660 (without the PG&E incentives this would be $130/tCO2e).

There are other options that could significantly improve lighting efficiency that we have not considered here. One option would be to replace all indoor lighting with light-emitting diodes (LEDs). Another option would be to install light tubes, which provide natural daylighting by piping light from a dome on the roof (which may be as small as 10 inches in diameter) through reflective tubing into a classroom or hallway (Solatube International, 2008).

(ii). Monitoring-based commissioning

Monitoring-based commissioning refers to installing permanent energy monitoring systems in buildings along with retro-commissioning efforts. The goal is to detect inefficiencies and malfunctions in building control systems that may be unnecessarily wasting energy and could otherwise go undetected for years. As we will demonstrate below, this has the potential for very large emissions reductions with a simple payback of less than two years.

Table 4 compares data from two existing studies of building commissioning. “UC/CSU/IOU” refers to a monitoring-based commissioning (MBC) pilot project done as part of the University of California – California State University partnership agreement for 2004-2005. The table shows the results of the first 13 MBC projects done under the partnership (Brown et al, 2007). “Mills et al” refers to a 2004 study from Lawrence Berkeley National Laboratory that looks at the savings from commissioning of 175 buildings across the United States (Mills et al, 2004).

	UC/CSU/IOU	**Mills et al**	**UC/CSU/IOU**	**Mills et al**
	project average	project average	project median	project median
Electricity	8%	11%	8%	9%
Hot Water/Steam	20%	37%	20%	36%
Simple Payback	3.1	2.1	2.5	1
Commissioning cost ($/ft2)		0.47		0.27

Table 4. Comparison of two studies of building commissioning. From Brown et al. (2007)

In addition, two pilot projects of MBC have been done on Berkeley’s campus, for Soda and Tan Halls. These projects each cost roughly $0.9/square foot. The Soda Hall project saved 9% on electricity and 14% on steam, while the Tan Hall project saved 14% on electricity and 19% on steam. (Borgeson et al, 2007)

We can estimate the savings for implementing MBC across the Berkeley campus. We assume an 8% reduction in building electricity use and 20% reduction building steam use, and apply these reductions to the 2007 baseline electricity and steam use data. We assume a cost of $0.9/square foot (plus additional maintenance costs of 10% of upfront cost per year) and assume that savings persist for 5 years.

With these assumptions, we find a payback of 1.7 years and CO2e reductions of 24,000 tons per year (an 11% reduction over 2007 levels). This represents a very large potential emissions reduction from a single measure that has a very short payback time (when the PG&E incentives are included). The cost per ton of conserved carbon is -$290 per ton CO2e; without the PG&E incentives the cost would be -$10/tCO2e.

(iii) Energy Efficiency in Labs

a. Fume Hoods

The average fume hood consumes three and a half times as much energy as the average house and the UC Berkeley campus has approximately 1,300 hoods. Energy use due to fume hoods can be reduced through conservation measures (ie. shut the sash campaigns) as well as replacing existing CAV hoods with more efficient VAV models. Although energy savings can be achieved through behavior change alone, in order to meet the Universities carbon goals, it will be necessary to use more efficient technologies.

More efficient steam hoods have been developed, but they have not yet been approved for use in California. However, Cal/OSHA is evaluating the safety of these new hoods, namely the "Berkeley Hood" developed at LBL, and such hoods can be used if a Cal/OSHA variance is obtained. These fume hoods have proven to save 50-75% energy over conventional models without compromising safety (Mills 2005). By replacing all existing hoods with these new ultra efficient models the University would save 15,797-23,696 tons(Borgeson et al 2007) of CO_2 equivalent each year(which is equal to 8-11% of 2008 emissions. Using current cost estimates energy saving would result in a four year payback. For a more detailed analysis of the savings potential for SAV and "Berkeley Hoods) please see the 2007 CalCAP class report.

b. Plug Loads

Plug loads along with unique HVAC requirements are one of the reasons that labs consume significantly more energy compared to other campus buildings. Yet UC Berkeley has not yet taken any steps to encourage the purchase of more efficient equipment. Lab equipment does not fall under the UCOP Purchasing Policy because such equipment is not Energy Star® rated. Labs 21, however has a wiki page which lists the energy use of such equipment. This resource could be used to identify more efficient equipment.. If the University adopts a purchasing policy which encourages and incentivizes the purchase of more efficient equipment modest but definite carbon savings will result.

(iv). HVAC

The heating ventilation and air conditioning (HVAC) loads of campus buildings accounts for greater than half of campus emissions. These emissions include all of the steam and natural gas used for heating which produced 95,906 tons of carbon dioxide equivalent emissions in 2007 (2008 Sustainability Assessment) as well as the electricity used for cooling and ventilation. This report analyzes the potential for savings for several different HVAC technologies, including changing the systems from CAV to VAV, radiant panels, hydronic radiant baseboard heaters and chilled beams.

Variable Air Volume Retrofits: Many of the oldest buildings on campus use constant air volume HVAC systems meaning that the same amount of conditioned air is moved through the building regardless of temporal demand. By converting the system to variable air volume the system only needs to circulate and condition as much air as is needed to maintain temperature and carbon dioxide levels, significantly reducing the associated energy use. Retrofits are often relatively inexpensive as they may only involve changing fans and installing sensors. In fact this is the course of action that is being pursued for several lab buildings in the Strategic Energy Plan (SEP). This is likely the best method in lab buildings in mild climates like ours. We are assuming that lab building loads are driven by the minimum number of air changes not temperature. If this is not the case research indicates that other technologies would result in greater efficiency (Rumsey 2006).

Conventional HVAC systems heat air and circulate the warm air. This is referred to as a method of convective heating. However, since water can contain much more heat than air for a given volume, it is more efficient to use water to move heat throughout a building. The following systems employ this strategy and are thus called hydronic systems.

Radiant Ceilings: Convective heat transfer (such as that employed by traditional HVAC systems) relies upon a medium such as air to transfer heat. Radiant heating (such as that we get from the sun) is a method that does not rely upon a medium and instead, heats objects directly. It is more efficient to rely upon radiant heat transfer than convective heat transfer since it heats occupants directly while allowing the surrounding air may to be a few degrees cooler. This has also been shown to result in higher occupant comfort. Radiant heating can be employed through the use of radiant ceiling panels or floors (radiant floors are not a viable option for retrofits but should be considered in new construction), which deliver 90% of their heat radiantly, eliminating the need to condition air. Since air is not required to condition the rooms, it is possible to downsize air handlers to supply ventilation air only. In cases where the space is within 25 feet of an operable window and the area of the operable portion of the room's windows equals 4% of the naturally ventilated floor area, natural ventilation can be used so the ventilation load can be eliminated. Literature generally cites radiant systems as being 30% more efficient than VAV with recirculation, but it is difficult to find reputable case studies in our climate that uses radiant ceilings exclusively for heating. Radiant ceiling panels are being installed as part of the California Hall retrofit and the project may provide some data as to the efficiencies Berkeley can achieve with the technology. The cost of this type of system is application dependent and should be calculated by a cost estimator, however they can usually be expected to have a reasonable payback. This will not be a viable option in retrofits of buildings with historic or decorative ceilings because of the exposed panels.

Hydronic Radiant Baseboard Heaters: These heaters act similarly to radiant ceiling panels but rely more upon convective heat transfer since objects in the room reduce radiant heat penetration. This results in somewhat less efficient operation. However, since they are cheaper than radiant ceilings, they can be a preferred option in rooms with unobstructed perimeter wall area (typically beneath windows) or rooms with decorative or historic ceilings.

Chilled Beams: Chilled beams, also known as induction diffusers, can be either active or passive. Passive beams are only capable of cooling and will not be discussed because cooling is generally not used in non-lab buildings (and lab building loads are not driven by cooling loads). Active beams consist of coils within a long beam recessed in the ceiling. Hot water is circulated through this coil and air is forced over it as it enters the space. Air circulates throughout the room, rises back to the beam and is reheated by the coils. Since the air is reheated in the room, not as much of it needs to return to the air handling unit, thus fan energy is saved. Because the system does not use radiant heat and relies upon active air circulation it is not as efficient as baseboard heaters or radiant ceilings but may be applied in some applications. Chilled beams have been more expensive than VAV systems in the past, but now that larger companies are beginning to offer them, they have become comparable in price to VAV.

It is important to note that in order to achieve the most efficient heating and ventilation for many buildings it will be necessary to convert from forced air systems to radiant or chilled beam systems. Due to this, improving the efficiency of these systems or converting from CAV to VAV, may not be the most cost effective option since they will eventually need to be converted to a different system altogether. This is an example where pursuing small savings will not put the University on the path to achieving large savings.

IV. Potential Savings from Steam Plant Retrofit:

The steam plant is responsible for over 40% of the University's emissions. While there is certainly potential to improve the efficiency of the plant at several points including, the actual system, the distribution pipes and individual building heat exchangers, the facility will continue to produce significant amounts of carbon until an alternative feedstock is found or the campus transitions to a different technology like geothermal source heat pumps (gsph) and/or solar thermal. We estimate that improvements to building efficiency coupled with improvement in the efficiency of the steam distribution loop and heat exchangers could reduce the demand for steam by 30-50%. It may be possible to generate 100,000 MMBtu's of steam by using gsph on campus, which would save 6309 tons of CO_2. Steam generated from by GSPH only generates 21% of the carbon dioxide that is generated by the current steam plant, and will continue to be less carbon intensive as the grid decarbonizes.

Of existing market ready technology geothermal and solar thermal technologies are the main contenders to provide the remainder of the energy. Because solar thermal arrays will not always produce energy when it is needed it will need to be used in conjunction with another technology.

Geothermal technology has many advantages, it requires little maintenance, it is reliable, it works well with radiant systems (which need warm water instead of air) and it has a much smaller emissions coefficient than most other forms of heat energy. Given the current PG&E mix and a ground temperature of 60º F geothermal will produce heat, which produces only 21% of the emissions associated with the current cogeneration plant. Assuming only 15% of the demand for heat campus wide could be reduced through efficiency the campus would be able to reduce it's steam related emissions below the 80% below 2000 levels if geothermal was the only heat source. Importantly geothermal energy is gathered by using electricity and as this becomes less carbon intensive the footprint associated with geothermal will become smaller as the footprint of cogeneration grows.

Unfortunately it is difficult to assess the upfront cost of installing geothermal, or the amount, which can be generated on campus. The main cost associated with geothermal is likely to be drilling bores. The campus should consider building geothermal systems whenever they build a new building because the additional cost of digging a bit more is relatively small. Geothermal does not need to be built at one time as a central plant because the efficiency of the plant is not strongly correlated with size, making distributed geothermal a better choice than a central plant. There are many factors, which can affect cost and can't be assessed without a thermal conductivity test, and drilling test bores, but we can use the recent geothermal installation at CCSF as a rough guide. They're installation had a payback under 15 years.

Unfortunately there is not much room on campus to dig geothermal wells. Given a rough estimate of on campus open space it is possible that 100,000MMBtu's (given 2007 loads) of the campuses heat loads could be met through on campus geothermal installations. This would save the University a bit under 6,800 tons of CO_2/year. It may also be possible to generate geothermal on open land in the hills. It's difficult to ascertain the cost of installation given the slope of the land. It would also be necessary to install lines to carry hot water to buildings and some electricity to pump the water.

Because UC Berkeley purchases steam that is generated by cogeneration there are different ways to arrive at an emissions factor for purchased steam. The CalCAP inventory uses the California Climate Action Registry (CCAR) methodology for determining the emissions attributable to steam. CCAR assigns the a proportion of the total plant emissions based on the ratio of steam to electricity produced, so if the plant produces equal kWh's of steam and electricity they will both have the same emissions factor. Such accounting does not take into account the fact that steam is generated from heat which would otherwise have been wasted. An alternate method of accounting for emissions takes this into account by subtracting the amount of carbon dioxide that would normally be produced by a natural gas fired power plant and assigns the remaining carbon dioxide to the steam. This methodology was proposed in the 2007 CalCAP Course Project Report. However the emissions factor of the electricity that UC Berkeley buys from PG&E is only 0.524 lbs CO_2 /kWh (PG&E 2009) as opposed to the 1.34 lbs CO_2/kWh emissions factor assumed for a natural gas fired plant in the 2007 report. Because the steam plant produces more carbon intensive electricity than the PG&E average UC Berkeley should be accountable for those emissions. If one assumes an efficient steam cogeneration plant which produces 0.4 kWh of electricity and 0.5 kWh steam for every 1 kWh natural gas used (this is a normal efficiency for a new plant), but assigns electricity generated the same emissions factor as average PG&E electricity one MMBtu of steam creates 0.0746 tons CO_2 versus 0.0794 tons CO_2/MMBtu which is the average emissions factor used in campus reporting. If we assume a more realistic efficiency for the steam plan, where 30% of initial energy is converted to electricity and 40% is converted to steam the emissions factor is 0.111 tons CO_2/MMBtu. It is important to note that as the emissions factor of PG&E electricity becomes less carbon intensive over time the emissions attributed to steam will become greater given this methodology. While the University should consider incorporating a more accurate view of its emissions into its inventory this report will use the current university emissions factor to compare future scenarios.

V. Potential Savings from On-Campus Renewable Electricity

We investigated the possibility of installing renewable energy generation on campus – either solar PV on rooftops or wind on the Hill Campus. In both cases, the net cost per ton of CO2e saved was positive; in other words, these investments do not pay back. However, they may still make sense if the alternative is to purchase carbon offsets. According to the Department of Energy, as of July 2006 the price of certified renewable energy credits produced and sold in California ranged from 2-3.3 cents/kWh, or $66-$110 per ton of carbon dioxide equivalent ("Green Power Markets", 2008). In the next sections, we detail our calculations of the electricity generation potential and economics of solar and wind and compare the cost of on-site generation with the cost of purchasing renewable energy credits.

A. Solar

There are a limited number of roofs which the University has deemed suitable for solar. Table 5 shows the space available on these roofs and the resulting solar potential, as calculated by the Office of Sustainability[6]. In total, solar could supply 14.3 GWh/year, which is 7% of 2007 electricity consumption. This would offset 2% of 2007 emissions. However, as the grid decarbonizes, the solar installed on Berkeley roofs offsets fewer and fewer emissions. By 2030, under the policy scenario outlined above in which the grid decarbonizes by 80% by 2050, the solar PV will only offset 0.8% of Berkeley's emissions.

Building	Net Area (sq ft)	Solar production (kWh/yr)	Installed (peak) capacity (kW)
3300 Regatta (Richmond)	400,000	7,419,422.58	3,333.33
Valley Life Sciences	31,175	578,251.25	259.79
Tolman Hall Total	30,000	556,456.69	250.00
University Hall	28,588	530,266.13	238.23
McCone Earth Sciences	23,750	440,528.22	197.92
UC Printing Services	23,000	426,616.80	191.67
Rec. Sports Facility Total	19,800	367,261.42	165.00
2417 Haste	17,397	322,689.24	144.98
Kroeber Hall Total	15,120	280,454.17	126.00
Hearst Field Annex Total	15,000	278,228.35	125.00
Davis	14,400	267,099.21	120.00
Hildebrand	13,805	256,062.82	115.04
Morgan	12,500	231,856.96	104.17
Zellerbach Hall Total	12,000	222,582.68	100.00
Cory Hall Total	10,200	189,195.28	85.00
Univ. Art Museum Total	9,800	181,775.85	81.67
Moffitt Library Total	9,543	177,008.87	79.53
Building south of Morrison	9,450	175,283.86	78.75
Wurster Hall Total	9,400	174,356.43	78.33

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[6] Solar production was calculated by assuming average annual insolation of 5.47 kWh/m^2/day and a 10% conversion efficiency. Installed capacity was calculated by assuming that a 1kW panel requires 120 square feet. (Source: Kira Stoll, Office of Sustainability)

Barrows Hall Total	8,510	157,848.22	70.92
2000 Carleton St. Total	7,938	147,238.44	66.15
UC Press (1995 Univ. Ave)	7,225	134,013.32	60.21
2233 Fulton	7,000	129,839.90	58.33
Hearst Gym Total	6,400	118,710.76	53.33
Moses	5,338	99,012.19	44.48
Latimer	5,100	94,597.64	42.50
Donner	4,735	87,827.41	39.46
Stephens	3,960	73,452.28	33.00
Eshleman	2,960	54,903.73	24.67
Soda Hall Total	2,400	44,516.54	20.00
Part of MLK	2,211	41,010.86	18.43
2224 Piedmont	1,703	31,588.19	14.19

Table 5. Available roof space for solar PV and potential generation capacity.

We then calculate the net present value cost of solar per ton of CO2e emissions averted. The net present value cost is the upfront installed cost less the discounted future savings. Operation and maintenance costs are assumed to be negligible. We further assume that the solar panels last 25 years and we assume a discount rate of 7%. The cost of electricity is held constant at $0.10/kWh.

As shown in Appendix B, the total upfront cost (net rebate) of installing solar on all eligible roofs is $29 million. The electricity savings are valued at $1.4 million per year. Thus, the net present value of the investment and savings over the lifetime of the panels is $13 million. The cost per ton of CO2e saved over the lifetime of the installation is $200/tCO2e (or $120/tCO2e if we do not assume any decarbonization of the electricity grid). This is likely to be more expensive than the cost of purchasing renewable energy credits, at least for the next several years.

B. Wind

Wind turbines could be installed on Berkeley's Hill Campus, which has an area of 800 acres. Using a wind map with 5km resolution, we estimate that the average wind speed on the Hill Campus is about 5 +/- 0.7 meters per second at a height of 80 meters (3Tier, 2008).[7] We use a calculator provided by the Danish Wind Energy Association to estimate how much wind could be generated from different turbines operating at this height. We consider turbines ranging from 1MW to 2.3 MW in size. The detailed calculations are given in Appendix C. Installing 1MW turbines is found to be least economical.

As shown in Appendix C, it is possible to generate 15 GWh/year of wind energy on the Hill Campus. This corresponds to 7% of 2007 electricity consumption and will offset about 2% of 2007 CO2e emissions. We find that the upfront cost of installing wind is roughly $24 million, and the cost per ton of CO2e is $130-160/tCO2e ($70-$100/tCO2e if we do not assume any decarbonization of the grid).

In short, both wind and solar combined can offset only a small fraction (roughly 4%) of Berkeley's electricity use. Both appear to be slightly more expensive than

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[7] According to 3Tier, the company that produced the online wind map, the map is accurate to within 1 m/s for 85% of sites in the United States.

directly producing renewable energy credits, although this could change in the future. Our analysis suggests that wind is slightly cheaper than solar, despite the relatively poor wind resource available. However, our analysis of wind did not take into account the seasonal variability of wind speeds in the Bay Area and therefore is likely to have underestimated the true cost of wind. In light of these considerations, we feel that on-campus energy efficiency should be a higher priority than either wind or solar at the moment.

VI. Other Sources of Emissions

The sources of greenhouse gas emissions not yet discussed in this report include: transportation (commuting, campus fleet, and air travel), refrigeration, outdoor lighting, water consumption, and solid waste. These either make a very small contribution to total emissions or (in the case of commuting and air travel) they are not directly under the university's control. In this sort of broad-scale analysis, we do not feel it appropriate to extensively discuss sources that account for only 1-2% of total emissions, as this is well within the noise of the assumptions we have made so far about emissions reductions opportunities. Here we present some broader policy recommendations regarding emissions reductions from these sectors, without attempting to calculate the magnitude of their contribution to overall emissions reductions goal.

A. Transportation

(i). Campus Fleet:

The Campus fleet is responsible for a very small portion of UC Berkeley's emissions (less than 1%) but is an area that the University has complete control over. The University has already made progress by purchasing low emissions vehicles but it will need to continue to buy more efficient vehicles and run them on cleaner fuels. It is impossible to forecast what the best vehicle technologies will be in the future but the University should strive to run diesel fueled vehicles with biodiesel and purchase more efficient vehicles and those which run on electricity or other alternative low carbon fuels.

(ii) Commute:

UC Berkeley can only affect the carbon intensity of staff/faculty/and student commute indirectly through incentives. These incentives include: subsidized transit passes, incentives for carpooling, incentives for driving more efficient cars like hybrids, and ensuring that parking remains scarce and expensive. The availability of affordable housing near campus or transit also affects the transportation options of the campus community. By collaborating with local government the University should strive to ensure that affordable housing alternatives exist near the University and along transit corridors.

(iii) Air Travel:

Air travel currently accounts for 10% of University emissions, yet significantly reducing flights of students and faculty conflicts with the educational mission of the University, and there are not currently viable options for less carbon intensive long distance transportation. UC Berkeley should expand the use of videoconferencing equipment to eliminate less critical travel. The University will need to purchase offsets for the remainder of the air travel related emissions.

B. Waste

The University will be able to minimize the emissions associated with solid waste by minimizing the amount of waste, which cannot be recycled as well as increasing the diversion of recyclable material. UC Berkeley should make every effort to comply with the UC Policy on Sustainable Practices section on purchasing. This document outlines guidelines, which mitigate waste by discouraging the purchase of products with large amounts of packaging or high "end of life" impacts.

UC Berkeley will also need to strive to divert all recyclable waste. Infrastructure already exists for the recycling of bottles and cans, but effective education and social marketing campaigns will be necessary to increase diversion. The university will need to begin composting all campus organic material, including paper towels in bathrooms, and food scraps from campus vendors. The University must also continue its leadership in diverting construction waste.

C. Water

UC Berkeley can reduce water demand through better efficiency as well as recycling. Efficiency work will be the most cost effective solution to pursue in the near term. A 2005 survey of campus restroom fixtures (Daniels, 2005) demonstrates that Berkeley can achieve large water savings by installing modern code compliant toilets and urinals, and there is potential to switch directly to very low flow fixtures like 1/8 gfp urinals and 1.2 gpf toilets. There is also potential for water savings by reducing the amount of once through cooling in labs, and expanding the use of drip irrigation. By partnering with EBMUD the campus may be able to receive incentives for reducing its water demand, improving the economics of such measures.

In the future the University may be able reduce its demand for potable water by using grey water for irrigation, but this will not be a viable option in the near future as the campus does not have a readily available source of grey water and there will need to be a significant capital investment to "double plumb" the campus. There is much interest in the possibility of building an on site water reclamation plant, but such a solution is very dependent upon potential funding and emerging technologies.

VII. Policy Recommendations

There are several barriers to achieving the goal of carbon neutrality that can only be addressed by policy measures at the university level. Most of our policy recommendations are centered around energy efficiency, since that is where we envision the largest cuts in emissions through on-campus actions. In order to make these cuts in energy efficiency gains, we recommend:

1. <u>Lengthen Paybacks</u>: Requiring the university to consider energy efficiency improvements with payback period longer than 3 years. 5-10 year paybacks may be required for some efficiency measures. Other universities have adopted similar measures. For example, Harvard's Green Campus Loan Fund provides loans for energy efficiency projects that offer a payback of 5-10 years or less. (Borgeson et al, 2007)
2. <u>Expand Institutional Capacity</u>: In order to identify and complete efficiency projects at the rate necessary to achieve interim carbon targets Berkeley will

need to allocate more human resources to the effort. This can be done through hiring additional staff, hiring contractors, or updating the job descriptions and performance review criteria of current staff to reflect CalCAP related responsibilities. Last year's CalCap reported noted, "one of the major problems Berkeley faces, if not the major problem, to implementing emissions reductions programs on a large scale is the lack of available staff to identify, implement, and maintain projects." Another option would be to hire contractors to perform energy efficiency upgrades much faster than the current pace of retrofits. The University of British Columbia's Ecotrek program provides an excellent example of how this could be done. This program, which took 2 years to design and 3 years to complete, renovated and upgraded 6.8 million gross square feet in 280 buildings, reducing energy use by 27% and emissions by 26% relative to 2002-2003 levels. (Borgeson et al, 2007)

3. <u>Reevaluate New Technology Every 5-10 Years</u>: Because energy efficient technologies change so rapidly, we recommend a mandatory re-evaluation of progress in energy efficiency every 5-10 years to determine whether new technologies have improved to the point of being reliable and cost-effective. In many cases it may be best to "leap frog" better technologies in favor of the best to insure the greatest cost effectiveness.
4. <u>Comfort Cooling Policy</u>: The University needs a tighter policy regarding comfort cooling. The University should not allow comfort cooling in buildings where it is not needed for laboratory equipment or other temperature-sensitive research materials (manuscripts, specimens, etc.).
5. <u>Resolve Split Incentives in Purchasing</u>: Because the individuals and departments which purchase equipment do not pay for the energy consumed over the life of such equipment, UC Berkeley should develop incentives to encourage the purchase of energy efficient appliances. This should apply to Energy Star® appliances as well as those identified by Labs 21 as being more efficient.
6. <u>Establish New Building Codes</u>: Building scientists project that new buildings have the potential to dramatically progress toward zero net energy over the next several decades. We recommend that UC Berkeley's standards require campus buildings to reflect Architecture 2030 goals including Zero Net Energy Buildings by 2030.

There also several policies that the University could implement to reduce its emissions in the transportation sector (staff/faculty/student commuting and air travel), which comprises about 22% of current emissions. Because of its urban setting, Berkeley already has a significant fraction of staff and students using public transportation or carpools to get to campus. The University already has numerous policies to incentivize public transportation and carpools. According to the Office of Parking and Transportation, "53% of campus faculty/staff and 92% of students commute by transportation other than a single occupant personal vehicle" (Office of Parking and Transportation, 2008). Although the University cannot directly control people's transportation choices, the following policies would help promote sustainable transportation

1. Increasing the fee for parking permits
2. Increase subsidies for transit passes
3. Increase the incentives for carpooling or driving a very efficient car
4. Make biking easier by increasing bike racks and access to showers
5. Work with regional government to promote affordable transit oriented housing
6. Expand the use of biodiesel in campus trucks
7. Continue to purchase alternative fuel or ultra low emissions vehicles for the campus fleet
8. Improving videoconferencing facilities and promoting these facilities amongst faculty as an alternative to flying. The University could also provide financial incentives to faculty and students who use videoconferencing instead of flying.

Appendix A. Potential for Energy Efficiency in Buildings

In Section III, we estimated the potential for savings from energy efficiency in existing buildings at 30-50% by 2030. For non-laboratory buildings, this estimate was based on the following sources:

1. Goldstein (2008) estimates that 35-50% savings could be achieved through efficiency in 20-40 years.
2. Brown et al (2008) estimate the potential cost-effective energy savings by 2030 at 30%.
3. Brohard et al (1997) considers a case study of four building retrofits in California and finds savings of 40-50%.
4. The American Physical Society (2008) notes that the California energy code was revised in 2002, 2005, and 2008, and that each revision resulted in a 10-15% improvement in energy efficiency, an annual rate of about 4% (APS, 2008). If this rate of improvement were sustained until 2030, it would imply a 60% reduction in energy use.

For laboratory buildings, our estimate of the savings potential from efficiency was drawn from the following sources:

1. According to the U.S. government's "Labs for the 21st Century" initiative, potential energy savings in labs is 30-50% (Matthew et al, 2004)
2. An older study found a savings potential of 50% for labs in California (Mills et al, 1996).
3. According to the Harvard Green Campus Initiative, buildings built according to the "Labs for the 21st Century" initiative save an average of 33-60% (Woolliams et al, no date).

We also provided two scenarios for improving energy efficiency in new buildings. In the more ambitious scenario, new buildings are zero net energy by 2030; in the other scenario, new buildings are 80% more efficient than existing buildings by 2030. The zero net energy by 2030 scenario is based on the "2030 Challenge", which calls on architects to design new buildings that are 50% more efficient than existing buildings today, increasing to zero net energy by 2030 (Architecture2030, 2008). According to the American Physical Society, the goal of zero net energy buildings by 2030 is feasible, but difficult (APS, 2008). This is also the goal adopted by the state of California in their "Long Term Energy Efficiency Strategic Plan," released in 2008 (California Public Utilities Commission, 2008). Our less ambitious scenario is based on a study by Kats (2003), who finds the average energy reduction in 60 LEED-certified buildings to be 30%, relative to existing buildings. In this scenario, we assume that new buildings can be built 30% more efficient than existing buildings today, with that percentage increasing to 80% by 2030.

Appendix B. Economics of Solar

Based on values reported in the literature, we assume an upfront cost of $6.9 per peak Watt for systems smaller than 50kW, and an upfront cost of $6.2 per peak Watt for systems larger than 50kW.[8] We further assume that Berkeley will take advantage of the California Solar Initiative's Performance-Based Incentive for PV, which pays a rebate of $0.37/kWh over the first five years of operation ("California Solar Initiative Rebates", 2008). (We use the value of $0.37/kWh, but the CSI rebates decline over time, so the longer that Berkeley waits before installing solar, the less favourable the rebate will be). The CSI rebate is discounted at an annual rate of 7%.

Assuming a system lifetime of 25 years, discount rate of 7%, and negligible operation and maintenance costs, the net present value of the investment in solar is $13 million. The cost per ton of CO2e emissions averted is $200/ton, or $120/ton if we do not assume decarbonization of the electricity grid.

Appendix C. Economics of Wind

The potential generating capacity of wind is estimated using a calculator provided by the Danish Wind Energy Association. We choose three representative turbines to consider: Nordex N90/2300 (2.3 MW), Vestas V80 2000/80 (2 MW), and Nordex N43/1000 (1 MW). The 2-2.3 MW turbines operate at a height of 80 meters, where the average wind speed is 5 m/s. The smaller turbine operates at 50 meters, where the wind speed is 4.6 m/s. (3Tier, 2008) Table 6 summarizes the operating characteristics of the turbines (Danish Wind Energy Association, 2003). According to the National Renewable Energy Laboratory, turbines should be spaced 5-10 turbine diameters apart. We assume a spacing of 10 turbine diameters, which means that a maximum of 6 Vestas turbines, 5 Nordex N90 turbines, or 14 Nordex N54 turbines could be installed on the 800 acre Hill Campus.

Wind Turbine	Turbine height (m)	Blade radius (m)	Power (kW)	Power (GWh/yr)	Number of turbines	Total power output

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[8] According to NREL, the median cost of a 10-50 kW(AC) system is $8.25/W and the median cost of a 50-150 kW (AC) system is $7.25/W (Braun and Varadi, 2006). According to LBL, the average cost of a system smaller than 30 kW (AC) is $9.6/W and the average cost of a system larger than 30 kW (AC) is $8.8/W (Wiser et al, 2006). Averaging these estimates gives roughly $8.9/W for a system less than 50 kW and $8/W for a system larger than 50 kW. We use a conversion factor of 0.77 to convert the price per AC watt to price per peak watt (PVWatts, no date).

				per turbine		(GWh/yr)
Vestas V80 2000/80	80	40	2000	2.4	6	15
Nordex N90/2300	80	45	2300	3.1	5	15
Nordex N54/1000	50	27	1000	0.78	14	11

Table 6. Operating characteristics of selected wind turbines.

To calculate the economics of installing wind, we assume an upfront cost of $2 million per MW, annual operation and maintenance costs of $25,000/MW, wind turbine lifetime of 25 years, and discount rate of 7%.[9] With these assumptions, we find that costs are cheapest for the Nordex N90/2300 turbine. The upfront capital cost is $23 million and the cost per ton of conserved carbon is $130/ton.

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[9] The National Renewable Energy Laboratory estimates the capital cost at $1.6 - $2 million per MW of capacity, the operation and maintenance cost at $15-$25/MW, and the turbine lifetime at 20-30 years ("Wind Energy Finance", 2003). A Lawrence Berkeley National Laboratory report project a turbine cost of $1.9 million per MW in 2008 (Wiser and Bolinger, 2008).

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