University of California Strategies for Decarbonization: Replacing Natural Gas

TomKat Natural Gas Exit Strategies Working Group
Report to the TomKat Foundation

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Foreword

Carbon dioxide (CO_2) emissions from burning of fossil fuels is the main cause of climate change, a global phenomenon with widespread harmful—potentially devastating—effects. Although no country, region, or institution can stop global warming by itself, local jurisdictions can become leaders by cutting their own emissions and demonstrating technologies and practices that others can emulate and adjust to their own conditions. Effective leaders show the way forward and create incentives for the rest of humanity to drastically reduce energy-related CO_2 emissions and emissions of other greenhouse gases (GHGs).

California has become one of the most important climate leaders and is poised to do a great deal more. Historically, the state has been at the forefront of efforts to manage air pollution, and the state's policies and technologies have been widely adopted globally. As efforts to create a strong U.S. policy on global warming have faltered, California and other entities within the United States have stepped forward to create strong sub-national policies with the aim of disseminating those approaches more broadly and demonstrating continued engagement with this important problem.

The University of California Carbon Neutrality Initiative

The University of California system can play a central role in California's climate leadership. Its researchers are at the forefront of climate science and technology and the design and evaluation of policies and strategies for targeted climate action (1). Since the energy crisis of the 1970s, UC campuses have been at the forefront of energy efficiency innovation. Acknowledging UC's capabilities, its legacy of energy and climate leadership, and its three-fold mission of research, teaching and public service, in 2013 the university pledged to become carbon neutral (i.e., reach net zero emissions from its buildings and vehicle fleet) by 2025 (2). The UC Carbon Neutrality Initiative (CNI) aims to reduce emissions and use the university's extensive and complex infrastructure as a setting for applied research to demonstrate how deep decarbonization can be achieved practically. There are many bold visions for deep decarbonization, but advancing from vision to action requires attention to real world constraints such as costs, regulatory compliance, scaling and other factors that the practical efforts at UC can help to reveal.

To provide oversight, research and recommendations for the overall Carbon Neutrality Initiative, UC President Janet Napolitano has convened experts from across the university, including faculty, students, administrative leaders, and operations staff. The primary oversight group is the Global Climate Leadership Council (GCLC), formed in 2014. The GCLC subsequently established an Applied Research Working Group which, in early 2016, formed the Task Force on Carbon Neutrality Financing and Management to study the barriers impeding progress toward the goal and to recommend potential solutions.

The TomKat Carbon Neutrality Project

In early 2016, the TomKat Foundation made a generous grant to the UC Santa Barbara Institute for Energy Efficiency to establish the TomKat UC Carbon Neutrality Project, a research effort to develop solutions to two of the most challenging aspects of achieving carbon neutrality. The TomKat Strategic Communication Working Group is researching ways to foster broad-based attitudinal and behavioral change in support of carbon neutrality. The TomKat Natural Gas Exit Strategies Working Group, whose work is the subject of this report, has explored how to eliminate campus reliance on natural gas, the main source of on-campus CO2 emissions.

Subsequently, the UC Santa Barbara Institute for Energy Efficiency, in partnership with the National Center for Ecological Analysis and Synthesis, convened the authors of this report to study options for reducing the use of natural gas. Our 27-member team includes academic researchers having a wide range of expertise, students, and energy managers from five UC campuses and the Lawrence Berkeley National Laboratory, and a key representative of the Office of the UC President, who helped coordinate our work with other activities of the UC Carbon Neutrality Project, including the President's Task Force on Finance & Management.

This document is intended to serve as a resource for the University of California, other universities, and any other entity committed to pursuing deep decarbonization through the elimination of natural gas from its operations.

Contact information

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Chapter 1. Summary

Summary of Research Findings and Recommendations

1.0 Summary

Introduction

Having pledged to become carbon neutral by 2025, the University of California has embarked on a large-scale effort to evaluate options for achieving this goal. For UC, the central challenge to deep decarbonization lies in reducing and, perhaps, ultimately eliminating the use of natural gas, a fossil fuel consisting primarily of methane. Nearly all CO_2 emissions (96%) from UC operations come from direct combustion of natural gas (a "Scope 1" emission) and from purchased electricity generated from fossil fuels (a "Scope 2" emission). Therefore, a cost-effective exit strategy for conventional natural gas is vital to achieving the carbon neutrality goal. The UC carbon neutrality goal does not include "Scope 3" emissions, which are other emissions indirectly related to the University's activities, such as from gasoline burned in employee-owned vehicles.

This report is the result of an independent academic effort focusing on how UC can translate its experience into replicable and scalable emission control strategies. Our research team was designed to ensure that our analysis and proposals were rooted in the practical realities of implementation within one of the world's largest university complexes. Contributors thus include scholars and practitioners from a wide variety of backgrounds in the natural and social sciences and engineering, in addition to operations staff at several of the main UC campuses. We used literature review and new benchmarking studies to reach our conclusions.

We begin by describing current energy and natural gas use at UC. We then present three complementary approaches for transitioning away from natural gas: (1) reducing energy demand via improved energy efficiency, (2) substitution of renewable gas (i.e., biogas and hydrogen produced without GHG emissions) for natural gas, and (3) electrification of end uses. We have identified a promising short-term path, but as we will show, the most transformative options entail technical, economic and administrative challenges. Thus, we conclude with a vision of a strategy that builds on successes, documents failures from experiments, puts a priority on retaining a diversity of options, and explicitly narrows uncertainties. This strategy will help UC to achieve its own carbon neutrality goals while also demonstrating how other large and complex institutions can set their own goals and implement the actions needed to achieve them.

Natural Gas: The Central Challenge to Carbon Neutrality

Since 2001, natural gas use in the United States has increased by roughly 30% (3). As a low cost and lower-CO_2 replacement for coal in electricity generation, natural gas has contributed to an overall decline in U.S. CO_2 emissions since 2007 (4, 5). Within the state of California, the reliance on natural gas is pervasive with a cumulative electricity generating capacity of 45 GW (57% of total) and actual generation of ~117,000 GWh (60% of total) in 2015 (6). Essentially all the rest of the state's capacity comes from renewable power and imports (mainly hydroelectricity from the Pacific Northwest). Natural gas is currently abundant and relatively inexpensive, and likely to remain so for the foreseeable future (7). Market forces by themselves favor the continued use of natural gas and are expected to drive a rise in the role of gas elsewhere in the country. Although natural gas emits less during combustion than other fossil fuels, it still emits CO_2, making its continued widespread use inconsistent with deep decarbonization of the energy sector. Finding alternatives to natural gas must be at the center of any strategy for achieving deep decarbonization.

How UC uses natural gas

As of 2015, two-thirds of UC's Scope 1 and 2 greenhouse gas emissions come from on-campus combustion of natural gas (Figure **1.1**a). About two-thirds of this gas is used in large combined heat and power plants (CHP) owned and operated by five UC campuses and designed to cogenerate heat, cooling and electricity (Figure **1.1**c). The other third goes to residual uses, such as heating and cooling of buildings supplemental to or not served by central plants, and other localized uses.

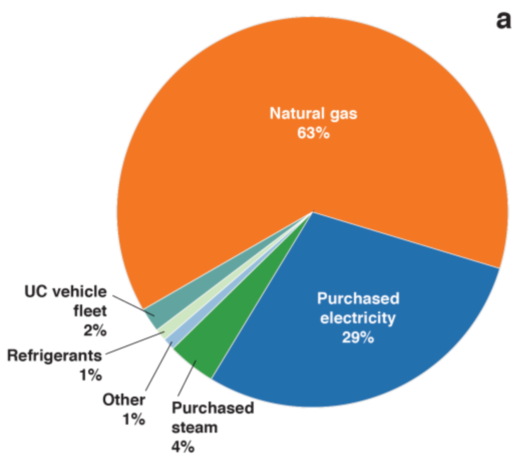
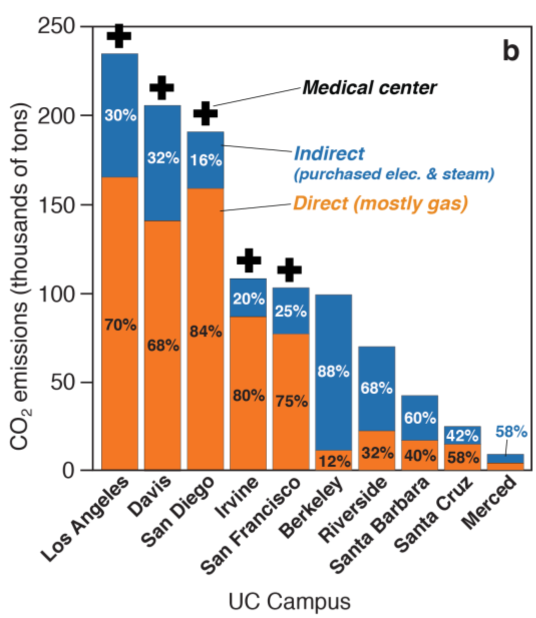
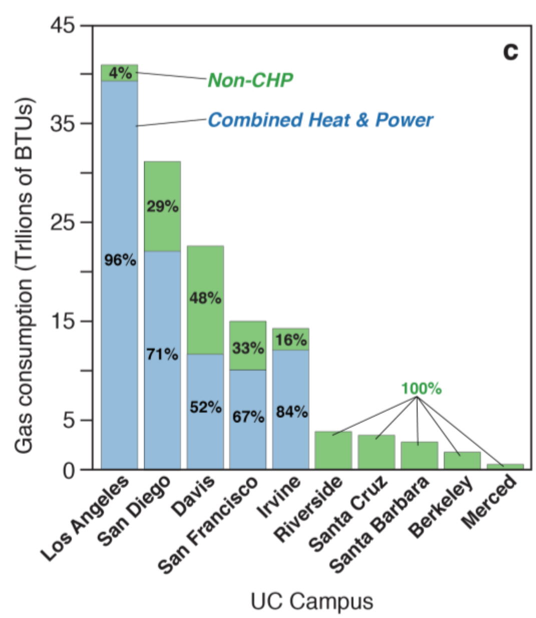


Figure 1.1. 2015 Emissions and natural gas consumption at UC campuses. a) Breakdown of emission sources: natural gas burned on UC campuses accounts for 63% of the university's CO_2 equivalent greenhouse gas emissions, including both direct (Scope 1) and emissions related to purchased electricity and steam (Scope 2). (b) Magnitude and share of natural gas emissions by campus. The 10 campuses vary in size and climate, with all five of the largest campuses having a medical center (shown with "+"), which creates special energy needs. (c) Breakdown of CHP and non-CHP direct gas consumption by campus, with all five of the largest gas users relying on CHP.





Two additional campuses have CHP plants not reflected in Figure **1.1**c: UC Berkeley's CHP plant was operated by outside contractors, (with emissions classified as Scope 2) until recently, but came under university operation in 2017; UC Santa Cruz's plant came online in 2016.

In addition to the current abundance and low cost of natural gas, several other factors have made the use of natural gas attractive to the UC system:

- UC's CHP plants, which produced half of total system-wide electricity used in 2015 (Figure **1.2**), constitute large investments. Premature retirement and replacement of the plants would be a costly option.

- Central CHP plants, and their centralized heating and cooling systems, are generally highly efficient and have relatively low operating costs because they capture and re-use waste heat. Campus CHP plants currently produce electricity at an operational cost significantly lower than purchased electricity, with the added co-benefits of heating, cooling, and process services for helping to heat the campuses, further reducing utility costs.

- Gas turbines used for CHP are extremely efficient when operating at their design capacity. However, their efficiency drops (and NOx or other emissions can rise) at reduced power outputs. Some plants can be turned down to 60% of design capacity, providing some flexibility. However eventual migration completely away from CHP remains challenging with respect to both feasibility and transition.

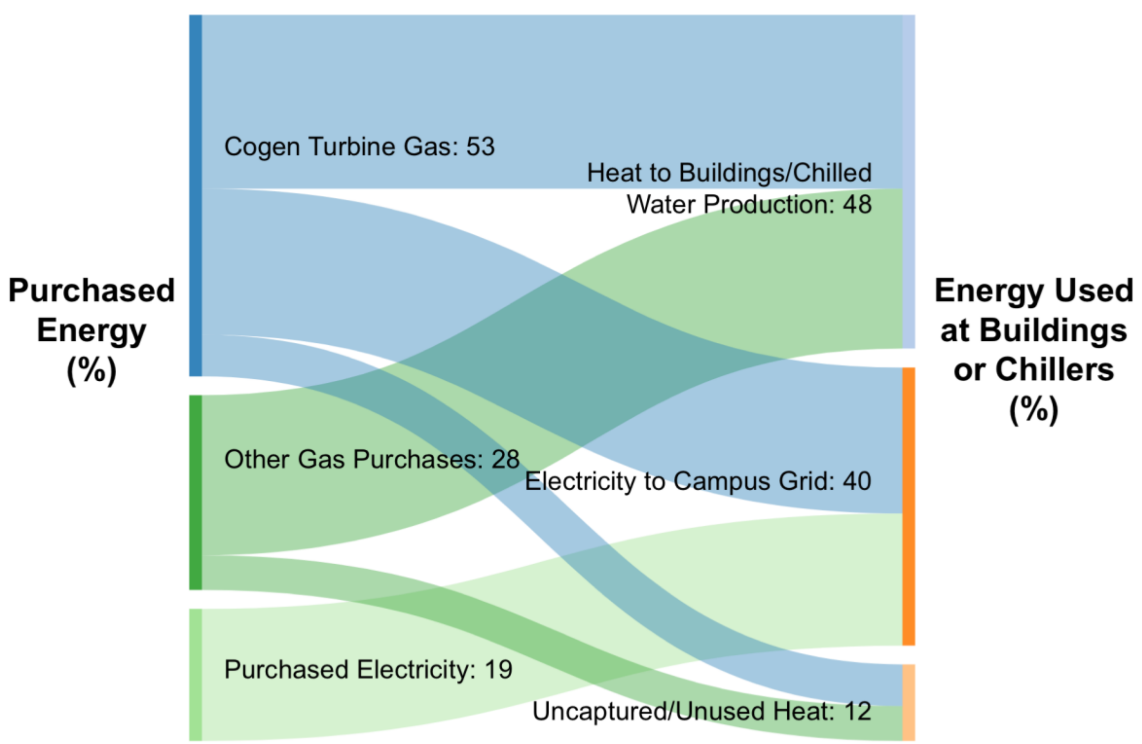


Figure 1.2. Sankey diagram for UC 2015 systemwide purchased and cogenerated energy as percentages. This is a site energy analysis for purchased energy converted by cogeneration or combustion into energy used at buildings or chillers. The electricity fraction is somewhat higher by GHG emissions and much higher by cost.

The institutional context for eliminating natural gas

UC's ten campuses and five medical centers are spread across almost the entire state of California. Collectively, they represent ~1% of California's building footprint. Each campus operates semi-autonomously, with support and guidance from the UC Office of the President. As public institutions, UC campuses are particularly attentive to choices that affect costs and may affect their ability to provide public education at reasonable cost while simultaneously engaging in world-class research.

Energy needs and gas use profiles vary considerably from campus to campus, and there are important differences in existing infrastructure. Furthermore, each campus is subject to different financial constraints, and their growth plans vary. Some, notably those with hospital complexes, are very large and can use CHP technologies at scale while others have smaller energy loads.

In light of these important differences, the following strategies should be viewed as a set of options and pathways that campuses may draw upon to assemble their individualized plans. There is no central blueprint for reducing reliance on natural gas.

Three Approaches for Cutting Gas-Related Emissions

Our research considered three approaches to reduce the UC's reliance on natural gas:

1. **Energy efficiency.** Reducing energy demand through investments in deep energy efficiency.
2. **Biogas.** Replacing natural gas with renewable biogas, with a potential role for hydrogen.
3. **Electrification.** Electrifying end uses that currently depend on natural gas and obtaining electricity from carbon-free energy sources.

Energy storage will create synergies with all three approaches.

Other means of eliminating greenhouse gas emissions from natural gas combustion, such as capturing carbon at the time of combustion and storing that carbon off-site, are not considered in this report. New technology might, in the future, make small-scale carbon capture and storage feasible.

Throughout, we have focused on options that actually reduce emissions within the UC system. We have not addressed the potential role for optimizing emission cuts across the UC system as a whole—for example, by allowing the individual units to trade emission credits. Nor have we examined the potential role for the UC system to purchase offsets from other entities—an option that is explicitly envisioned by the Campuses and UC Office of the President if UC's own efforts do not achieve net zero emissions by 2025.

Figure **1.3** illustrates how these three approaches might be implemented on a typical UC campus. In our analysis, we focus on how each approach can realistically contribute to achieving the UC's carbon neutrality target. Our criteria are plausible economic viability, environmental impact, operational flexibility, scalability, inherent risks of adoption, and their feasibility within the UC's unique institutional context.

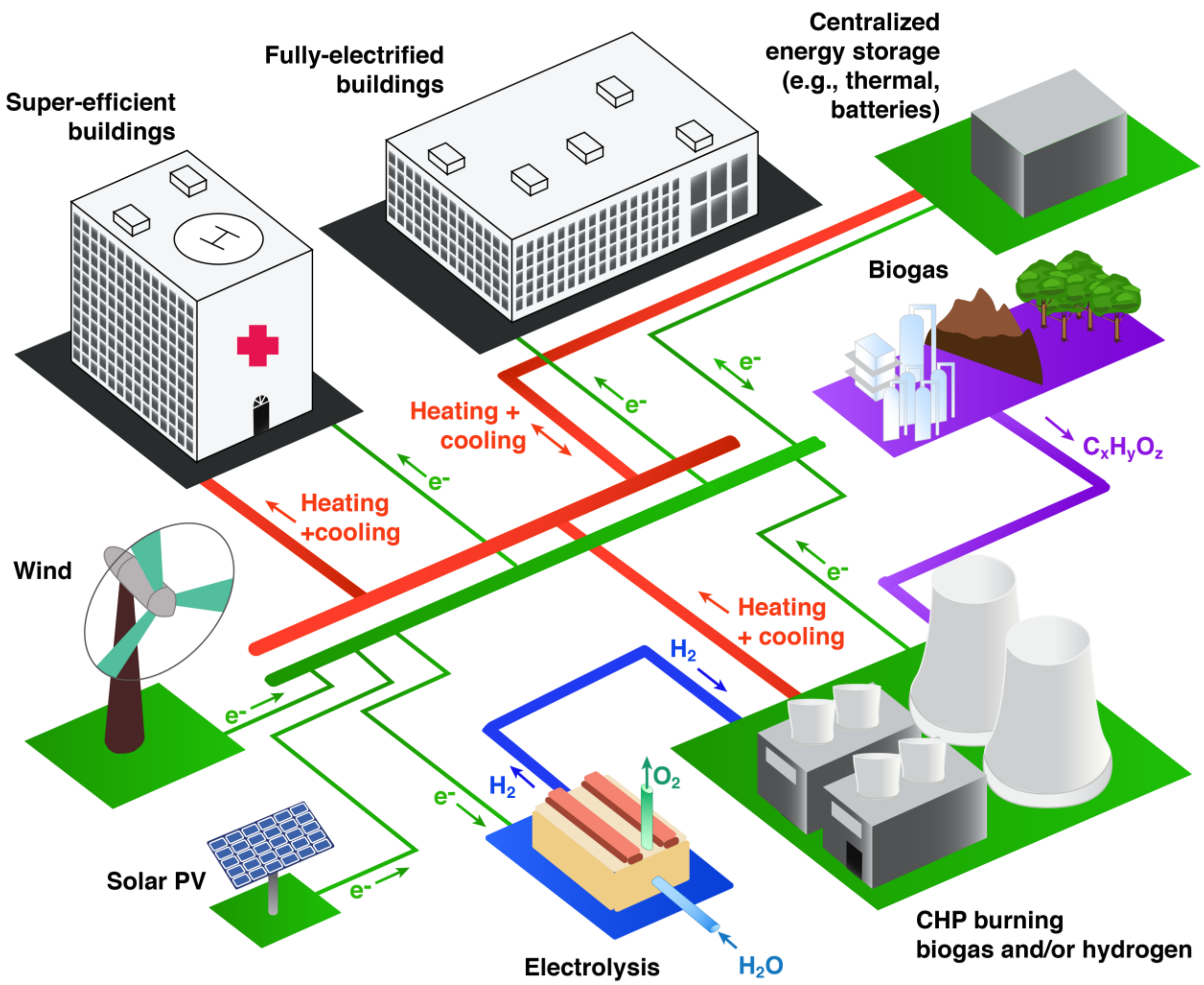


Figure 1.3. Stylized schematic of three approaches that could be implemented on a UC campus including deep energy efficiency, end-use electrification, and the substitution of renewable natural gas for fossil-based natural gas. These options complement one another, and can dramatically reduce natural gas emissions across the UC system. Chilled water thermal storage is already common on UC campuses. This will likely be supplemented with emerging battery technologies, plus possibly hot water and hydrogen as other energy storage modes. Storage enables and sometimes synergizes other approaches, for instance facilitating the ongoing operation of combined cooling, heating, and power (CHP) plants at a continuous level (where they are more efficient)—while sources and loads become more variable in a more diversified system. As a practical matter, wind facilities would be located off campus and power purchased via the grid; solar facilities could be on and off campus; and biogas facilities would be off campus.

Energy Efficiency: An Essential Option

All technically and economically realistic pathways to UC's carbon neutrality goal start with deep reductions in energy use because energy efficiency investments pay for themselves through lower operating costs and energy cost avoidance. Money saved can, in turn, be used for other purposes such as investing in other emission control efforts. Where energy savings are achieved through well-coordinated retrofits those interventions can also be used to address other maintenance and performance problems in older buildings, including deferred maintenance backlogs.

UC's ten campuses and five medical centers experience widely varying constraints in their potential for deeper efficiency. Central to analyzing the options is whether buildings are new or existing. For new buildings, deep energy efficiency will be critical—alongside, most likely, all-electric or nearly all-electric design, since that makes complete elimination of direct combustion of fossil fuels possible. We address the topic of electrification and in tandem, deep efficiency, for new buildings below. In this section, we focus on the much bigger issue for existing building stock: retrofits. For more on this strategy, see the Energy Efficiency Chapter.

Existing buildings and their heating, cooling, ventilation, lighting, and process systems are often inefficient. Some buildings have significant heating demands in summer to counterbalance poorly controlled cooling. These kinds of pervasive system deficiencies reflect a legacy of older technologies from a previous era when energy costs were lower and minimizing environmental impact was less central to the UC system mission. This legacy offers opportunities to significantly reduce energy use.

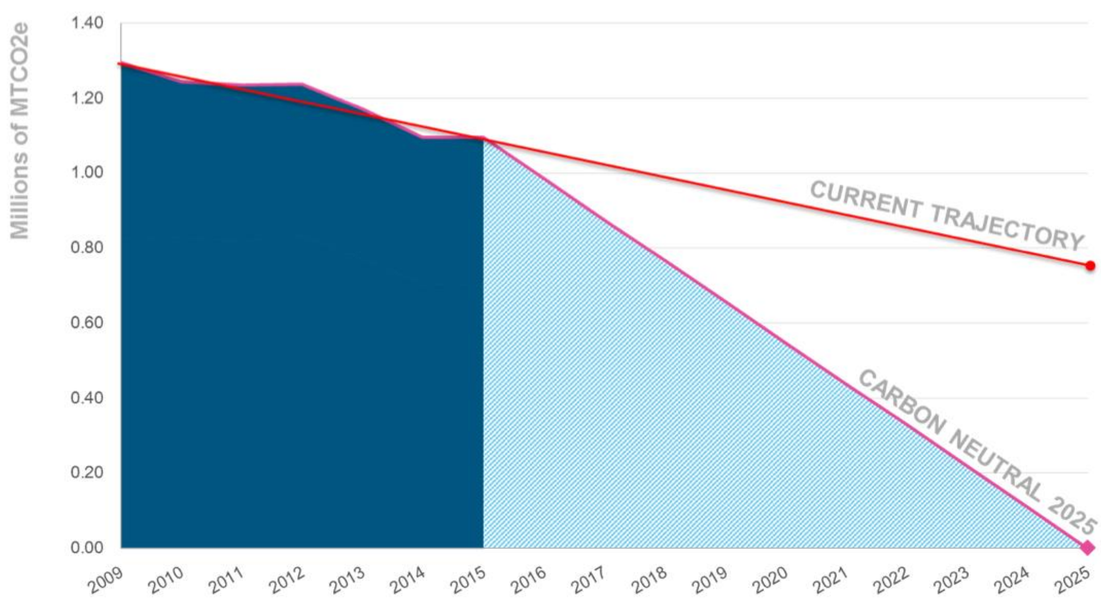


Figure 1.4. UC's recent rate of progress toward eliminating carbon from operations. Progress in bending the curve downward is anticipated in 2016 to 2018 based on solar PV coming on-line and biogas development. Additional acceleration of efforts will be required to reach carbon neutrality in 2025.

Total energy savings potential

Case studies have confirmed that deep energy efficiency retrofits have the potential to reduce by half the energy use of late 20th century design buildings (8-10), and several UC campuses have considerable experience in this arena. Through retrofit projects implemented since 2004, UC has reduced GHG emissions by an amount equivalent to 13% of total 2015 Scope 1 and 2 emissions (11). Most of this reduction has occurred since 2009, during a period when overall UC emissions began to decline (Figure 1.4). One campus, UC Irvine, has reduced energy consumption at a rate twice the system average.

Relative to 2015, we estimate that further cost-effective retrofit efficiency improvements could cut UC electricity use by 38%, and natural gas by 29%. Electricity savings translate into natural gas savings by reducing the need for electricity from gas-fired CHP plants. Most electricity savings would come from improved efficiency in lighting, laboratory ventilation, and general HVAC retrofits. Demand reduction associated with some retrofits will also reduce costs, often in conjunction with energy storage (12). Most natural gas savings would likely occur through general HVAC retrofits and monitoring-based commissioning. Although some campuses have experience with deep retrofits of individual sub-systems, such as adaptive LED lighting, institutional experience retrofitting multiple, interrelated building sub-systems, such as converting conventional labs to "smart labs," is more limited. In 2009 UC introduced bond-based internal loans to finance the bulk of energy efficiency retrofit costs. Continued debt financing, a logical funding option, can be constrained by campus debt limits and by the fact that there are many competing uses. Recommendations for overcoming barriers to energy efficiency are discussed in depth in Chapter 2 of this report and in the report of the Carbon Neutrality Initiative Finance and Management Task Force Report (www.ucop.edu/carbon-neutrality-initiative).

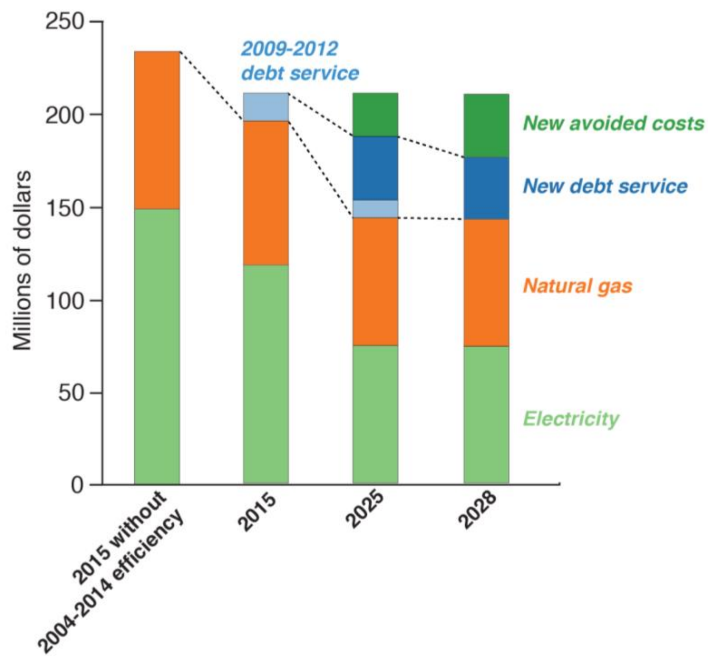


Figure 1.5. Energy budget for existing UC buildings, illustrating potential savings from energy efficiency that could be reinvested in decarbonization for: a derived baseline case, 2015 without 2004-2014 energy efficiency projects; 2015, based on billed usage; 2025, the target date for carbon neutrality under the CNI; and 2028, at which point debt service for 2009-2012 cohort of EE projects will be fully retired. Estimated and projected avoided energy costs generated by energy efficiency projects in existing buildings total ~$24M net of debt service already captured from 2004 to 2014, and an additional potential ~$22M in 2025 and ~$33M in 2028. See Energy Efficiency Chapter.

Economics of energy efficiency

Unlike other approaches that can increase costs, well planned energy efficiency improvements will reduce net costs. Furthermore, the financial gains from energy efficiency (e.g., as seen in Figure 1.5) may be used to underwrite a significant fraction of the cost premium for decarbonization options (biogas and electrification, discussed below). For this reason, cost-effective, discrete actions to reduce energy consumption are always attractive and always the first, best option.

Biogas: A “Drop in” Option

As noted above, approximately two-thirds of UC’s systemwide CO_2 emissions result from burning natural gas. Seven of the campuses currently operate central combined heating and cooling power plants (CHPs) where natural gas is burned to generate electricity and cogenerate building heating and cooling. Two thirds of UC’s natural gas consumption occurs in these CHP facilities. Campuses with and without CHP plants additionally use natural gas to produce distributed electricity, steam, and hot water. Steam is very useful for high-heat applications such as sterilization in labs and medical facilities, and natural gas consumption can be intensive in these types of applications. In this section, we discuss the technical capabilities and issues related to replacing natural gas with a variety of “renewable fuels”, which include biogas, hydrogen derived from renewable sources, renewable fuels, and other fuel types. However, the overwhelming majority of renewable fuels will, in the short run, be biogas. For additional detail on this strategy, see the Biogas Chapter.

In the interim before eventual retirement of CHPs and electrification of buildings, two methods are under consideration to decarbonize natural gas. One method is to replace fossil natural gas with biogas. The other method is to lower the CO_2 content of natural gas by injecting it with hydrogen. Both options are discussed below, following an overview of biogas production and current use of natural gas at UC.

What is biogas?

Biogas, also known as biogenic methane, is produced from the anaerobic decomposition of organic materials such as manure, food waste, agricultural wastes, some crops grown for biogas, fermentable landfill materials, and biosolids at wastewater treatment plants. These high moisture materials are considered the most suitable sources of biomass for anaerobic decomposition. Once conditioned to remove impurities like CO_2, water, sulfur (H_2S) and heavy metals, this biogas is essentially identical to utility-compliant fossil natural gas and can be substituted directly for it.

Organic materials, such as wood, that are higher in dry matter, can be used to produce biogas by thermochemical technologies like gasification and pyrolysis. Suitable feedstocks for gasification systems in California include dead trees and other woody materials that are removed from natural forests as part of wildfire prevention programs, orchard and vineyard removals, and urban tree removals. The gases derived from thermal gasification of biomass are not yet commercially viable in the United States but can be used to produce hydrogen, methane, or liquid fuels. Some pilot facilities that use diverse gasification technologies are in development in California (13).

Although chemically essentially identical to conventional natural gas, biogas is considered carbon neutral because it is a renewable resource whose carbon content derives from plant matter that fixes carbon from atmospheric CO_2. In contrast, burning fossil natural gas transfers carbon once stored in a geologic reservoir to the atmosphere. Harvesting biogas from landfills can also help to reduce the amount of methane escaping from these facilities into the atmosphere.

In recent years, there has been extensive attention to methane leaked and vented during production of conventional fossil natural gas. This source of emissions is important because small amounts of leaked methane can offset the advantages that natural gas has over other fuels, such as coal, and make natural gas even less attractive as a fuel in settings, such as California, that are aiming for big reductions in warming emissions. At present, no comparable literature exists on emissions from venting and leaking during production and transmission of biogas. A full life cycle accounting of all emissions associated with biogas must be conducted. Only biogas sources that reduce GHG emissions significantly compared to fossil natural gas are of value.

UC's current investment in biogas

The UC system is already a consumer of biogas at multiple campuses. For example, UC San Diego purchases biogas credits from a sewage treatment plant on Point Loma, about ten miles away. Biogas from the plant is injected into the natural gas pipeline system on Point Loma where it displaces conventional gas; UC San Diego then draws conventional gas to power a fuel cell. (The credits allow the fuel cell to qualify as a renewable energy source, earning valuable financial treatment under California policy.) UC has committed to procure biogas up to 50% of current natural gas use, if available at prices that meet UC's established price thresholds, and has already executed two agreements to obtain biogas credits out of state. UC has already executed two agreements to obtain biogas credits out of state. In the first project, UC is constructing a biogas facility in Louisiana adjacent to an existing landfill. This UC-owned facility will collect landfill gas and treat it through a processing facility, after which the biogas will be injected into an interstate natural gas pipeline. In the second project, UC has an offtake agreement with a biogas facility near Green Bay, Wisconsin, under which the university has agreed to purchase biogas generated from the anaerobic digestion of organic waste from local food processing streams. At full capacity, these two 20-year agreements will supply carbon-neutral fuel to offset 10% of all natural gas currently burned on UC campuses.,

Availability of biogas

Biogas credits (and perhaps direct combustion of biogas if produced near UC campuses) is a drop-in option today, but does it scale? The National Renewable Energy Laboratory estimates that the current biogas resource in the U.S. would satisfy only about 1.5% of the nation's total natural gas consumption (14). However, today's market is new and rapidly evolving, and there is substantial evidence for supply elasticity. Biogas producers respond — up to a point — to consumers' increased willingness to pay. As in all new markets, there are structural barriers and policy issues that limit significant expansion in biogas supply. In the long-term, stable price signals and policy certainty may convince producers and policymakers to overcome these barriers and expand supply (15).

Through an open solicitation process, UC Office of the President has determined that sufficient additional biogas resources are available to meet UC's needs. Therefore, the UC system should be able to offset its natural gas consumption and emissions using biogas in the short term, once appropriate pricing is negotiated. But is this a scalable solution beyond UC? The size of the current biogas resource in the U.S. suggests that biogas can only play a small role in the nation's long-term decarbonization strategy. To expand its use, structural changes, such as dedicating substantial land and other resources to biomass cultivation and gasification, would be needed—options that will, themselves, have environmental implications that need further investigation. Biogas thus can play a niche role as part of a larger decarbonization strategy but, by itself, is not a scalable replacement for all current natural gas used.

That niche role may, nonetheless, be very important since it may be infeasible to replace natural gas in some of its current uses. It may be preferable to continue operating CHP plants through their useful life rather than retire them prematurely, given their efficiency and the cost of replacing them.

De-rating or “turning down” CHP plants by as much as 40% may be possible at some campuses, offering a possible transition from total reliance on CHPs to all-electric operation. However, this strategy requires a campus-by-campus evaluation because there are likely to be unique impacts on emissions, thermal efficiency, and other costs.

Hydrogen as a longer term complement to biogas

Production of hydrogen from renewable energy sources can complement biogas use and provide a useful mode of storage in the short-term. In the long-term it might serve as the primary means of sustainably producing and delivering renewable fuel. At the same time, such renewable production of hydrogen can support more thorough adoption of renewable electricity (solar and wind) in the electric utility grid network. All of this can be accomplished by using renewable electricity—that would otherwise be curtailed during periods of peak supply—to make hydrogen energy carrier by electrolysis.

The hydrogen might be used as a limited partial supplement to natural gas in conventional cogeneration turbines, used directly in fuel cell cogeneration, or used as a transportation fuel. The storage capability could augment a campus’ ability to provide lucrative ancillary grid services.

One challenge to such an integration of hydrogen into campus energy systems is the relative inefficiency of a renewable energy-to-hydrogen-to-cogeneration fuel cycle. This makes sense primarily when the energy is truly surplus or the storage function has high value. Another challenge is integrating hydrogen with the existing natural gas infrastructure. Above a few percent concentration, there are concerns that hydrogen might corrode seals and embrittle materials; current natural gas-burning technologies such as turbines are not typically rated (or warrantied) for use with high concentrations of hydrogen. Technically, these problems are solvable, but solutions may require replacement of infrastructure at unknown cost.

Electrification: The Ultimate Option?

The third major action that can be taken to reach carbon neutrality is to replace conventional natural gas with carbon-free electricity. In tandem with UC-wide and California-wide efforts to reduce emissions from the electric power system, electrification has already begun on several UC campuses, and UC has committed to procuring green energy, including its opening of an 80-megawatt solar power installation to supply roughly 10% of the total UC system’s electricity usage and 20% of direct purchases. Other universities, such as Stanford University and University of British Columbia (UBC), have also begun more ubiquitous electrification, although differences in context may limit application of their specific strategies to UC. UBC, for example, is located within a power grid that has large amounts of essentially emission-free hydropower. The cost of Stanford’s actions appears to have been high and beyond what the UC system can afford. For additional detail on this approach, see the Electrification Chapter.

Assessing electrification projects

To pursue electrification incrementally, the first step is to ensure that as campuses construct new buildings, the buildings do not require natural gas. The electrification potential of existing buildings will depend upon current hot water and local gas use and how amenable those uses are to substitution according to the size of opportunity, efficiency or practicality of the electrical substitute, cost-effectiveness, and the implications of existing campus infrastructure.

Heat is the defining problem for electrification

The defining problem for electrification analysis is the use of electricity to provide heat at different temperatures. At most UC campuses, heating is the most-carbon intensive service provided, the largest fractions of GHG emissions and the most significant opportunity for electrification.

The simplest way to turn electricity into heat is by flowing electricity through a resistor, which can provide any temperature required at a university campus. That option can be costly, however, since most options for generating electricity are expensive relative to natural gas for producing heat. An alternative, using electricity to run a motor that drives a "heat pump" that moves available heat from a lower to a higher temperature, uses less electricity. Today's heat pumps add cost and complexity, are usually limited in their ability to provide high temperature heat (e.g., for sterilization uses), and often use refrigerants that have significant global warming potentials. Some of these problems—such as refrigerants—are readily addressed, but most others require significant improvements in technology.

Typical campus building heating scenarios can be broken into three categories:

1. Campuses with central steam or high-temperature water distribution systems
2. Campuses with central low-temperature water distribution systems
3. Campuses or portions of campuses that use local (e.g., single-building) natural gas combustion for heating

Each scenario presents different opportunities and challenges for electrification (Figure **1.6**). One key consideration associated with steam or high-temperature water distribution systems is that high-temperature heat pumps are not yet a mainstream technology, and transitioning these distribution loops to low-temperature heat pumps and low-temperature water distribution can lead to heat exchanger sizing issues in existing buildings (i.e., heat exchangers sized for high temperatures are too small for low-temperature water) or pipe sizing issues in distribution systems. Energy efficiency has a major role in these situations to reduce the loads seen by heat exchangers and distribution systems. Energy storage may also play a role in managing retrofit scope.

Local booster heaters (Figure **1.6**, right hand column) could be used to address high temperature requirements in buildings served by undersized heat exchangers. In considering the various options for all three types of installations, other key considerations are the availability of space and the need to increase the capacity of the electrical service to ensure reliability. In addition, there are other local applications of steam, high-temperature water or natural gas combustion that require high temperatures. UC Berkeley compiled a list of gas and steam devices in buildings they are targeting for electrification (Table 1.1). Electrifying these "orphan loads" can be challenging in some cases. The local booster heaters shown on the right side of Figure **1.6** offer various ways to handle high-temperature needs for orphan high-temperature devices.

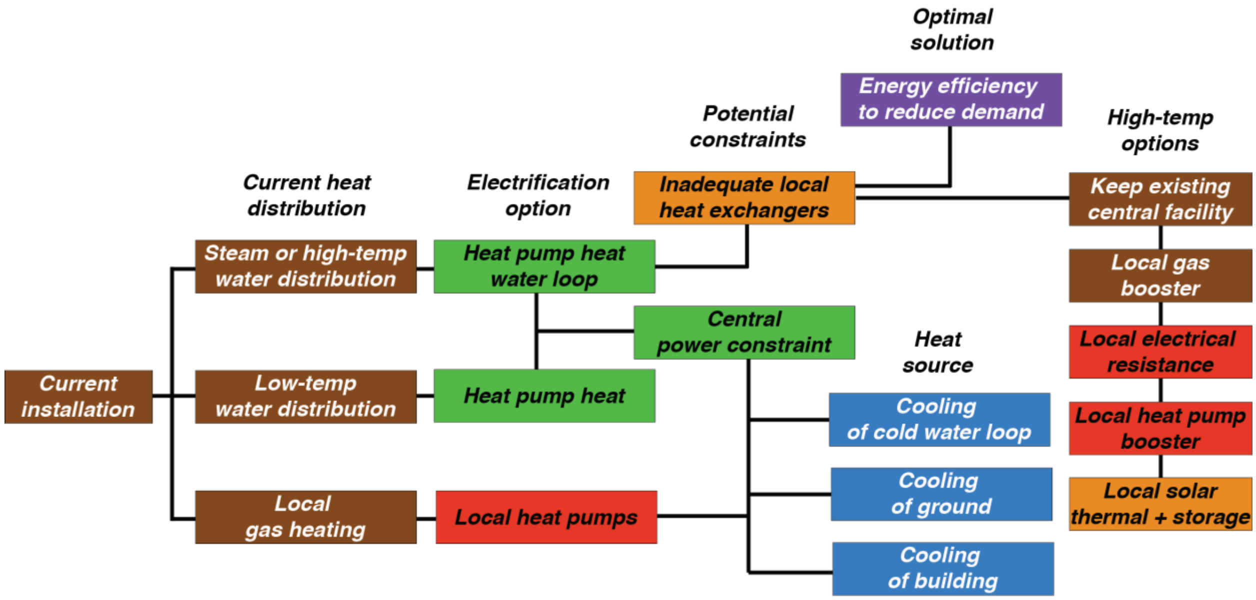


Figure 1.6. Classification of electrification opportunities for building heating on university campuses. Nodes are colored according to whether they involve natural gas combustion (brown), central electrification (green), local electrification (red), cooling (blue), energy efficiency (purple), or other miscellaneous options (orange).

Cooling as "heat collection"

When "cooling" is viewed as "heat collection," campus cooling systems present an intriguing opportunity for increased efficiency and cost savings through low grade heat recovery with a central role for electricity and water as energy carriers.

In a typical district cooling system, chilled water supply lines deliver cooling energy to buildings via low-temperature chilled water. Cooling coils in building air handlers extract heat from the building air distribution systems, and chilled water return lines send that heat energy back to the central chiller plant(s). At the central plant, the chiller system sends the collected heat into the atmosphere and then sends lower-energy chilled water back to the buildings to collect more heat energy.

Table 1.1. "Orphan" Steam and Gas End Uses (Compiled by UC Berkeley)

Steam Uses	Gas Uses
Autoclaves	Kitchens/cooking
Absorption chillers	Kilns
Animal care/cage washers	Bunsen burners
Bottle/rack washers	Residential wall heaters, hot water
Dish washers	Laundry facilities/dryers
Library humidification	
Clean steam generator	

A campus with a steam district heating system has a high-energy heating system that cannot effectively use recovered heat from a low energy chilled water system. This is one of the reasons that many campuses have begun converting their steam district heating systems into hot-water district heating systems. The lower temperature and lower energy hot-water system can then be effectively coupled with a chilled water district cooling system for heat recovery. That is, the heat recovered from the buildings in the chilled water system can be used as a heat source for the hot water district heating system through the use of electric heat recovery chillers (i.e., heat pumps) instead of standard chillers that reject heat to the atmosphere via cooling towers. While the heat pumps can be located centrally and serve hot water to the buildings via a hot water distribution system, an alternative concept distributes the heat recovery chillers throughout the campus at the building level and significantly reduces the amount of new hot water distribution piping required. Given the high cost and complexity of installing a new hot water piping distribution system throughout a campus, a distributed heat pump system appears promising and offers a feasible path for electrification of campus heating systems. Use of heat recovery chillers (water-source heat pumps) to make use of heat in the chilled water return lines is also a viable electrification strategy for buildings not connected to a central plant.

A new 80,000 square foot genomics laboratory is under construction at Lawrence Berkeley National Laboratory that uses heat recovery chillers, air-source heat pumps, and point-of-use electric heat to provide all space and water heating needs without the use of natural gas.

Stranded Assets

The faster the rate of electrification, the more assets that may be stranded—retired before their economic operating life has ended. In the case of UC, the assets at the greatest risk of being stranded are the large CHPs, but also other gas-burning infrastructure such as furnaces, boilers, dryers, pipeline networks, etc. For campuses with central heating facilities, the supporting system of pipes installed to deliver the heat are another asset that may be stranded. These stranded assets are financial losses on the books of the campuses that own them, but the losses will be partially or fully offset by financial gains from operating savings and avoided environmental impacts.

From UC's perspective, the ideal strategy to avoid stranded assets would be to replace gas-fired equipment with electric alternatives at the end of their economic lives; however, given the long lifetimes of gas-burning infrastructure, normal retirement schedules are inconsistent with the desired rapid decarbonization (i.e., by 2025). Thus, stranded assets cannot be avoided, but the costs can be minimized. For example, strategic procurement, that is, anticipating replacements and coordination with other renovations, can dramatically lower costs.

Key conclusions about electrification

After exploring the electrification option to replace natural gas use we conclude:

- A critical issue for electrification of heating is the temperature required for the end use. The maximum temperature provided by heat pumps is limited and may not be sufficient for some applications. Higher temperature heat pumps are beginning to emerge on the market, but are not yet widely available.

- New buildings are typically the easiest to make all electric. A recent cost study conducted for UC assesses first costs for all-electric construction to be generally neutral relative to gas-based construction—within the uncertainty of the cost estimation process (16). We envision and recommend a shift to all-electric designs for new building construction that cannot be connected to a CHP plant, an option that is consistent with the UC Finance and Management Task Force's recommendations.

- Electrification should be evaluated for new buildings that are connectable to CHP plants, in the context of integrated campus planning for future buildings, energy efficiency, and carbon neutrality.

- Existing stand-alone buildings are generally more cost-effective to decarbonize through electrification than existing buildings connected to central heating loops based upon combined heat and power.

- Gradually disconnecting buildings on the periphery of the central heating distribution system — "pruning" — is a good strategy, particularly for central systems that are at or near capacity.

- The different techniques available to address high-temperature applications served by under-sized heat exchangers or to address orphan loads (e.g., cage washers, sterilizers) should be evaluated and compared. High-temperature heat pumps should be included in such an evaluation.

- As dependence on renewables has grown, so have concerns about reliability of electricity delivery. Increased use of storage technologies, including batteries, can help address those concerns. Battery costs have declined substantially and are expected to continue to do so in coming decades.

Toward Leadership in Deep Decarbonization

The UC Carbon Neutrality Initiative is in its early stages and much work remains to be done, particularly in the quest for alternatives to natural gas. This effort must proceed with twin goals in mind:

- **Embrace the challenge of transformation.** The first goal is to fully embrace the challenge of achieving carbon neutrality in the UC system by 2025, with ongoing transformational effort by students, staff, and faculty. We have identified a promising short-term path, with the longer-term path more uncertain. The University of California is well-positioned to build on more than a decade of progress in energy efficiency and more recent steps to develop renewable electricity and biogas supplies. Where the greatest barriers are revealed, it is imperative to continue to proceed in a manner that creates new information about emission reduction options and has the potential to generate new pathways towards the carbon neutral goal. University of California's approach is consistent with a branch of industrial organization and regulation theory that examines how real world organizations tackle difficult problems (17). Research demonstrates that organizations separate seemingly "wicked" and intractable problems into more tractable components, implement options (in effect, "experiments") to test ideas at small and system scales, and then learn rapidly what works or might be possible. This "learning-by-doing" approach emphasizes exploratory and pioneering efforts toward organizational transformation and will benefit the UC system and society as a whole as we proceed to meet climate targets.

- **Pursue scalable solutions.** The second goal is to pursue solutions that are transferable and scalable or that forge new paths whenever possible and to document and communicate the results of our experimental approach. In keeping with its history of leadership in this area, UC must advance its carbon neutrality strategy in ways that offer models that can be leveraged to support decarbonization elsewhere in the world, because solving the climate problem requires a global effort. The Paris agreement signals a global approach to energy transformation and emission controls, with each country and subnational jurisdiction developing its own plans and learning — hopefully rapidly — what works and scales. Robust information about successes and failures in the UC system, disseminated rapidly, can help that global effort. The diversity of different infrastructures and approaches allow UC to demonstrate leadership on many fronts with many different strategies.

In pursuing these two goals, UC should be guided by three clusters of insights that emerge from our analysis and are already apparent in UC's planning for a low carbon future:

Insight 1: There is no universal solution, but there are three key building blocks.

First, there is no universal or optimum strategy to achieve near zero emissions. Solutions will differ in their nature and efficacy, and strategies that achieve substantial emission reduction in one setting may well prove economically or environmentally inappropriate in another, or may prove institutionally infeasible. UC and other organizations must continue to experiment with decarbonization strategies and share findings. Even in the absence of a universal approach, we believe that the three strategies identified in this report (energy efficiency, biogas and electrification) occupy a substantial part of the solution space available to large campuses, including the UC system. These three strategies are not mutually exclusive: indeed, they can and should complement one another if actuated with careful planning and execution. Federalist planning in the UC system can be a strength because it allows each campus to tailor its own solutions — provided that the UC system as a whole sets common goals, creates systems for sharing best practices, and facilitates collective efforts when necessary to create scale.

Insight 2: Efficiency, biogas and electrification are complementary

Second, our analysis reveals the existence of a set of solutions that are strongly complementary (Figure 1.7). Deep energy efficiency is an essential option which must be pursued at scale to the limit of its cost effectiveness. It is a significant part of the solution on all campuses — one that can reduce utility costs and offset increased costs that may be associated with biogas or electrification. For many campuses, efficiency can fully offset the price premium of biogas by 2025 as ongoing efficiency and longer-term electrification strategies are pursued. For campuses with CHP plants, deep efficiency must be pursued with an eye to the impact on operations and cost. Clearly, these campuses as a group face distinct options and strategies from those that don't have CHP systems. In this context, the availability of biogas may be particularly important since that allows continued operation of CHP units at cost-effective levels while still decarbonizing energy services.

In tandem with deep efficiency and appropriate uses of biogas, the options around electrification are essential to deep and sustained decarbonization across the whole UC system. Electrification is relatively easy for new construction and relatively difficult for retrofit of existing building stock. For new construction, electrification offers substantial flexibility for decarbonization, and the costs appear to be within the uncertainty in cost estimation practices. For the existing building stock, more calculations are needed to assess the value of overhauls and retrofits. The UC system can help establish metrics and demonstrations for doing those calculations.

Insight 3: Uncertainty remains but can be managed

A path toward carbon neutrality is emerging for UC, however uncertainty remains as to the best path to address the last 15% of emissions and post-2025 migration of infrastructure (Figure 1.7). The cost, performance and institutional feasibility of each of the strategies we have explored are not fully characterized nor fixed. For example, it remains unclear the degree to which biogas should be scaled up to mitigate natural gas emissions across the UC system as a whole. Replicability and scalability issues have been raised, but the prevailing internal view seems to be that UC's strong contribution to the development of biogas markets overshadows these concerns. In the longer term, we expect the full electrification of many UC facilities to be expensive, although emergent energy technologies may alter that assessment as experience mounts. More research and experimentation will be needed to close these uncertainty gaps.

The potential effects of this uncertainty are evident in Figure 1.8, which illustrates annual emissions of CO_2 from combusted natural gas and biogas (although emissions from the latter are assumed to be carbon neutral) for the UC system over time into the future. In the top scenario, there are modest improvements in efficiency, but greater barriers to GHG reduction for the largest campuses with CHPs that must continue to run at a large fraction of capacity. In this scenario, the building electrification option also proves expensive outside of a limited number of applications, such as new buildings. In that scenario, most mitigation of natural gas GHG emissions consists of substitution by biogas (or other forms of decarbonized gas). The bottom panel shows an alternative view of the future in which deeper efficiency is achieved as organizations learn and experiment with CHP plant turndown. Costs decline and building electrification becomes widespread. In that future view, the existing natural gas network's role is much diminished, and future gas uses are more readily met with modest purchases of biogas.

While the UC system is making steady progress towards carbon neutrality, it is clear that some applications will be more difficult to decarbonize through electrification. Loads that may be especially stubborn include laboratory and other science and engineering uses such as autoclaves and animal cage washing on some campuses. The difficulties associated with electrifying these sources go beyond technical performance and cost to include space availability, contractual obligations, a general resistance to changing research and medical equipment and the costs of doing so. Quickly changing infrastructures that have well-served their intended purposes is difficult. Understandably, organizations are often reluctant to "fix" things that already seem to work.

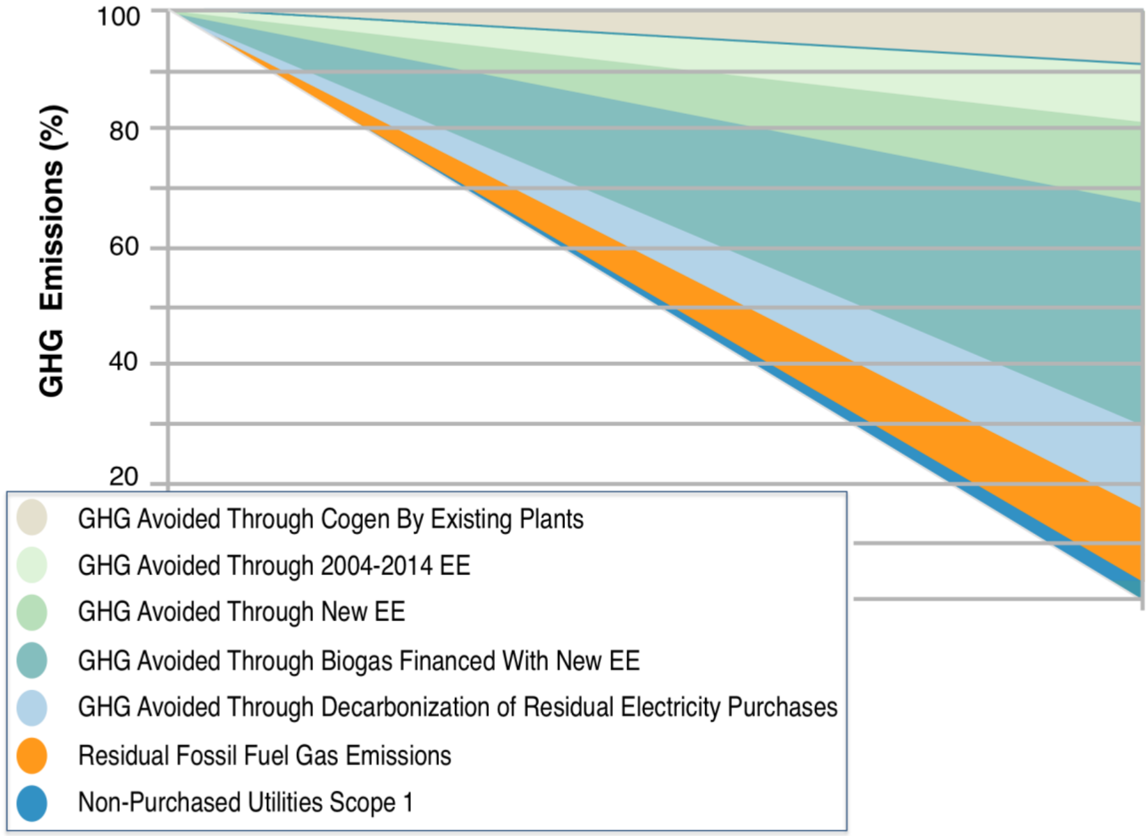


Figure 1.7. UC systemwide Scope 1 and 2 GHG emissions through time, illustrating the near-term strategy of financing biogas with energy efficiency savings in the context of some other actions. Wedges represent respective contributions to the goal of carbon neutrality of UC's actions: cogeneration in-place, 2004-2014 energy efficiency, new energy efficiency, and biogas that could be financed by new energy efficiency. An additional contribution from assumed decarbonization of electricity purchased from the grid is also shown. These collective approaches could potentially reduce UC's Scope 1 and 2 carbon footprint by 84%, leaving 16% residual from fossil fuel-based natural gas and other Scope 1 emissions. Electrification and other approaches explored within this study may be able to further reduce residual emissions.

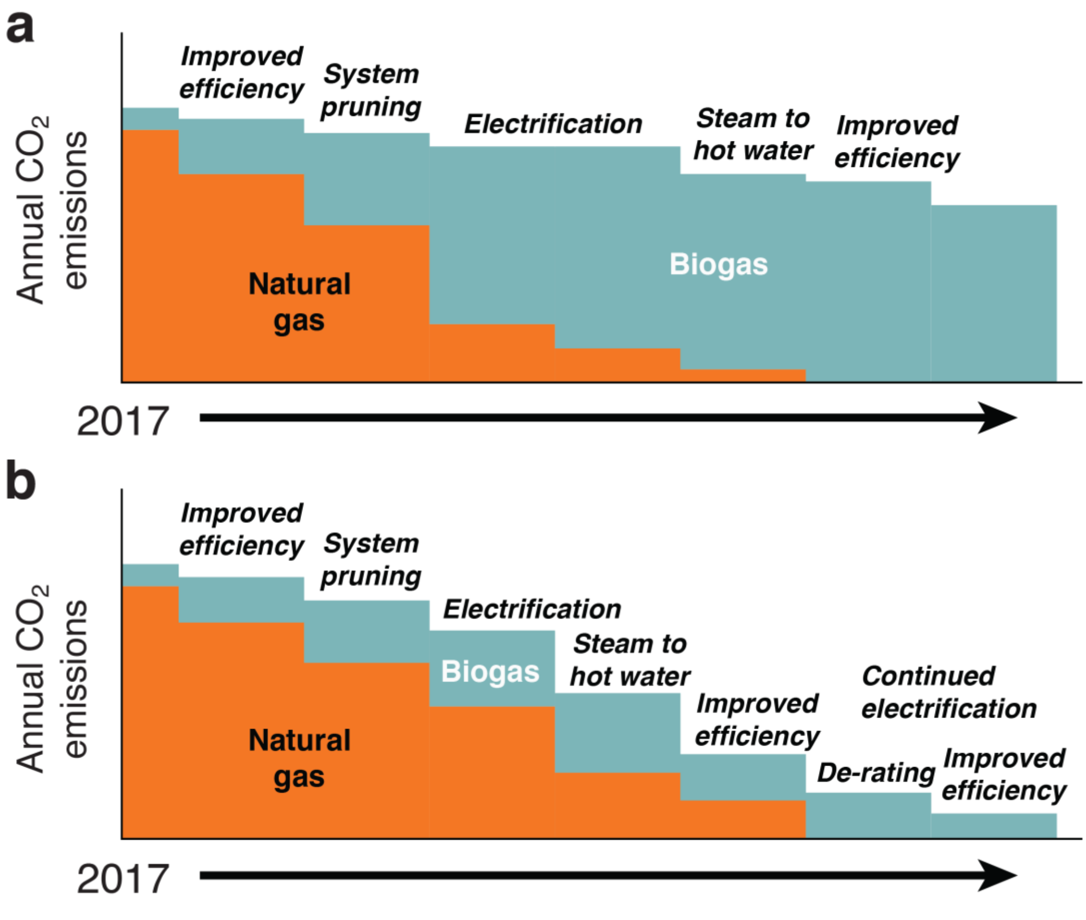


Figure 1.8. Schematic of two decarbonization scenarios. They unfold over time based on electrification with biogas used in place of natural gas. **(a)** A scenario where there are greater difficulties with electrification and moving beyond reliance on a CHP, leading to much higher ongoing reliance on biogas. **(b)** A scenario in which electrification proceeds more smoothly, for example through pervasive use of heat pumps, and a reduced ongoing reliance on biogas. Note that both scenarios rely on persistent and significant improvements in efficiency.

Conclusion

The University's carbon neutrality goal is ambitious, but attainable. UC must build on its substantial achievements but also continue to embrace bold and creative experimentation to accelerate, scale and protect advances in meeting is goal. The university is managing the big levers well by focusing on energy efficiency, securing biogas supply, investing in renewable power generation, and pioneering electrification retrofits and new building designs. Two strategies will facilitate its expanded efforts. First, UC should ensure that it keeps systemwide and campus-based processes aligned with an overall strategy that is attentive to long term costs and feasibility. It will be easy, as this process unfolds, to focus on the options that are close at hand. But deep decarbonization requires attention not just to what is doable now but also gaining the information and experience needed to make distant options—such as pervasive electrification—a reality in the future. The UC system should ensure that there is a dialog between the focused processes of implementation today and the broader strategy for what the system is attempting to achieve overall. That implies extensive measurement, scrutiny of options, and continued willingness to experiment with unconventional options.

The other strategy involves transparency—extensive documentation and communication so that the rest of the world can see and learn from what we are doing. Transparency allows others to find fault, but it also enables us to more quickly benefit from new information, technologies, and experience. University researchers can greatly enhance documentation and communication. The ability to respond rapidly is critical to slowing the rate of climate change.

Chapter 2.
Deep Energy Efficiency as the Foundation for Decarbonization

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Chapter 2 Contents

2.0 Energy Efficiency

In this chapter, we discuss the role and critical importance of energy efficiency in decarbonization. We demonstrate how cost savings from energy efficiency can be used to finance other aspects of decarbonization, such as the higher cost of biogas, a near-term strategy for decarbonizing fossil natural gas. We review UC's energy efficiency gains thus far and look at the current remaining energy efficiency potential on UC campuses. We also describe energy efficiency financing variations. We then explore the results of our analyses in the context of a full set of campus energy efficiency cases, present the UC system roll-up for this approach, and discuss optimization of combined heating cooling and power plants (CHP). Finally, we summarize our findings and present six recommendations for getting to scale with energy efficiency.

2.1 The Role of Energy Efficiency

Reduction of energy use through energy efficiency is the foundation of climate change mitigation strategy. Leading edge case studies have confirmed that deep energy efficiency can directly address half of greenhouse gas (GHG) emissions in existing (8, 10, 18) and new buildings (8, 9, 19). The path to halving overall building energy use through efficiency includes developing organizational support and confidence for implementing and valuing energy efficiency, and getting to scale for retrofits.

Energy efficiency is first in the loading order for GHG reduction because it is often a least-cost option that creates a neutral or positive cash flow. Energy efficiency measures lay the foundation and mitigate costs for other strategies to reduce Scope 1 and 2 emissions by:

- Reducing potential operating cost increases associated with electrification
- Reducing capital costs of electrification through load reduction
- Creating a potential source of positive cash flow to fund other emission reduction efforts (such as the "biogas premium" discussed in Section 2.1.1.)

Energy efficiency retrofits can also address maintenance issues and extend the life of building systems.

UC is already farther down the energy efficiency path than much of the rest of the world or even California as a whole. In 2004, UC launched an aggressive campaign to reduce energy use through a groundbreaking pilot partnership with energy utilities. In 2009, this program was supplemented by an innovative bond-based loan financing program (the CA Statewide Energy Partnership). The utility partnership includes sharing of best practices and statewide coordination among both UC campuses and utilities, and was complemented by demonstration of new technologies (20). The loan program recognizes the value of energy efficiency, integrating it into campus utility budgeting. These are examples of the exploratory and pioneering approach that has characterized UC's climate action progress.

Between 2004 and 2014, more than 600 projects in existing buildings reduced energy use by 240 million kWh per year of electricity and 15 million therms per year of natural gas (or cogeneration output equivalent). Most of this reduction has occurred since 2009 in a period where systemwide Scope 1 and 2 emissions dropped due to a combination of energy efficiency, renewable energy development, and reduced electricity emission factors (Figure 2.1). Overall emissions went down in this period even as UC grew in enrollment, research activity, and campus footprints. Emissions in 2015 would have been 13% higher without the 2004-2014 energy efficiency retrofits (11). These projects are currently avoiding $24 million[1] in energy costs annually, net of debt service, and there is considerably more potential for carbon mitigation and cost savings through energy efficiency (21). Some energy efficiency projects will result in cost reduction through management of electric demand – often with assistance from energy storage – in addition to energy use reduction. This will likely be complemented by energy storage projects creating synergies with other aspects of decarbonization.

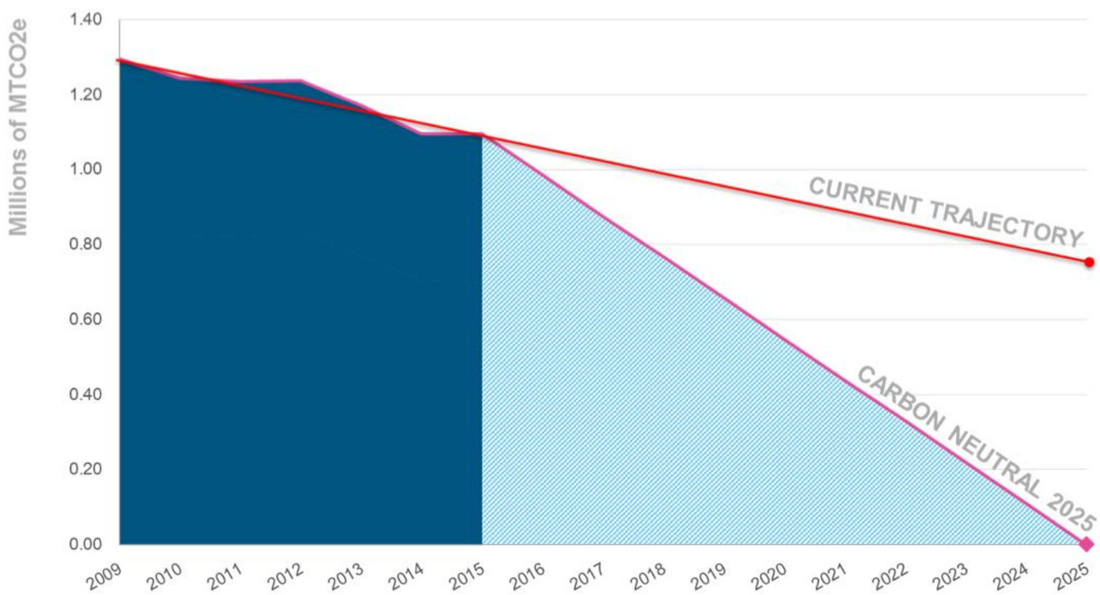

Figure 2.1. UC scope 1 and 2 greenhouse gas emissions and UC's recent rate of progress toward eliminating carbon from its operations. Progress in bending the trajectory downward is anticipated in 2016 to 2018 based on solar PV coming on-line and biogas development (which may be back-loaded to 2025, see Biogas Chapter). Additional acceleration of efforts will be required to reach carbon neutrality in 2025 (22).

The Efficiency and Optimization group of the UC-TomKat Carbon Neutrality Project undertook an evaluation of the future cost reductions that could be generated from energy efficiency in existing buildings and examined the role of energy efficiency in contributing to the decarbonization goals of UC's Carbon Neutrality Initiative. We reviewed the data from energy efficiency projects conducted from 2004 to 2014 on UC campuses and developed forward estimates of further systemwide average energy savings in four categories: interior and exterior lighting, monitoring-based building commissioning, smart labs, and heating ventilation and air conditioning (HVAC), which may be a separate project or part of a building re-commissioning or smart lab project. We identified systemwide average potential of 29% reduction in direct natural gas use or cogenerated thermal output, and 39% reduction in electricity use relative to 2015 baselines; (more detail provided in Section 2.2). We then applied these energy savings

[1] $28 million including new construction (project analysis, 2015 UC Annual Report on Sustainable Practices).

to 14 cases that generally correspond to UC campuses and medical centers (described in Appendix A). We assumed a typical capture of less than full efficiency potential. One reason is that more limited project portfolios, focusing on higher return on investment (ROI) projects, are needed to create substantial cash flow net of debt service.

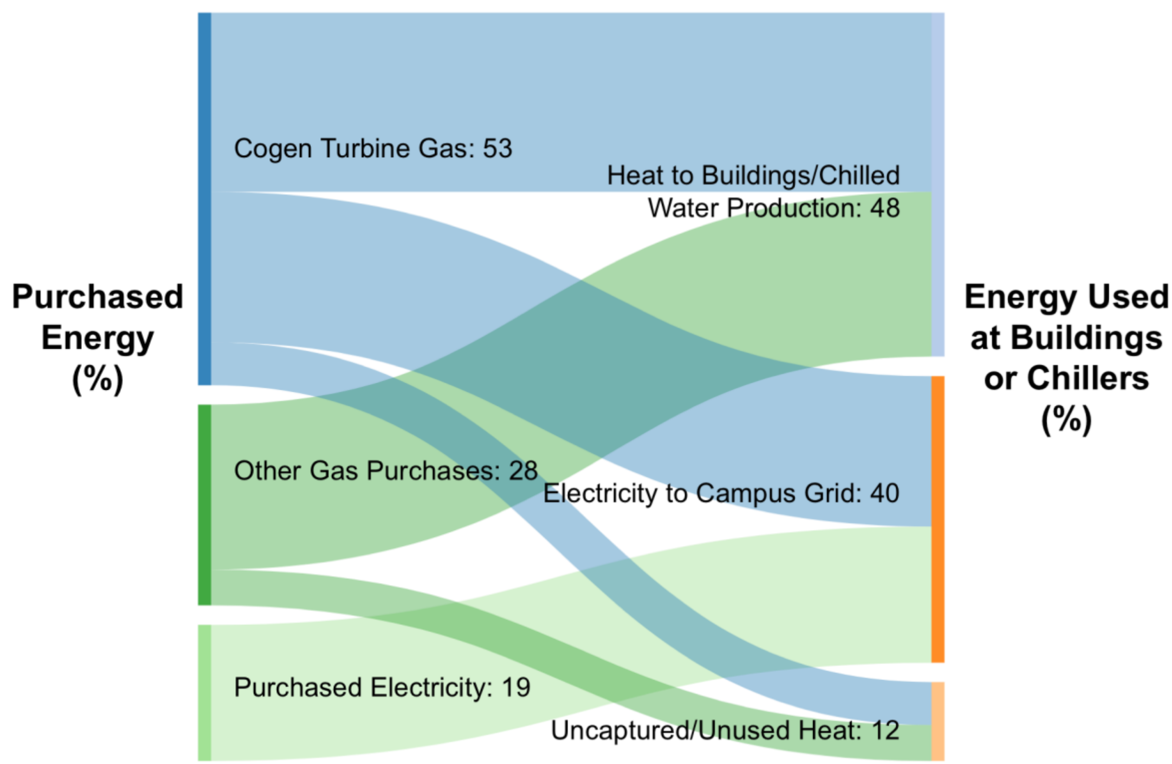

Figure 2.2. Sankey Diagram of UC 2015 systemwide cogenerated and purchased energy as percentages. This is a site energy analysis for purchased energy with natural gas converted through cogeneration or combustion into energy used at buildings or chillers. The electricity fraction is somewhat higher by GHG emissions and much higher by cost.

Another constraining factor is the lower cost of cogenerated energy. We generally applied efficiency only to directly purchased energy, which makes up half of electricity use and a similar fraction of natural gas or heat use by buildings. Figure **2.2** illustrates the overall systemwide fractions of cogenerated and directly purchased energy. Cogeneration output was not decreased in the analyzed cases, except for one campus case where such reduction is already occurring (Case I, Appendix A). When reducing use of cogenerated energy, efficiency ROI decreases sharply. There may also be operational constraints on reducing cogeneration output. (More information is provided in Section 2.6.)

Figure **2.3** provides a snapshot of key energy-related costs in 2015, 2025 and 2028 for the following analyzed scenario:

- **2015** (without 2004-2014 EE)**:** Derived baseline case, without 2004-2014 energy efficiency projects
- **2015:** 2015 costs, based on billed usage.
- **2025:** Date by which UC has pledged to eliminate GHG from its buildings and vehicle fleet.
- **2028:** Slightly longer timeframe, by which campuses will be able to benefit more from the savings created by energy efficiency, because the debt service for the 2009-2012 cohort of EE projects will be fully retired.

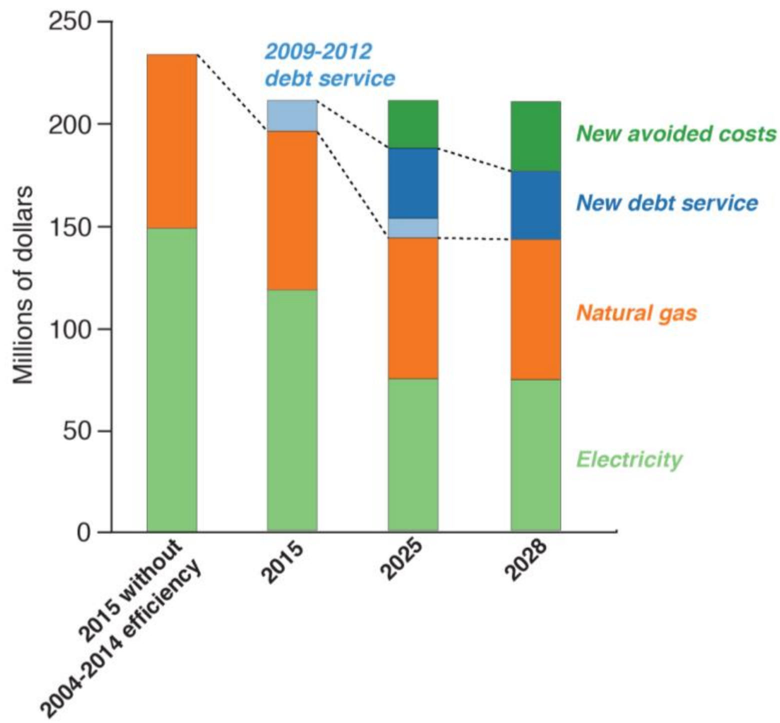

Figure 2.3. Energy budget for existing UC buildings, illustrating potential savings from energy efficiency that could be reinvested in decarbonization.

Figure **2.3** illustrates the avoided energy costs (actual and projected) generated by energy efficiency projects in existing buildings — ~$24M net of debt service already captured from 2004 to 2014, and additional potential of ~$22M in 2025 and ~$33M in 2028. This analysis includes both previous and new efficiency, and two tranches of efficiency debt service that vary within the timeline.[2]

Our primary finding is that energy efficiency is a valuable resource that has already significantly reduced campuses' carbon emissions while enabling them to avoid tens of millions of dollars in annual energy costs from purchased utility budgets. To meet the Carbon Neutrality Initiative (CNI)'s 2025 target, the

[2] Another intermediate tranche of debt service, 2013-present, does not vary within the timeline.

imperative is getting to the scale and pace necessary to capture the remaining energy-savings potential. To this end, we concur with the recommendations of the CNI Financial and Management Task Force, which also underscore the importance of energy efficiency (22).

2.1.1 Funding the "Biogas Premium"

A near-term decarbonization strategy is to substitute biogas for natural gas, as discussed in the Biogas Chapter. Biogas is more costly than natural gas, and funding for the cost difference between the two — the "biogas premium" — is needed. Our analysis of UC's remaining potential energy efficiency cost savings indicates that these savings may be sufficient to finance the cost premium of substituting biogas for natural gas.

As described above and in Section 2.2 below, we reviewed UC post-implementation energy efficiency data and other research to estimate energy efficiency retrofit potential for interior and exterior lighting, HVAC, monitoring-based building commissioning, and smart labs. Based on the circumstances present for each campus case (e.g., fraction of energy cogenerated vs purchased, purchased electricity price), we developed retrofit targets for energy efficiency, reducing energy use from 2015 levels by 4-28%, with debt service ratios of 70% or less.

We estimated that energy efficiency cost savings, combined with retired debt service for previous energy efficiency projects, could underwrite 14 to 100% of the campus biogas premium. This percentage varies primarily with the fraction of building energy use that is directly purchased vs. cogenerated by a particular campus. We typically applied efficiency only to directly purchased energy, not cogenerated energy, and we were conservative in estimating the amount of efficiency that would not impact cogeneration production (except in one case where CHP turndown is already occurring, Case I).

By 2025, six of 14 cases can fund the full biogas premium. In the UC roll-up for all campus and medical center cases, 52% of the biogas premium is funded in 2025. After the 2009-2012 debt service is paid in full in 2028, eight of 14 cases can fund the full biogas premium. Across all the UC campuses and medical centers, 75% of the biogas premium can be funded in 2028. Note that two CHP cases (Case J and Case N) may have relatively limited supplemental gas and electricity purchases that can be cost-effectively reduced by energy efficiency. These two cases account for the majority of the systemwide unfunded biogas premium in 2025.

Figure **2.4** illustrates the reductions in GHG emissions possible from deploying the near-term strategy of financing biogas with energy efficiency savings, in the context of other past and future actions. Projected reductions are compared to a pre-climate action baseline that starts in the 1970s. The wedges represent respective contributions to the goal of carbon neutrality of UC climate actions: cogeneration in-place, 2004-2024 energy efficiency, new energy efficiency, and funded biogas premium. Decarbonization of residual electricity use through increases in the supply of renewables by UC or utilities is also shown. These collective approaches can potentially reduce UC's Scope 1 and 2 carbon footprint by 84%, with 16% residual from fossil fuel-based natural gas and other Scope 1 emissions. Electrification and other approaches explored within this study may be able to further reduce the residual.

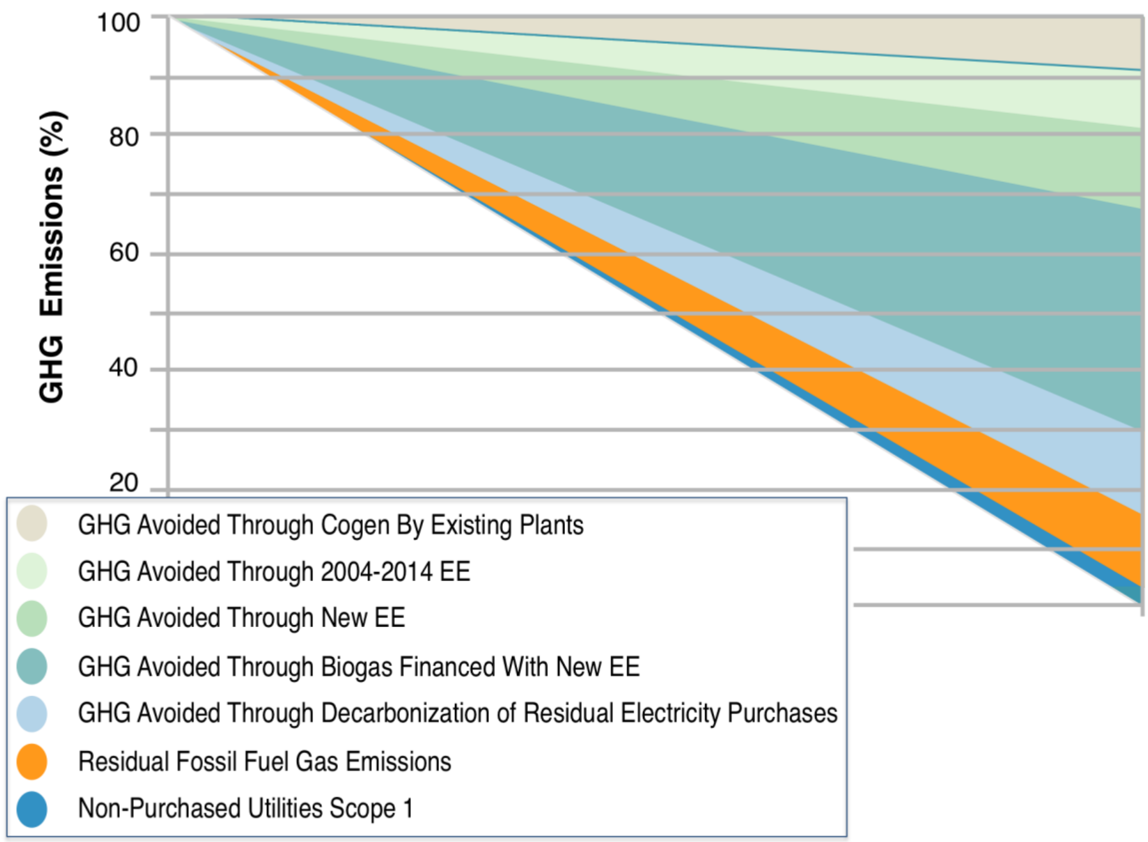

Figure 2.4. UC systemwide Scope 1 and 2 GHG emission reduction potential from past and future climate actions, including the near-term strategy of financing biogas with energy efficiency savings. Projected reductions are compared to a pre-climate action baseline that starts in the 1970s. Wedges represent respective contributions to the goal of carbon neutrality of UC's actions: cogeneration in-place, 2004-2014 energy efficiency, new energy efficiency, and biogas that could be financed by new energy efficiency. An additional contribution from assumed decarbonization of electricity purchased from the grid is also shown.

We briefly explored another hypothetical scenario pursuing the full identified efficiency potential (29% reduction in gas use, 39% reduction in electricity use). This would reduce the overall energy footprint, but the lower ROI would impact the positive cash flow, particularly as cogeneration output is reduced (issues with reducing cogeneration output are discussed in Section 2.6). We conclude that the scenario illustrated in Figure **2.4** is much closer to the optimum for funding biogas than a maximum efficiency potential scenario.

2.2 Energy Efficiency Potential

UC systemwide energy efficiency initiatives have already resulted in significant avoided GHG emissions. We quantify further energy efficiency potential based on an evaluation of key evidence, including:

- The track record of efficiency retrofit projects completed as part of the Statewide Energy Partnership and UC/California State University (CSU)/Utility Energy Efficiency Partnership (11)
- Potential deep energy efficiency projects analyzed in the "Deep Energy Efficiency and Cogeneration Study" (23) and updated in "Deep Energy Efficiency: Getting to Scale" (11)
- Potential for new monitoring-based commissioning projects across the UC system (11)
- A meta-analysis of retro-commissioning potential in the U.S. (24)

We also look at evidence regarding administrative and behavioral approaches to achieving energy savings (25-29). We do not include quantifications from these studies in the overall estimates of further efficiency potential because some parts of these studies partially overlap with the measures already identified and because there is less of a UC track record for other (occupant-related) strategies.

Energy storage projects will contribute direct cost reduction through electric demand charges, and create synergies with other aspects of decarbonization (12). UC already employs chilled water energy storage on several campuses, often in conjunction with combined cooling, heating, and power plants. Rapidly emerging battery technologies are likely to soon play a significant role in on-campus energy storage, with hydrogen and hot water also having potential.

Beginning with UC's proposal for a pilot partnership with utilities and a technology demonstration program (30), then extending this trajectory through innovative financing, UC's energy savings accomplishments have been enabled by an exploratory and pioneering approach to energy efficiency and climate action. UC Irvine, for example, has been a leader in energy efficiency. The campus has pioneered the "smart" labs concept, and achieved the greatest scale of energy efficiency retrofit relative to campus size for lighting and overall retrofits. Its avoided carbon dioxide equivalent (CO_2e) emissions from all retrofits are more than double the systemwide average (11).

Sections 2.2.1 through 2.2.6 describe the types of projects identified to achieve UC's full energy efficiency potential.

2.2.1 Deep Energy Efficiency

In 2014 UCOP commissioned ARC Alternatives, a green energy consultant specializing in public sector projects, to conduct a deep energy efficiency study[3] for UC campuses (23). This analysis built on previous planning efforts and focused on scaling deep efficiency measures in UC buildings with floor area greater than 40,000 gross sq. ft. The deep efficiency focus meant that the most financeable comprehensive measures were prioritized over incremental measures. Campuses served by municipal electricity providers were included in the study to expand its scope beyond campuses that had so far accumulated the bulk of UC's energy use reductions through the utility partnership, which, until 2016, included only investor-owned utilities. Medical centers were also included.

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[3] This "Deep Energy Efficiency and Cogeneration Study" study also included improvements in efficiency to cogeneration plants that are not further explored here.

This study used simple models that proved useful for planning to identify the resources needed to achieve deep efficiency at some scale. Projects were characterized in three categories: smart labs, deep HVAC, and smart lighting. Monitoring-based commissioning was considered as one major delivery mechanism for deep HVAC, but energy use reduction from monitoring-based commissioning itself was not included. Avoided CO_2e emissions from deep efficiency projects were estimated to total 13-22% of emissions from natural gas, steam and electricity use, and 12-21% of Scopes 1 and 2 CO_2e emissions relative to a 2014 baseline. Ranges are indicative of differences in low and high scenarios, and differences in reducing use of directly purchased vs. cogenerated energy.

2.2.2 Efficiency at Scale

In 2016, the UC Global Climate Leadership Council commissioned a project, known as "Deep Energy Efficiency: Getting to Scale (Lighting)," to explore the challenges of accelerating the pace of energy efficiency retrofits, with lighting as an illustrative example. Through a deeper analysis based on case study projects across UC campuses, the project report updates the efficiency potential from light emitting diode (LED) lighting with advanced controls (11). The project expands on the ARC Alternatives 2014 Deep Energy Efficiency analysis by including more buildings and direct reductions through additional monitoring-based commissioning.

The updated potential of deep efficiency projects, consistent with the ARC Alternatives study but incorporating the new lighting analysis, identified avoided CO_2e emissions from deep efficiency projects as 13-38% of natural gas, steam and electricity use, and 13-36% of total Scope 1 and 2 CO_2e emissions relative to a total 2014 baseline (11). These totals cover remaining potential, with reductions to date from project portfolios subtracted where appropriate.

2.2.3 Monitoring-Based Commissioning

The UC system has extensive experience with efficiency projects centered on monitoring-based commissioning. UC helped establish this approach, which encompasses ongoing monitoring of building equipment to detect faults, then optimizing performance using energy information systems (metering and building diagnostics). It includes measurement-based accounting of energy use reduction (30). As part of a study conducted for the California Energy Commission, Mills and Mathew analyzed a set of 24 UC and CSU monitoring-based commissioning projects implemented in 2004 and 2005 within the UC/CSU/IOU partnership (31).

The analysis identified the following savings in these buildings:

- Total source energy savings, median value, 10%
- Median electricity savings, 9%
- Median fuel savings, 9%
- Median hot water/steam savings, 12%

These results were similar to a broader study that compiled commissioning results from 643 non-residential buildings, of which 561 were existing facilities (rather than new construction) (24). The following savings were identified for the retrofit buildings:

- Total primary energy savings, median value, 16%
- Median electricity savings, 9%
- Median fuel savings, 16%
- Median combined central thermal savings, 31%
- Median central hot water savings, 12%
- Median central chilled water savings, 16%
- Median central steam savings, 19%

The identified remaining UC systemwide efficiency potential from monitoring-based commissioning is consistent with these detailed investigations.

2.2.4 Administrative Approaches to Deepen and Retain Efficiency Savings

Analysis of monitoring-based commissioning projects indicates that an ongoing organizational process to monitor operation and optimize energy use is critical to deepen and retain energy efficiency savings. ISO 50001 is an international energy efficiency standard that establishes a continual improvement process to enhance procedural and organizational approaches to organized energy management and efficiency projects. The ISO Superior Energy Performance program is an optional component of ISO 50001 that uses an accredited third-party verification organization to quantify savings achieved through energy efficiency.

A study of 10 non-UC facilities associated mostly with larger industrial companies identified savings of 4.1% in the first year and 11.1% in the first quarter of the second year after ISO Superior Energy Performance training (25, 26). A related study analyzed results at 26 facilities following the process over a longer time period. For the projects analyzed, the average split between capital and operational projects (according to expenditure) was 26/74. Savings ranged from 6-31% total building energy savings over three years and between 17-42% savings over 10 years (27). These studies provide evidence that savings can be generated through consistent administrative focus and protected over the timescale at which UC is pursuing its carbon neutrality goal.

2.2.5 Occupant Behavior

While there have been many efforts in the UC system to influence energy-consuming behavior on campuses (such as reminders and rewards for shutting laboratory fume hood sashes and turning off equipment), there has been little analysis to confirm and document persistent savings associated with building occupant behavior. One unpublished analysis, conducted by sustainability practitioners at Lawrence Berkeley National Laboratory, assessed the potential savings from keeping 300 variable air volume hoods at the lab closed while not in use. They identified potential annual savings of approximately 2% of the building-related Scope 1 and 2 greenhouse gas emissions and 7% of the building-related emissions from natural gas (based on fiscal 2015 emissions; calculation details in (29)).

Another study quantified energy savings attributable to five efficiency measures that are dependent on occupant behavior in an office building modeled across four typical U.S. climates and two building code timeframes (28). The occupant-controlled measures included lighting control, plug load control, thermal set point control, more extensive heating and ventilation system control, and window control. Based on the simulation results, individual occupant behavior measures achieved moderate savings, and integration of the five measures yielded savings of 25-41% across the modeled cases.

These two analyses indicate a strong potential for emissions reduction from behavioral measures. However, given the variability of human behavior and most campuses' limited experience with inducing behavioral savings on a sustained basis, savings from occupant behavior have not been included within the overall energy efficiency potential estimated in this report.

2.2.6 Summary of Remaining Energy Efficiency Potential

To determine the remaining energy efficiency potential of UC facilities systemwide, we used 2015 total use by buildings as the baseline. We estimate that an additional 38% of electricity and 29% of natural gas or equivalent cogeneration output can be avoided through a combination of energy efficiency projects including interior and exterior lighting, deep HVAC, smart labs and monitoring-based commissioning. This is a high estimate, but not an upper limit. We estimated total use by buildings based on purchased utility amounts and assumptions about cogeneration operation (See also Figure 2.6). Figure 2.5 and Figure 2.6 illustrate the breakdown of efficiency potential for electricity and natural gas, respectively.

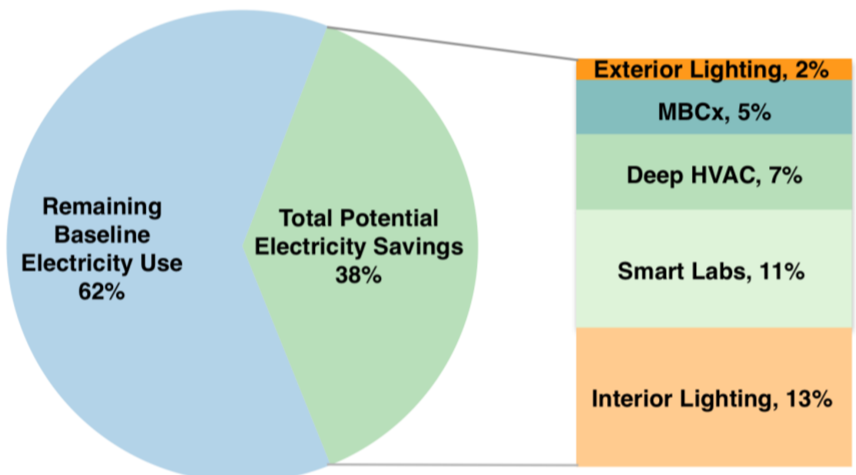

Figure 2.5. UC systemwide electricity efficiency potential relative to a 2015 total building electricity use baseline.

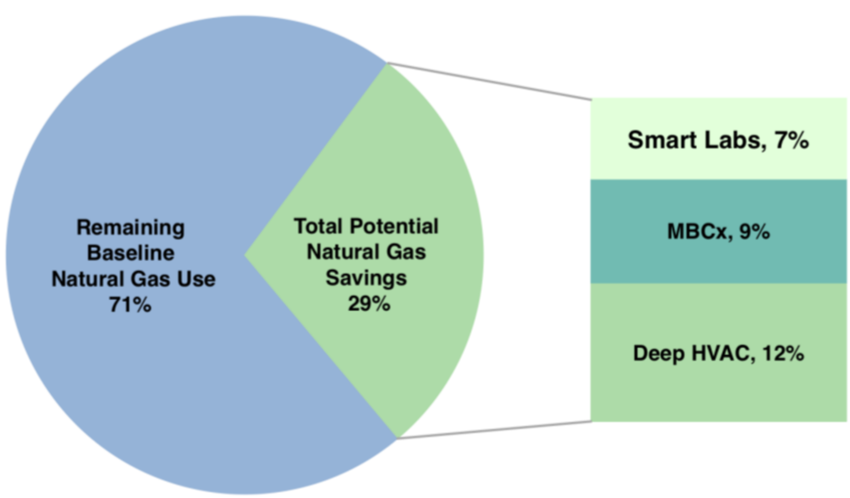

Figure 2.6. UC systemwide natural gas (or equivalent thermal) efficiency potential relative to a 2015 total building natural gas use baseline.

2.3 Financing Variations

Though energy efficiency eventually reduces costs, up-front funding for deep energy efficiency projects is a significant barrier to implementing at scale. We explored two funding mechanisms for financing new efficiency projects: bond-funded loans and energy-cost savings reinvestment. These approaches are compared below.

2.3.1 Incentive and Bond-Funded Loan Programs

Since 2004, UC has been able to undertake a substantial program of energy efficiency retrofits at scale due to two programs offering incentives and bond-funded loans:

- **UC/CSU/Utility Energy Efficiency Partnership**. This partnership provides incentives for energy efficiency retrofits, including monitoring-based commissioning. During the pilot phase, 2004-2005, incentives covered 100% of project costs. In 2006, the program shifted to partial incentives of $0.24 per kWh/yr and $1.00 per therm/yr, with some project caps and more overall incentive funding available (11). This program enabled many of the efficiency gains described in Section 2.2.

- **Statewide Energy Partnership.** In 2009, UC introduced its Statewide Energy Partnership Program, which augmented UC's participation in the utility partnership with bond-based loan financing to cover much of the balance of project costs. This program made $178 million in loan financing available to campuses in the first three years, with additional amounts subsequently authorized. For planning purposes loan terms were 5% interest, 15-year duration, and maximum 85% debt service ratio (debt service could be no more than 85% of the avoided energy cost).

Future energy efficiency improvements needed to meet the university's carbon neutrality goals may be funded through new debt (i.e., bond funded loans). There are significant challenges to this approach including campus debt capacity limits. Steps to overcome these barriers are being explored (20). Incentives are likely to continue to be available to incrementally expand projects or deepen project scope. The debt service approach is analyzed for each of the campus cases in Section 2.4.

The following funding mechanism offers an alternative or complement to debt financing as a way to leverage energy cost-savings to achieve scale and realize more of the potential of energy efficiency on UC campuses.

2.3.2 Energy Cost-Savings Reinvestment

Energy Cost-Savings Reinvestment is a funding mechanism whereby campuses dedicate unobligated funds as seed money to create an initial portfolio of aggressive energy efficiency projects. The cost savings resulting from reduced energy use are sequestered and reinvested in additional energy efficiency projects. The combined energy-cost savings accumulate in the same fashion as compound interest, and can then be leveraged over time to cultivate a large energy efficiency portfolio. By investing in high ROI projects, more funds become available to achieve scale more quickly. This approach would enable campuses to avoid incurring debt, although they would not experience positive cash flow initially. Positive cash flow begins when reinvestment is reduced and becomes full when reinvestment is stopped. With debt service, some positive cash flow can begin immediately, but does not become full until the debt is retired.

As an example, consider Case A - Non-CHP analyzed in Section 2.4 and described in Appendix A. If new electric and gas efficiency measures are funded by energy cost-savings reinvestment rather than bond-funded loans/debt service, with the same goal of affording full biogas premium in 2025, the efficiency portfolio needed will vary as shown in Table 2.1, below.

Table 2.1: Comparison of Efficiency Financing Variations

	Case A - Non-CHP Reinvestment Moderate	**Case A - Non-CHP Reinvestment High**	**Case A - Non-CHP Bond-Funded Loan**
Annual Energy/EE Debt Service (1) Budget now-2025	~$12 million	~$12 million	~$12 million
Seed Funding	~$1.8 million	~$3.6 million	N/A
Total Project Spend	~$4.5 million	~$9.0 million	N/A
New Debt	N/A	N/A	~$8 million
Gross Debt Service Ratio (Elec)	N/A	N/A	62%
New Gas Efficiency	12%	24%	24%
New Electric Efficiency	5%	10%	10%
Biogas Premium 2025	Full	Full (with surplus)	Full
Biogas Premium 2028	Full (with surplus)	Full (with surplus)	Full
2028 Annual Energy/EE Debt Service (1)	N/A	N/A	~$0.8 million
2028 Surplus	~$0.8 million	`~$1.5 million	~$0.8 million

Notes:

1. *Biogas Premium* represents the fraction of gas use for which the premium for biogas can be afforded within the combined energy and energy efficiency debt service budget. Base natural gas cost is assumed constant at $5/MMBTU. Premium for biogas is assumed to be $3/MMBTU. Electricity prices vary by campus.
2. *2028 Annual Energy/EE Debt Service Surplus* is the combined energy and energy efficiency debt service surplus resulting from full roll-off of the 2009-2012 loan cohort in 2028.
3. *Gross Debt Service Ratio (DSR)* is the debt service ratio for the energy efficiency portfolio before payment of biogas premium is considered. Net DSR is 100% with biogas premium. Number is based on projects in 2017-2021 plan.
4. *New Debt* is the amount of new debt required to fund the new energy efficiency portfolio.
5. *Seed Funding* is the amount of initial capital required to fund projects that produce savings for reinvestment. (Capital is not preserved as full avoided energy expenditures are re-invested.)
6. *New Gas / Electric Efficiency* is the amount of current energy use avoided through new energy efficiency (EE). For CHP cases percentage applies to supplemental gas and electricity purchases only. Percentage of use at the buildings is within potentials or campus plans. For "gas" percentage can be high because base includes CHP thermal output. For electricity percentage can be high because some campuses appear to already be incorporating new construction loads into EE planning and CHP load projections.

New efficiency projects can be undertaken with debt financing to reduce electricity and gas use by 24% and 10%, respectively. With new bond-funding at $8.2M, the loans will result in increased forward debt burden. Alternatively, assuming $1.8M in initial funding to create energy savings for reinvestment, only 12% and 5% reductions are needed for gas and electricity, respectively, without debt burden. With $3.6M in reinvestment, 24% and 10% reductions can be achieved for gas and electric, respectively. The higher amount of reinvestment produces a surplus in 2025. Since this campus case has residual debt service from 2004-2014 efficiency projects, a surplus is achieved in 2028 for each alternative.

In summary, $8.2 million in debt funding and $3.6M in seed funding will achieve similar reductions in gas and electricity use; the reinvestment option will not initially produce positive cash flow, but will produce higher and earlier surpluses.

Note that energy cost-savings reinvestment is not included in the analyses in Appendix A: Tables A-1 through A-4.

2.4 Campus Cases

The impact of deep energy efficiency on projected energy utility budgets varies significantly based on campus characteristics. To differentiate these budget impacts and the resulting degree to which decarbonization can be financed through energy cost-savings, 14 cases were developed which roughly correspond to conditions on campuses and medical centers.[4] These are shown in detail in Appendix A. Cases are modeled on conditions at 14 UC campuses and medical centers that have various combinations of the following characteristics:[5]

- **Campus Type:** CHP or Non-CHP, with or without a Medical Center
- **Gas/Electricity Ratio:** Low, High, Very High
- **Electricity Price:** Very Low, Low, High, Very High
- **Energy Efficiency Improvements to Date:** Minimal, Low, Moderate, High or New Campus
- **2009-2012 Debt Burden:** Minimal, Low, Moderate, High

The following assumptions and constraints formed the foundation of the simple analyses:

1. Biogas price was assumed to be $8 per MMBTU, a conservatively high estimate—purchases to-date have been at a lower price for 2025.[6]
2. These numbers only included budget for 2015 existing buildings. For new facilities added after 2015, we assumed that campuses would augment their utility budgets as needed, and these amounts are not included here.
3. CHP operations were not modified or retired in the analyzed timeframe, with one exception (Case I) where plant turndown is already being implemented in practice.
4. Integrated planning of CHP loads from new facilities (32) was included only when energy efficiency planning indicated this is already occurring.

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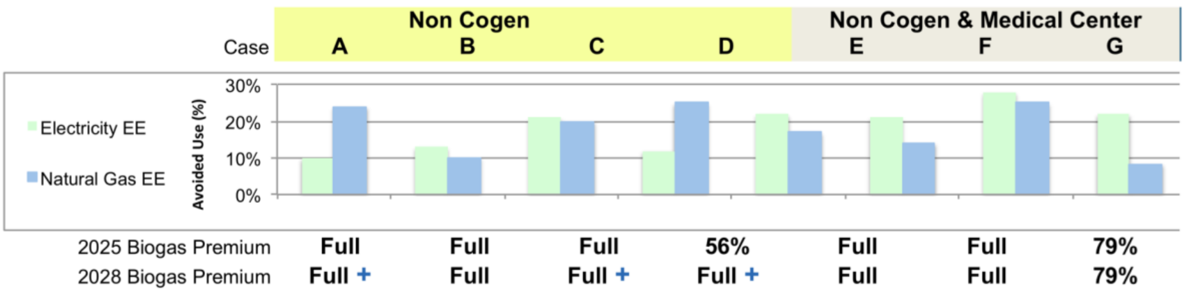
[4] UC has 10 campuses, five with medical centers. In one case utility accounts are not differentiated between main campus and medical center.

[5] Not all permutations exist.

[6] Base price assumed to be $5/MMBTU, based on current price being paid by campuses, premium assumed to be $3, for a total biogas price of $8. Biogas is being purchased from LA and WI at $7+.

Energy efficiency targets for these cases are all within, and often well below, the deep energy efficiency potential estimates presented in Section 2.2. This is consistent with target debt service ratios.

a.



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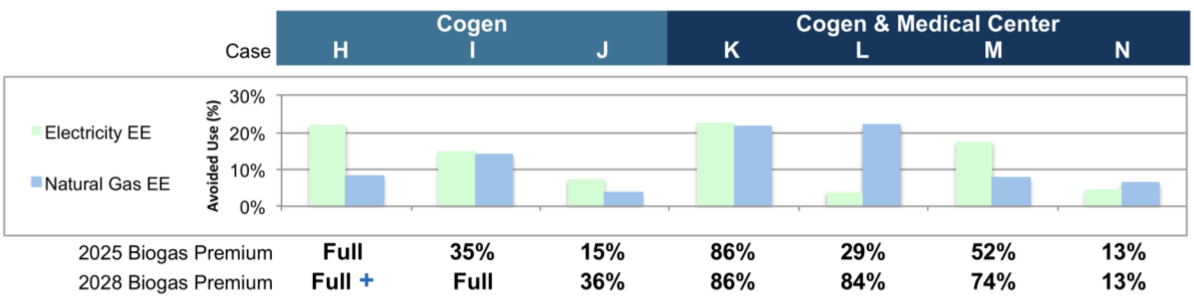


Figure 2.7. Projections for 14 campus cases, clustered by type. a) Cases without CHP. b) Cases with CHP. Five UC campuses have medical centers. We have seven medical center cases because in two cases part of the medical center is at least partially served by a CHP fueled by natural gas from the main campus CHP account. Each case finances energy efficiency with new debt. Energy-cost savings reinvestment variations (described in Section 2.3) are not included. Higher efficiency variations are presented in cases K-M. Tables A-1 through A-4 in Appendix A present more comprehensive results of the projections.

The campus cases in Figure 2.7a and b include four different outcomes:

- Biogas premium not fully funded
- Biogas premium fully funded in 2025
- Biogas premium fully funded in 2028
- Biogas premium fully funded in 2028 with budget surplus

Full funding of the biogas premium is achieved most easily in the non-CHP cases, where energy efficiency is not constrained by CHP operational efficiency. Five out of seven non-CHP cases, including two medical centers, finance the full biogas premium in 2025. Another non-CHP case finances the full biogas premium in 2028 (Case D). Three non-CHP cases have a budget surplus in 2028 (Cases A, C, D). The differences between 2025 and 2028 timeframes illustrate the budget significance of the full roll-off of the 2009-2012 cohort of debt service in 2028.

While financing of the biogas premium through energy efficiency is more challenging on CHP campuses, one CHP case can finance the full biogas premium in 2025 (Case H) and will generate a budget surplus in 2028, and one more CHP case can finance the full biogas premium in 2028 (Case I).

The ability to fund the biogas premium is sensitive to price. If the biogas target price is assumed to be $7 per MMBTU, the target 20-year average price for procurement under UC's Biomethane Program, then three more cases can fund full biogas needs in 2025 and one more case can fund full biogas needs in 2028. Only two out of fourteen cases would be unable to fund the full biogas premium in 2028 at this price.

Campus type is most predictive of ability to finance decarbonization. Fewer CHP cases finance the full biogas premium. Within the CHP subset the most significant factor affecting financing of the biogas premium is the amount of electricity and gas purchased supplemental to CHP production. Reducing use of cogenerated energy has a much lower return on investment, with little, if any, positive cash flow net of debt service. Factors impacting the ability to turn-down cogeneration production are explored in Section 2.6.

Integrating planning for new facilities will allow implementation of more high ROI energy efficiency and give campuses more ability to finance decarbonization without impacting CHP operations. Some campuses are already planning for this deeper efficiency (32). This is included in the projection for cases I and K. This was not quantified for other CHP campuses, so the analysis is conservative with respect to high ROI reductions from efficiency and positive cash flow.

If positive cash flow is not a goal, more energy efficiency might be achieved for some CHP cases, up to or exceeding the identified potentials. The potential to turn down production of some, but perhaps not all, cogeneration plants by up to 40% (to 60% of capacity) is discussed in Section 2.6.

Other factors affect the budget shifts available from energy efficiency (and debt service) and the resulting ability to finance decarbonization. A higher electricity price would increase campuses' ability to shift budgets with energy efficiency. Higher 2009-2012 debt burden, corresponding to deeper and earlier avoidance of GHG emissions, in keeping with the intent of the CNI, means that the ability to fully finance decarbonization occurs later, in 2028.

2.5 Sum of All Campus Cases

In Table 2.2, we present the cumulative total of the UC campus budget cases presented in Figure 2.7a and b. Only debt service and high energy efficiency variations are included.

The total fraction of biogas premium funded is 52% in 2025. After the 2009-2012 debt service is paid in full in 2028, the total fraction of biogas premium funded increases to 75%. In 2028, the individual campus cases would generate an aggregate surplus of $2 million within the nominal $214 million combined energy and debt service budget.[7] Two CHP cases with minimal identified supplemental gas and electricity purchases make up the bulk of the remaining biogas spend.

[7] Does not include debt service from 2013-current loans, which will not change between now and 2028.

New debt of $360 million would be incurred. Reduction in energy spend net of debt service (before decarbonization) would be $19 million per year, and $14 million per year of 2009-2012 debt service would be fully retired in 2028.

Table 2.2. Systemwide Totals Based on Debt Service and High Energy Efficiency Scenarios

	Systemwide Totals
Annual Energy/EE Debt Service (1) Budget now-2025	~$210 million
New Debt	$340 million
Gross Debt Service Ratio (Elec)	21 - 70%
Gross Debt Service Ratio (Gas)	47 - 70%
% Total Building Use (New Gas Efficiency)	10 - 25%
% Supplemental to CHP	12 - 76%
% Total Building Use (New Electric Efficiency)	10 - 28%
% Purchases Supplemental to CHP	Up to 92% (2)
Biogas Premium Funded in 2025	52%
Biogas Premium Funded in 2028	75%
2028 Annual Energy/EE Debt Service (1) Surplus	~$2 million

Notes:

1. Only 2009-2012 loan and new loan debt service included.
2. Approaches 100% for case where campus is probably already integrating with new construction and/or modifying CHP operations.

2.5.1 UC Energy and Carbon Neutrality Budgeting

Figure 2.8 depicts budgeting that integrates spending on energy with debt service on loans that fund energy efficiency. This is in the spirit of the Finance and Management Task Force recommendation that campuses integrate purchased utility and carbon management budgets (22). The systemwide timeline illustrates a level energy utility/debt service budget for existing facilities for 2015, 2025, and 2028. The electricity and gas use and spending, decreases from 2015 to 2025 as a result of energy efficiency projects, and new debt service increases accordingly. Natural gas and electricity use hold constant from 2025 to 2028. Biogas premium payments begin in 2025, supplanting some electricity and gas base price spending, and some expiring debt service. Biogas premium payments increase in 2028 with additional debt service roll-off. A significant surplus of ~$2M is achieved in 2028.

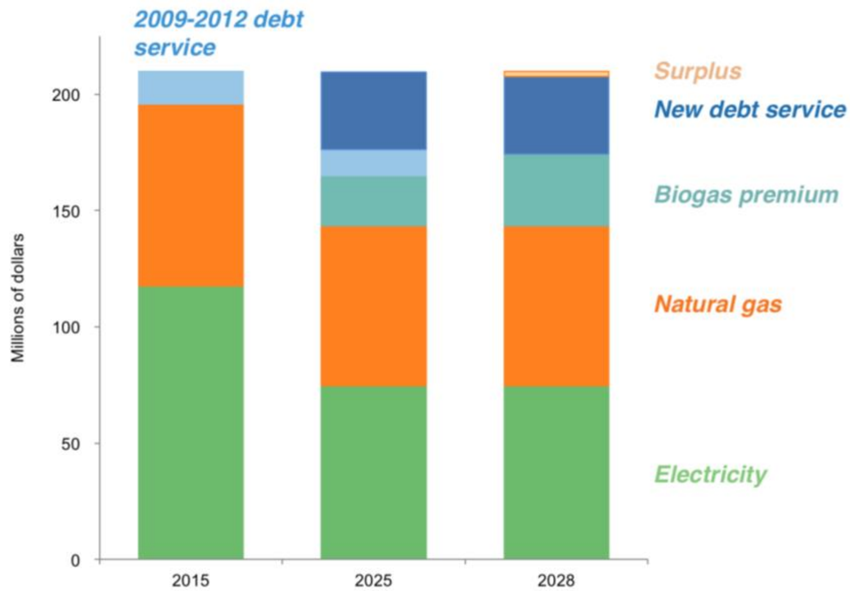


Figure 2.8. UC energy and efficiency debt service spending, including biogas premium for existing facilities, 2015 to 2028

2.6 Optimizing Combined Heating Cooling and Power Plants

As more and deeper energy efficiency measures and renewable energy technologies are adopted at UC campuses, the energy demand met through traditional means, including existing CHP, will shrink. At least one type of CHP has the potential (already realized on at least one campus) for turndown by as much as 40% (to 60% of capacity). This is the lower limit for the turbine configuration and emission control technology to maintain criteria pollutant levels (i.e., NOx). Plant efficiency is lower when operating at reduced loads. This is described in detail in the case study in Section 2.6.1. The ability of other UC CHP and emission control technologies to similarly throttle back operations has yet to be explored.

A fully implemented energy efficiency program would reduce CHP operations for most cogeneration campuses. When the turndown potential exists, it may eventually be pursued on a case-by-case basis—the potential for turndown creates flexibility in planning deep energy efficiency. However, full efficiency implementation may not be pursued on cogeneration campuses because the current economic benefit (i.e. potential for positive cash flow) is not as great as for efficiency that only reduces use of directly purchased energy. This is partly due to reduced cogeneration efficiency at part load, but primarily due to the beneficial economics of cogeneration with current energy pricing.

Potential for turndown of CHP may be more important in another context: CHP that do have turndown capability may be able to participate in Ancillary Services markets, supporting integration of renewable energy into the grid by providing capacity or voltage support. On the day of an anticipated opportunity to provide a bid for Ancillary Services, the plant might operate at 60-95% of full capacity, then ramp up if a bid is made and accepted. To compensate for purchasing electricity and gas to cover the unserved campus load around the event, the revenue would need to be greater than the costs incurred.

2.6.1 Issues and Potential for CHP Part Load Operation: A Case Study

Combined heating cooling and power plants are typically optimized for operation at full output, with lower performance at part load. In particular, operating a gas turbine (the prime mover in a typical UC CHP) at part load results in decreased combustion turbine efficiency and possibly reduced combined cycle efficiency. Further, when the combustion turbine load drops enough, emission rates of criteria pollutants from the turbine increase dramatically, by orders of magnitude. Indeed, the manufacturer only guarantees performance at certain load conditions and above. Nevertheless, emissions from the plant may be kept within permitted limits if there is sufficient exhaust post treatment capacity.

UC Irvine provides a relevant case study. There, solar power and energy efficiency result in reduced loads and necessitate scaling back the main campus CHP production. This plant occasionally operates at as low as 60% of full capacity (40% turndown).

The main campus cogeneration plant has been operating its currently installed 13.5 MW Titan™ 130 Solar Turbines gas turbine since 2014 (the original turbine was installed in 2007). The gas turbine is used to meet a large portion of the campus electrical demand and also to meet the majority of the campus heating and steam demand. To operate within South Coast Air Quality Management District (SCAQMD), emissions from the stack of the heat recovery steam generator (HRSG) must be less than 2 ppm NOx and 3 ppm CO at 15% O2. To achieve sufficiently low emissions, the engine uses lean premixed combustion to produce single digit ppm levels of both NOx and CO. The gas turbine is guaranteed to operate at single digit NOx as long as the turbine is operated above a minimum of 8 MW of electric power output.

After exiting the gas turbine, the exhaust gas enters a heat recovery steam generator (HRSG), which contains a CO and NOx removal section. Carbon monoxide removal occurs by flowing the exhaust through a platinum catalyst, resulting in a catalytic combustion process that changes CO to CO_2. After the CO removal process, ammonia (NH3) derived from urea is sprayed into the exhaust prior to a vanadium pentoxide catalyst, which reduces the ammonia and NOx to nitrogen and water. This NOx reduction process is more commonly referred to as selective catalytic reduction. These processes are sensitive to temperature, and any large deviation in operating temperature can result in improper operation, resulting in a pollutant emission violation. The combination of lean premixed combustion and downstream exhaust gas cleanup allows for the gas turbine to operate within the SCAQMD criteria pollutant emission limits.

Operational data for the UC Irvine central plant has been captured and averaged over 15 minute intervals. Data from January 2014 through October 2016 has been provided to the Advanced Power and Energy Program (APEP) from the UC Irvine central plant operators. All of the following analyses are produced using this data. As a reference, the part load efficiency for the current engine is shown in Figure 2.9.

In general, the gas turbine is operated such that sufficient steam is produced to meet all campus steam and heating demand, and to reduce utility electrical imports. Originally, the interconnection agreement between the local utility (Southern California Edison) and the campus allowed for no electrical export from the campus back to the local grid, resulting in continuous import of approximately 2 MW of utility electricity. Subsequent revisions to the interconnection agreement, and installation of advanced power system technologies, allowed for inadvertent export (or export for short durations) to occur, allowing central plant operators to reduce utility imports from 2 MW to a few hundred kW.

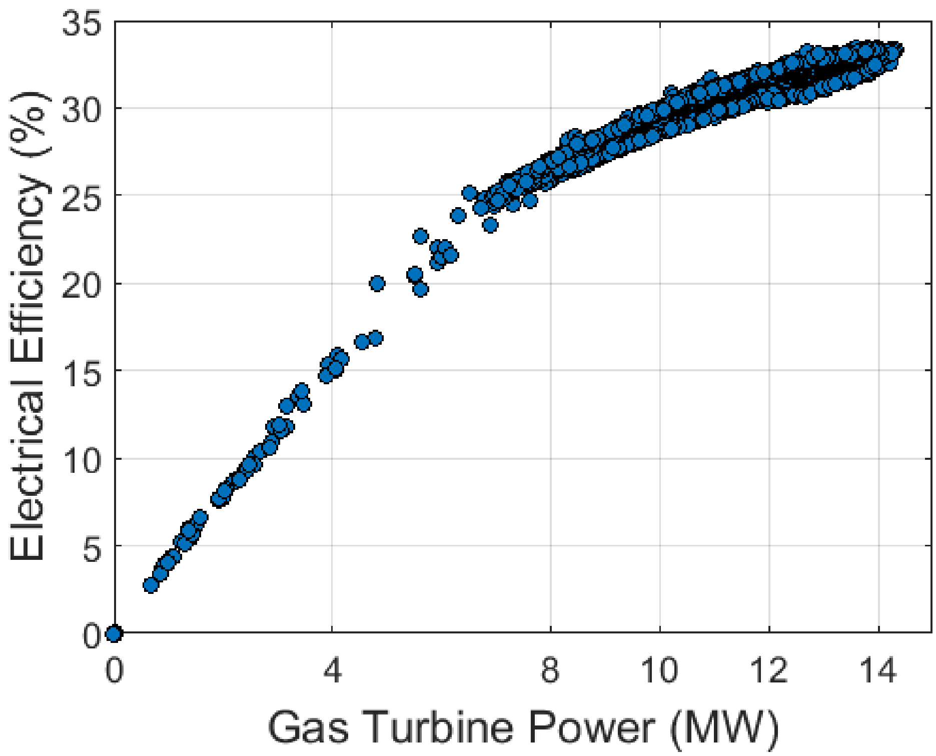


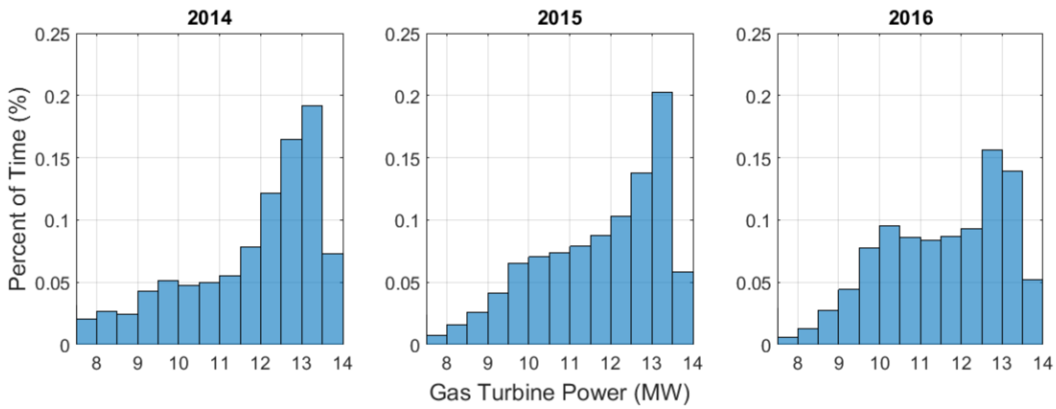
Figure 2.9. Part load efficiency for the 13.5 MW gas turbine at UC Irvine. Note that this efficiency is for the gas turbine electricity only. Electricity produced by the steam turbine (after the heat recovery steam generator) and heat used on campus from the combined cycle power plant are not included.

While the agreement between the local utility and campus was changing to allow for increased onsite generation, energy efficiency measures were being adopted across the campus. In addition, solar PV systems were installed across parking structures in 2015, increasing on-campus peak PV system capacity from 1 MW to 4 MW. For central plant operators, any electricity generated by the 4 MW solar PV system is "must-take" power, meaning that operation of all central plant systems must be modified to accept all solar PV power. Note that the additional 3 MW of solar PV was adopted in 2015. APEP is currently pursuing collection of generation from all solar PV systems installed across the UC Irvine campus.

Figure 2.10a shows the percentage of time that the gas turbine was operated at various power settings in 2014, 2015, and 2016. Figure 2.10a and the load duration curves in 2.10b show that in all three years, instances occur where the gas turbine is operated at or near full capacity. However, the amount of time at which the gas turbine is operated at part load increases through time. Note that the 2015 data combined operation before and after the installation of 3 MW of solar PV. In addition, these figures include operation at night, when campus electrical demand is lowest.

When the operational data are filtered to show gas turbine operation between the hours of 11 AM and 3 PM, June through September, (when solar PV production is greatest), a larger difference in gas turbine operation is observed between 2014 and 2016 (Figure 2.11a). During this filtered time period, operation between 8 MW and 12 MW increased from 18% in 2014, to 23% in 2015, to 43% in 2016. Operation between 8 MW and 10 MW increased from 3.7% in 2014, to 6.9% in 2015, to 12% in 2016.

a.



b.

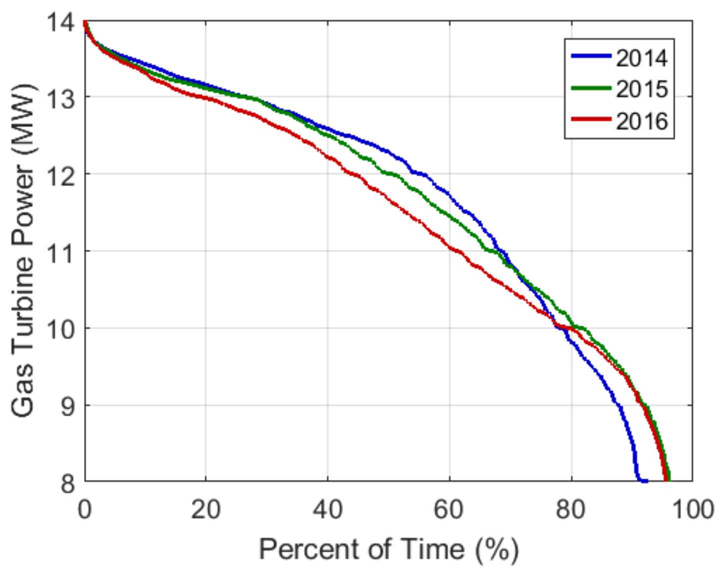
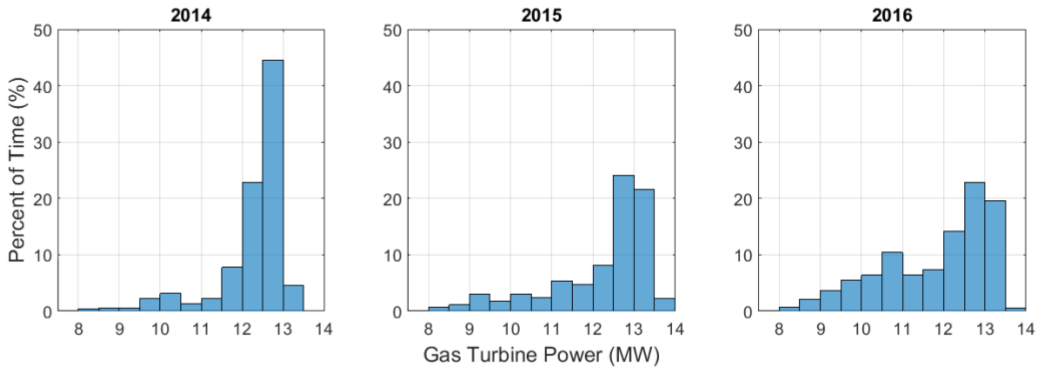


Figure 2.10. UC Irvine gas turbine operations. **a)** Percent of time UC Irvine gas Turbine operated at various power settings for the years 2014, 2015, and 2016. **b)** Load duration or percent of time at a given turbine power (MW) for 2014, 2015, and 2016.

a.



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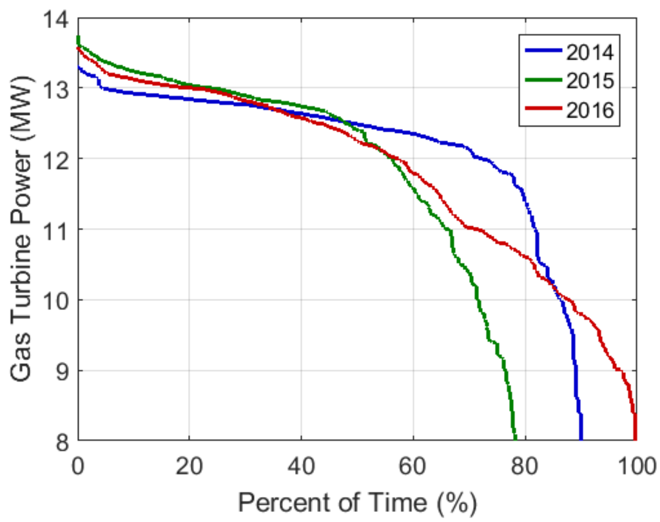

Figure 2.11. UC Irvine gas turbine operations during peak solar PV production hours. **a)** Percent of time UC Irvine gas turbine operated at various power settings, 11 AM-3 PM, June through September, 2014, 2015, and 2016. **b)** Load duration curves for the same time period.

At this time, it is unclear how additional solar PV capacity or energy efficiency measures will affect gas turbine operation. Anecdotal reports from central plant operators suggest that additional solar PV capacity would result in gas turbine operation below 8 MW, possibly resulting in a violation of SCAQMD pollutant emission limits. While it appears that the current pollutant clean-up system (particularly the selective catalytic reduction system) may be able to offset higher pollutant emission rates, efficiency of the engine begins to decrease rapidly below 8 MW output. This decrease in efficiency is not inherently bad, as the fuel energy not converted into electrical energy can still be captured in the HRSG. However, gas turbine and central plant modifications are required to boost turbine performance at part load operation and ensure that the maximum amount of waste heat is captured by the HRSG, while pollutant emission limits are not violated.

Research into CHP operation is currently being pursued. While the focus up until this point has been on altering current system operation, future work must evaluate other options, such as using more appropriately sized equipment, or switching to technologies that do not have the same mechanical or thermodynamic limitations as the systems currently in use. These improvements are necessary to increase energy efficiency, and to reduce the natural gas and biogas requirements of CHP-equipped campuses.

2.6.2 Energy Storage

Energy storage will play roles synergistic with all aspects of de-carbonization. One of the most important roles is in buffering loads to keep CHP plants operating in the most efficient fully loaded mode or at minimum levels for adequate emission control. UC already makes extensive use of chilled water energy storage on several campuses, often in conjunction with CHP plants. Operation of chilled water storage is already changing as increased utilization of renewable electricity shifts patterns of supply availability and cost.

Batteries are rapidly emerging as a promising energy storage mode as costs fall. Hydrogen is another potential storage mode that has potential on the supply side of CHP plants as discussed in Chapter 3. Heated water may also become an important storage mode.

2.7 Summary of Results

UC is recognized as having a strong track record of pioneering and exploratory efforts, which helps position its campuses for achieving carbon neutrality. UC innovations enabling energy efficiency include:

- Pilot energy efficiency partnership with utilities
- Bond-based loan (debt) financing for energy efficiency retrofits
- Monitoring-based commissioning
- Demonstrating new technologies
- Pioneering the “smart labs" approach to deep energy efficiency

Our analysis has focused on energy efficiency through the retrofit of existing buildings, assuming parallel efforts to move UC quickly toward all-electric new construction with deep energy efficiency. UC also has a record of innovation with new construction including development of benchmark-based energy performance targets for new buildings (33).

Remaining systemwide potential for energy use reduction through efficiency retrofits averages 39% of electricity and 29% of natural gas (or equivalent cogeneration output). A significant portion of this is achievable with high positive cash flow and without affecting cogeneration operations. The budgetary savings net of debt service from new energy efficiency by 2025 could be shifted to fund decarbonization. For campuses that invested early in energy efficiency and carry relatively large amounts of 2009-2012 debt service, that portion of budget capacity could also be redirected toward decarbonization as it is retired in 2025-2028. The pace and depth of energy efficiency projects must be increased to capture the economic potential in the timeframe of the CNI. Energy efficiency efforts must be ramped up for most campuses, and there are associated organizational challenges of getting to scale, but leading campuses have already met the technical challenges.

As an example of the potential use of net energy efficiency cost savings to fund decarbonization, this budget re-direction could provide a means to finance most of the systemwide cost of switching to biogas for all natural gas needs. This might be accomplished with reductions in directly purchased energy use without significantly reducing CHP operations. There is substantial variability in this potential among campuses.

There is potential for energy efficiency to reduce building energy use to the point of significantly reducing cogeneration output. One campus has explored turndown of its CHP by as much as 40% in conjunction with energy efficiency and renewables integration. This is the threshold below which criteria pollutant emissions become a constraint, inhibiting further turndown. Potential for similar turndown can be investigated for other campus plants, but may not be possible for all.

Because the return on investment for efficiency drops significantly when reducing cogenerated energy use, it is not clear that campuses will pursue such additional reductions solely on that basis. It is more likely that available CHP turndown capability will be utilized in provision of lucrative ancillary grid services. This prospect is both a use of CHP to facilitate renewables integration and a potential source of revenue to fund other campus decarbonization measures.

2.8 Recommendations

2.8.1 Organize purchased utilities and carbon mitigation as stand-alone financial units on each campus.

We recommend that UC campuses and UCOP together take immediate steps to organize purchased utility and carbon mitigation costs as an integrated stand-alone financial unit on each campus.

The analysis presented in this chapter makes clear that utility cost reductions achieved through energy efficiency can make a substantial contribution to other potential costs for carbon mitigation and, in particular, the potential cost premium associated with substituting biogas for natural gas. To realize this contribution, we recommend that UC campuses take steps to organize purchased utility budgets and carbon mitigation costs as unified stand-alone financial units. The creation of stand-alone cost centers for purchased utility and climate mitigation costs is also a principal recommendation of the UC Carbon Neutrality Initiative Finance and Management Task Force Report (22).

To ensure that budgets are managed to meet the 2025 Carbon Neutrality Initiative commitment, we recommend that campuses, in coordination with UCOP:

- Preserve current budgets for energy utility purchases and energy efficiency project debt service associated with existing facilities.
- Integrate utility and climate mitigation budget projections through 2025.
- Adjust existing-facility budgets over time to account for energy price escalation and inflation.
- Provide new energy utility budget allocations for new facilities or significant programmatic changes.

2.8.2 Accelerate implementation of energy efficiency programs.

We recommend that UC campuses and UCOP accelerate implementation of energy efficiency programs.

The UC Carbon Neutrality Initiative Finance and Management Task Force Report represents a significant effort to identify and resolve barriers to implementing energy efficiency (22). Overcoming these barriers is critical to scaling energy efficiency such that the full benefits of energy efficiency activities (including their contribution to reducing or financing other carbon mitigation costs) can be realized. Increased attention to energy management staffing is a key initial step.

2.8.3 Identify approaches to ensure the persistence of energy efficiency savings.

We recommend that campus energy managers and UCOP collaborate to identify approaches to ensure persistence of energy efficiency savings.

Persistence of energy efficiency savings is paramount to a long-term strategy that funds carbon mitigation through efficiency. ISO 50001 provides an international energy management standard specifically intended to ensure that institutional practices are put in place to protect energy savings.

2.8.4 Investigate technical constraints limiting part-load operation of CHP.

We recommend that technical constraints limiting part-load operation of combined heating cooling and power plants be further investigated.

The primary efficiency scenario explored in this study does not significantly impact cogeneration operations. The exception is one campus case where CHP operation at part load has already been demonstrated in conjunction with reduced loads from efficiency and substitution of solar power. Cogeneration turndown could provide flexibility in pursuing deep efficiency in other cases and would be important in an eventual migration to other plant types. Turndown capability could also allow participation in lucrative Ancillary Services markets.

Additional investigation is warranted to clarify constraints and identify opportunities to operate CHP at lower loads.

2.8.5 Prioritize medical center energy efficiency projects to calibrate their efficiency potential.

We recommend that medical centers prioritize implementation of energy efficiency projects to calibrate their efficiency potential.

Of the three medical center campus cases, two were able to fund full biogas premiums in 2025 and 2028. This assumed a reduced potential for energy efficiency for medical center cases (13-14% gas savings instead of 29% on average, and 19-21% electricity savings instead of 39% on average).[8] However, medical center savings potentials are not well grounded in demonstrated project performance compared to the primary campuses. Assumptions should be verified based on demonstrated performance from a larger number of completed medical center efficiency projects.

2.8.6 Pursue high energy efficiency and avoid use of natural gas in new construction and major renovations.

[8] In four cases it was not possible to fully disaggregate the medical center load from campus utility accounts. Disaggregation of medical center usage from campus utility accounts would allow more accurate planning of the extent to which efficiency can generate budget for carbon mitigation.

We recommend that UC campuses and UCOP focus on approaches to pursue high energy efficiency and avoid use of natural gas in new construction and major renovations.

New construction and major renovations present a cost-effective opportunity to pursue strategies that increase energy efficiency and avoid use of natural gas. We recommend that UC campuses change processes as necessary to capture energy efficiency in renovations, and to develop and maintain high performance new construction approaches. By all means, such strategies should be incorporated into all construction to limit, as much as possible, the need for future retrofits. In these facilities, efforts may be directed to ongoing energy management and commissioning to ensure new assets continue to be operated in an efficient manner.

Chapter 3.
Switching to Renewable Biogas

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Chapter 3 Table of Contents

3.0 Biogas

Biogas, also known as biogenic methane, is produced from the anaerobic decomposition of organic materials such as manure, food waste, agricultural wastes, some crops grown for biogas, fermentable landfill materials, and biosolids at wastewater treatment plants. Once conditioned to remove impurities like CO_2, water, sulfur (H2S) and heavy metals, this biogas is essentially identical to utility-compliant fossil natural gas and can be substituted directly for it. As noted above, approximately two-thirds of UC's systemwide CO_2 emissions result from burning natural gas. Seven of the campuses currently operate central combined heating and cooling power plants (CHPs) where natural gas is burned to generate electricity and cogenerate building heating and cooling. Two thirds of UC's natural gas consumption occurs in these CHP facilities. Campuses with and without CHP plants additionally use natural gas to produce distributed electricity, steam, and hot water. Steam is very useful for high-heat applications such as sterilization in labs and medical facilities, and these can be high-capacity but not necessarily high-overall use applications.

In this context, biogas plays an important part in UC's exit strategy for fossil natural gas, though this may not be a scalable solution for others. The current biogas resource in the U.S. would satisfy only about 1.5% of the nation's total natural gas consumption (34). In addition, the current cost of biogas is significantly higher than that of fossil natural gas, particularly for biogas produced in California. UC's operating budgets are extremely strained, so minimizing the cost premium for biogas is an important consideration. Therefore, UC is pursuing a procurement strategy that provides funding for new nationwide biogas supplies to encourage biogas production. This strategy is designed to lower the net cost of biogas and the cost of UC's Cap and Trade compliance while significantly lowering UC's carbon emissions.

In this chapter, we discuss the current availability of biogas resources, the challenges to biogas production in California, UC's strategy for obtaining biogas supplies at least cost, cost estimates, and how costs are distributed across UC campuses. We discuss other issues related to biogas production and procurement, including local, on-campus production possibilities, and we review biogas use at other universities. Finally, we discuss hydrogen as a longer-term sustainable complement to biogas.

UC Biomethane Program

UC's Biomethane Program is managed by UCOP's Energy and Sustainability unit, with oversight by an Energy Governing Board composed of representatives from each campus, primarily vice chancellors for administration, vice chancellors for planning and budget, and chief financial officers. In 2015, the Governing Board reaffirmed UC's commitment to its Biomethane Program, and this commitment was also reaffirmed by UC's Global Climate Leadership Council (GCLC) in June 2017. UC's Biomethane Program includes authorization to procure biomethane volumes up to 50% of the university's current natural gas use at a 20-year average price of approximately $7/MMBTU. When compared to the average cost of natural gas and carbon allowances at the time the commitment was made, it was determined that this pricing would be cost-neutral over the proposed 20-year contract period. This procurement strategy provides campuses the flexibility to implement projects to reduce their natural gas demand, while also reducing risk and managing cost through diversification of their fuel portfolios.

3.1 Availability of Biogas Resources

3.1.1 Nationally

The most recent assessment of biogas resources in the United States (see Table 3.1) was performed by scientists at the National Renewable Energy Laboratory (NREL) (35).

Table 3.1. U.S. Biomethane Potentials by Source

Source	Methane Potential (thousand tonnes/yr)	
	Total	Available
Wastewater Treatment Plants (WWTPs; 1)	2,339	1,927
Landfills (2)	10,586	2,455
Animal Manure (3)	1,905	1,842
IIC Organic Waste	1,158	N/A
Total	15,988	6,224

Source: Saur and Milbrandt 2014

Notes

1. Total potential for WWTPs is higher, given that the analysis was done for only half of the WWTPs in the country (water flow data for the rest is missing).
2. Total potential for landfills could be higher given that the estimate accounts for only the waste-in-place (WIP) recorded for a given year and does not take into account additional waste that may have come in since the record was taken (as it was done for the "available potential" estimate). It is an approximate value. Available potential for landfills is estimated using candidate landfills only. Available potential could be higher if we include "other" and "potential" landfills.
3. Existing digesters (dairy, poultry, and swine) capture about 62,942 tonnes/yr.

3.1.2 In California

The NREL analysis reveals that California has the most abundant potential biogas resources of any U.S. state (35). However, California's complex regulatory and permitting processes make in-state biogas project development and production significantly more time-consuming and expensive than in other states. The most recent assessment for California biogas sources, summarized in Table 3.2, comes from the California Biomass Collaborative (36).

Table 3.2. California Estimated Annual Biomass Residue Available and Equivalent Renewable Natural Gas (RNG) Potential

		Biomethane (or RNG) Potential	
Feedstock	Amount Technically Available	(billion cubic feet)	(million gge)(9)
Agricultural Residue (Lignocellulosic)	5.3 MM BDT(1)	51.8(8)	446
Animal Manure (Dairy & Poultry)	3.4 MM BDT(1)	19.5(1)	168
Fats, Oils and Greases	207,000 tons(2)	1.9(10)	16
Forestry and Forest Product Residue	14.2 MM BDT(1)	139(8)	1200
Landfill Gas	106 BCF(1)	53(6)	457
Municipal Solid Waste (food, leaves, grass fraction)	1.2 MM BDT(3)	12.7(7)	109
Municipal Solid Waste (lignocellulosic fraction)	6.7 MM BDT(3,4)	65.9(8)	568
Waste Water Treatment Plants	11.8 BCF (gas)(5)	7.7(11)	66
Total		351	3,030

Compiled by Rob Williams, University of California, Davis (36) and revised April 2014, Oct., 2015, Feb., 2016. RevA., April 2016. Revised biomethane column titles.

Notes and Sources:

MM BDT = million bone dry (short) tons,
BCF = billion cubic feet
gge = gallons gasoline equivalent

1. Williams, R. B., B. M. Jenkins and S. Kaffka (California Biomass Collaborative). 2015. An Assessment of Biomass Resources in California, 2013. Contractor Report to the California Energy Commission. PIER Contract 500-11-020.
2. From: Wiltsee, G. (1999). Urban Waste Grease Resource Assessment: NREL/SR-570-26141. Appel Consultants, Inc. 11.2 lbs./ca-y FOG and California population of 36.96 million. Biodiesel has ~9% less energy per gallon than petroleum diesel.
3. Technical potential assumed to be 67% of amount disposed in landfill (2012).
4. 67% of mixed paper, woody and green waste and other non-food organics disposed in landfill (2013), (waste characterization and disposal amounts are from: http://www.calrecycle.ca.gov/Publications/Detail.aspx?PublicationID=1346 and http://www.calrecycle.ca.gov/lgcentral/GoalMeasure/DisposalRate/Graphs/Disposal.htm)
5. From EPA Region 9; Database for Waste Treatment Plants
6. Assumes 50% methane in gas
7. Assumes VS/TS= 0.83 and biomethane potential of 0.29g CH_4/g VS (food waste) & VS/TS = 0.9 w/ BMP= 0.143g CH_4/g VS (leaves, grass)
8. Assumes 19MJ/kg HHV for lignocellulosic feedstock and 60% conversion efficiency to synthetic RNG via gasification followed by methane: Mensinger, M., R. Edelstein and S. Takach (2011). The Potential for Renewable Gas: Biogas Derived from Biomass Feedstocks and Upgraded to Pipeline Quality. American Gas Foundation & Gas Technology Institute. Aranda, G., A. van der Drift and R. Smit (2014). The Economy of Large Scale Biomass to Substitute Natural Gas (bioSNG) plants. ECN-E-14-008.
9. ~116 ft^3 methane is equivalent to 1 gge (983 Btu/scf methane and 114,000 Btu/gallon gasoline, lower heating value basis). Diesel gallon equivalents can be estimated by multiplying gge by 0.89
10. Assumes FOG biomethane potential of 400 litre CH_4/kg VS, 100% VS in FOG and practical digester conversion efficiency of 70%. BMP from: Allen, E., D. M. Wall, C. Herrmann and J. D. Murphy (2016). "A detailed assessment of resource of biomethane from first, second and third generation substrates." Renewable Energy 87, Part 1: 656-665.
11. Assumes 65% methane in gas

3.2 UC Biogas Development Strategy

To date, the university has executed two agreements to obtain biomethane that will eventually supply about 10% of UC's natural gas needs for all campuses and medical centers. These contracts support the construction and operation of new biogas facilities in Louisiana and Wisconsin.

3.2.1 Shreveport, Louisiana

Under the first agreement, UC is constructing a biomethane facility adjacent to an existing landfill owned by the City of Shreveport in Keithville, Louisiana. Currently, the gases (primarily methane) that originate from the landfill through the decomposition of buried waste are burned on-site without energy recovery. Once the project is completed, the collected landfill gas will be treated using a UC-owned processing facility and then injected into an interstate natural gas pipeline. This will provide a regulatory-certified biomethane supply for use by the university at all its campuses. At full capacity, the 20-year project will supply a carbon-neutral fuel to offset approximately 5% of the natural gas currently burned on UC campuses. Table 3.3 shows the basic cost arrangement for the campuses.

Table 3.3. Calculation of Final Cost to Campuses for the Shreveport Project Based on Current UC Contract Pricing

$7.12	Cost to produce and transport an MMBTU of biomethane
-$3.00	Sale of natural gas "component" of biomethane in Louisiana
$4.12	Value of environmental attribute "component" of biomethane

$4.12	Value of environmental attribute "component" of biomethane
$3.30	Campus purchase of natural gas in California
$7.42	Final cost to campuses for an MMBTU of biomethane

$7.42	Final cost to campuses for an MMBTU of biomethane
-$0.65	Avoided cost of cap and trade
$6.77	Cost realized by campuses

3.2.2 Green Bay, Wisconsin

Under the second executed agreement, the University has contracted with EEC Denmark to operate a biomethane facility in New Denmark, WI (near Green Bay). This contract is a type of "off-take" agreement, meaning that the university has agreed to purchase biomethane without making any capital investments. The biogas will be generated through anaerobic digestion of organic waste from several food processing streams including dairy wastes, beef slaughter wastes, rendering wastes, produce wastes, fats, oils, and grease. This 20-year agreement will supply a carbon-neutral fuel to offset approximately 3.5-7% of the natural gas currently burned on UC campuses, depending on actual production volumes. The contract price for the biomethane under this agreement is $7.50/MMBTU for 500,000-1,000,000 MMBTUs per year, resulting in an estimated annual cost of $3.75-$7.5 million.

Combined, these two biogas contracts will reduce the university's carbon footprint by approximately 36,600 metric tons per year. This biomethane will not physically replace any natural gas used on campuses. Instead, carbon credits (offsets) have been acquired which, through GHG accounting, will help reduce UC's institutional GHG emissions. Like other project costs, these biogas carbon credits were much less expensive than those available in California, or from projects that might be developed in-state.

While there might be local benefits to procuring biogas in state, UC's out-of-state investments in biogas development are consistent with its standard practice of procuring commodities, equipment and services of appropriate quality and cost from local, national or international sources. Obtaining biogas at least cost satisfies the need of key UC stakeholders — most importantly, students and their families — to contain costs while also achieving sustainable operations and contributing to global warming solutions, goals to which a large portion of the student body is committed.

UC's engagement in biogas development is a part of the progression of the technology and its market. For example, CHPs, with their inherent efficiency, are arguably one of the highest and best uses of biogas. UC's cogeneration capability represents 1% of the California building footprint, but 9% of the California building-supplying cogeneration capacity. Cogeneration is roughly twice as prevalent in California as in the rest of the U.S. (37), so it is to be expected that biogas supply would flow into California and be used by cogenerators such as UC. UC's participation is actively advancing the development of the technology, and it is expected that the university will also have an active role in further developing California's biogas resources.

3.2.3 Pipeline Natural Gas ("Directed" Biomethane)

Under cap and trade regulation and various other emissions reporting methodologies, the university can take advantage of "directed" biomethane also known as "displacement." Directing or displacing biomethane means that the university can inject biomethane into a natural gas pipeline at location X and remove equal volumes of natural gas at location Y, without having to ship the biomethane in the natural gas pipeline. For instance, it is permissible to inject the biomethane in Shreveport, Louisiana and take credit for it when it is consumed at UCLA.

To be able to take credit for biomethane at a different location from where it was injected, the university must establish contractual history with the biomethane from the source to the end consumption. This is done through a series of attestations that accompany each transaction point, which states that the volumes transferred are actually biomethane volumes. In practice, the act of displacement results in biomethane becoming two commodities: natural gas and the environmental attributes associated with biomethane. The natural gas commodity is bought and sold at each transaction point, and the environmental attributes are retained, as signified by the attestation.

3.2.4 Cap and Trade Requirements

Not all biomethane sources meet the objectives that the university is trying to achieve. To satisfy the California Air Resource Board's (CARB) cap and trade requirements to which the University is subject, the biomethane must meet the following two requirements:

1. The gas must be directly injected into the natural gas pipeline at the source.
2. The project's GHG reductions must be "additional" to what would have occurred in a business-as-usual scenario. To meet CARB requirements, the gas cannot have been productively used for at least three years (i.e., approved sources must be an increase in previous production or the recovery of previously vented or flared gas).

3.3 Additional Biomethane Sources and the Potential Role for Hydrogen

3.3.1 Biomethane Procurement

In December 2016, UCOP ran an open solicitation for additional biomethane supplies and received 25 project bids from 14 suppliers across the U.S. Two landfill projects were from a supplier in California. The other projects were out-of-state and included anaerobic digesters (n=12) with a range of feedstocks, landfills (n=10), and wastewater treatment (n=1). The volumes for each project ranged from 15,000-2,300,000 MMBTU/year. The largest single project could potentially supply about 14% of UC's total need. The seven least-expensive projects would supply 100% of UC's natural gas use. In other words, biomethane supplies are available. However pricing is high. The median price of all bids was $13.73/MMBTU, as shown in Figure **3.1**. This result was initially disappointing and briefly discouraging.

However, while none of the proposals met UC's pricing criteria, negotiations are underway with several of the suppliers to review alternative financial structures. It is now anticipated that UC will be able to secure supplies to fulfill the 50% authorization while meeting long-term pricing targets.

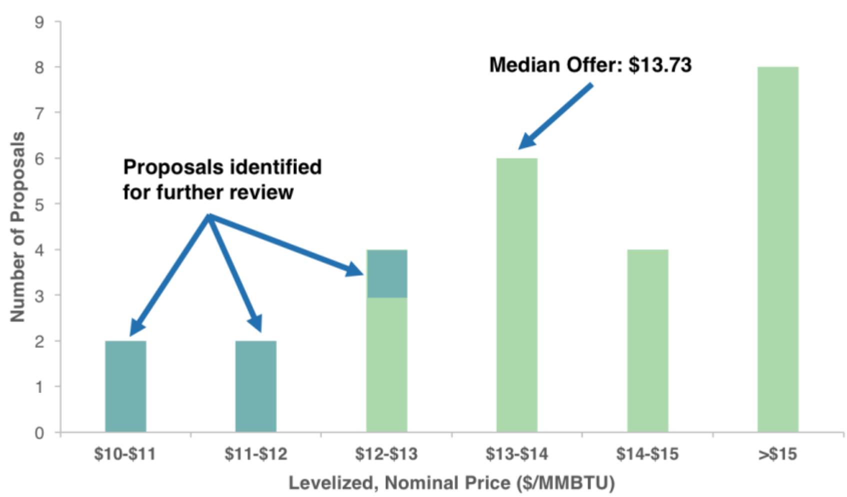

Figure 3.1. Distribution of contract bids for biogas to UCOP in January 2017

UC's Energy Governing Board is taking a "wait and see" approach to the execution of additional biomethane supply contracts beyond the 50% authorization. With eight years to the Carbon Neutrality goal, plans are not yet in place to develop a well-defined portfolio of new supplies (e.g., adding 5-10% in new supplies each year over the next five to 10 years). The early-year cost premium for biomethane, a potential funding challenge for the campuses, may be managed through means including cost recovery, hedging, and direction to higher-value markets as discussed in section 3.5.2 and 3.5.3. UC continues to evaluate the market, and may recommend the execution of new contracts based on changing regulatory or financial circumstances.

3.3.2 On-Campus Distributed Generation Resources

Biogas can be harnessed near the desired end load and used in small-scale distributed systems. Possible small-scale generation sources include:

- Anaerobic digestion. Anaerobic digestion can be used to directly generate electricity onsite or to provide a source of renewable natural gas. This option is attractive because it can help campuses comply with their organic waste diversion and zero waste commitments. UC Davis's "Renewable Energy Anaerobic Digester" (READ) project is an example of this technology. The READ system uses a combination of methane gas from the campus's closed landfill, and anaerobic digester biomethane produced using organic waste from campus dining halls and other local sources. It supplies 925 kW of renewable electricity to the campus grid. The electricity is generated by four 200 kW microturbines that directly burn the biomethane, with an additional 125 kW produced by converting waste heat from the microturbines into electricity using a Rankine-cycle (ORC) engine. This project also highlights the challenge of making biomethane a complete solution. At UC Davis, direct use of biogas was not economical, so the gas is burned to generate electricity. All feasible organic waste from the campus is sent to the biodigester, along with a significant volume of off-campus organic waste. And yet only about 0.5% of campus electricity needs are supplied by these biofuels. The economics of anaerobic digestion are primarily driven by waste management rather than energy generation.

- On-site fuel cell technology using "directed" biogas. In addition to electrical production, waste heat from the fuel cells can be used to support an absorption chiller, or possibly additional energy production using a low-grade heat generator. An example of this is UC San Diego's fuel cell, which uses directed biogas from a local wastewater treatment plant to supply 2.8 MW of renewable electricity to the campus microgrid. In addition to electricity, a 300-ton absorption chiller uses waste from the fuel cell to provide additional campus cooling capacity.

- Small-scale biomass generation for syngas production. Syngas is produced by the thermochemical conversion of biomass into a synthetic gas. This gas can then replace natural gas used in powering turbines providing onsite electrical generation. Syngas is generally produced through a high-heat gasification process.

Typically the quantity of biogas or producer gas that can be generated locally from campus resources is too limited to support stand-alone conversion facilities, which is why several institutions with carbon neutrality goals have decided not to use it as a primary decarbonization strategy (e.g., Cornell, Loyola).

3.3.3 Hydrogen as a Longer-Term Sustainable Complement to Biogas

Available biogas resources may be capable of offsetting some UC natural gas use. However, as stated above, the current U.S. biogas potential represents 1.5% of the national natural gas consumption. Energy efficiency, electrification of thermal loads (particularly heating), the maximized production of biogas, and extensive adoption of renewable power generation technologies will all support the decarbonization of the UC system, the U.S., and the world. Other technologies such as renewable fuels, should be considered to achieve long-term decarbonization. Renewable production of hydrogen can complement biogas use and provide a useful mode of storage in the short-term, and, in the long term, it can serve as the primary means of sustainably producing and delivering renewable energy. At the same time, such renewable production of hydrogen can support the much more thorough adoption of renewable electricity (solar and wind) in the electric utility grid network. All of this can be accomplished by using renewable electricity to make the hydrogen energy carrier through splitting of water molecules using electrolysis.

In particular, California, parts of Europe, and eventually the entire world will be faced with an increasingly urgent need to deploy utility-scale energy storage solutions to support the integration of large amounts of intermittent renewable power generation resources. One promising approach to address this need is the use of hydrogen as an energy storage medium in an approach referred to as Power-to-Gas (P2G) and/or Hydrogen Energy Storage (HES). Renewable electricity that would otherwise be curtailed is converted into a hydrogen energy carrier by electrolysis. The hydrogen can be used as a transportation fuel or converted back to electricity on-demand via fuel cells with zero greenhouse gas and zero criteria pollutant emissions. (See Figure 3.2 for the various use cases.) Beyond the storage function of converting electricity to gaseous fuel for later use, these systems can cycle up and down rapidly providing additional grid support functions including voltage and frequency regulation and rapid ramping up or down as needed. This technology is currently being deployed in Europe and Canada. It is only at the early demonstration phase in California and is not as widely known as other energy storage approaches such as batteries, pumped hydro, and compressed air.

With current knowledge and available technology, the hydrogen option appears to be very challenging. Two clusters of problems have emerged. Most hydrogen produced worldwide today is not zero-carbon, but instead produced by steam reforming of natural gas, with CO_2 as a byproduct. Zero-carbon alternatives include electrolysis using zero-carbon electricity or reforming of biogas. Of the two, electrolysis is more likely to occur on-site, thus avoiding the need for transport infrastructure. However, the cost of hydrogen from modern electrolyzers is a factor of 4-5 times greater than the cost of hydrogen from reformed natural gas, and if the UC procures biogas, it could be burned directly. The other challenge is integrating hydrogen with the existing natural gas infrastructure. Above a few percent concentration, there are concerns that hydrogen might corrode seals and embrittle materials; current natural gas-burning technologies such as turbines are not typically rated (or warrantied) for use with high concentrations of hydrogen. Technically, these problems are solvable, but many solutions require replacement of infrastructure at unknown cost.

In the long term, renewable hydrogen as an energy storage and transport medium may be able to serve UC, the nation, and world at a scale that supports: (1) handling the intermittencies of a 100% renewable electric grid, (2) ubiquitous low-cost transmission and distribution of zero-carbon energy, and (3) end-use conversion to heating, cooling, and electricity with zero carbon and zero criteria pollutant emissions.

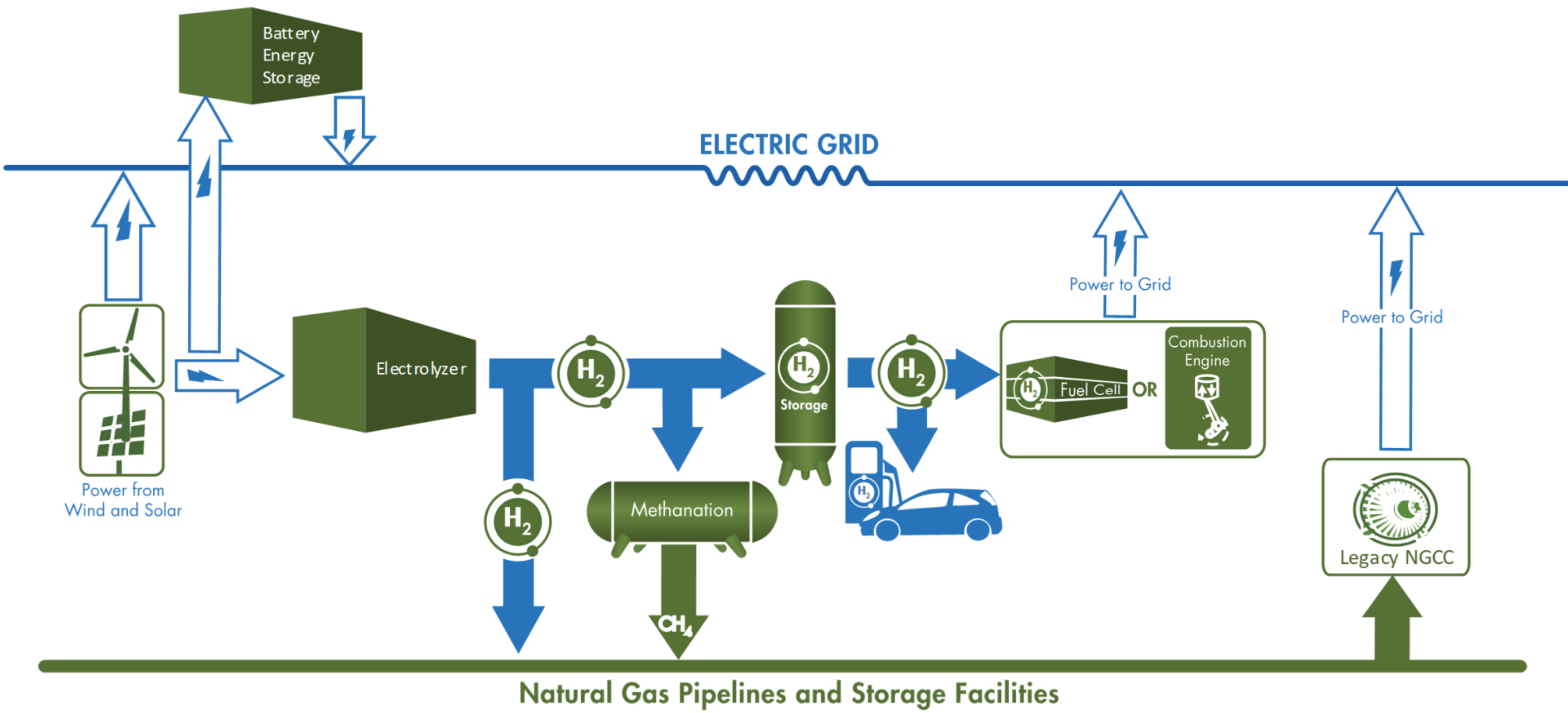

Figure 3.2. Various use cases for power-to-gas and hydrogen energy storage

When the utility grid network incorporates high levels of solar and wind resources, daily and seasonal variations in resource level will require storage over longer time periods. P2G and HES are uniquely suited to these long-duration storage needs because of the fundamental feature of separate energy and power scaling and potential for widespread integration with both power and gas transmission, distribution, and storage infrastructure. The power scales based on the size of the electrolyzer and fuel cell, while the energy scales separately based on the size of the hydrogen storage system. For batteries, power and energy both scale based on the number of batteries. Batteries also suffer from self-discharge making them not well-suited to long-duration energy storage.

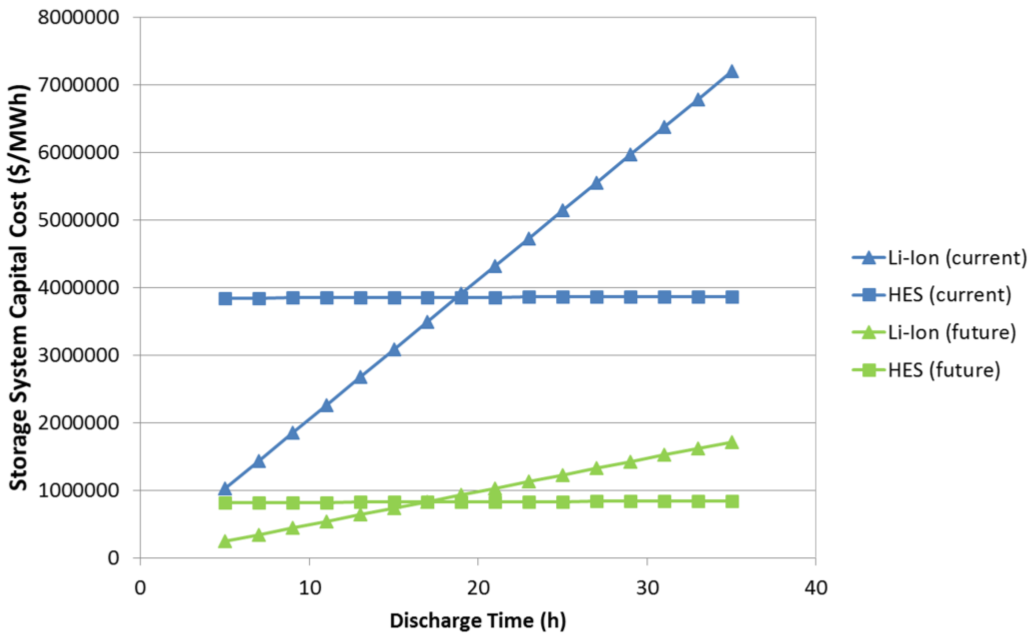

Figure 3.3. Costs of li-ion battery systems compared to hydrogen energy storage for various discharge times (storage capacities). Source: (38).

While battery system costs go up in proportion to the quantity of energy stored (duration), P2G cost is nearly independent of the quantity of energy stored when the existing gas grid is used as the storage medium, as shown in Figure 3.3. Although future costs are subject to uncertainty, the Li-Ion and HES cases assessed here reflect a cross-over in efficiency-adjusted capital cost with lithium-ion battery costs at a storage duration of between 17 hours and 19 hours of storage capacity.

3.4 Methane Leakage

Methane is a powerful greenhouse gas in the atmosphere, and leakage ("fugitive" emissions) from any system — whether fossil gas or biogas — contributes to climate change. Those upstream losses, however, are not currently included in the university's GHG emissions accounting. Cumulative radiative forcing of fugitive methane emissions is most often evaluated using a Global Warming Potential (GWP) factor which expresses the radiative forcing of methane over a specific time horizon (e.g., 20 years or 100 years) as a multiple of CO_2. Recent studies and reports tend to use a 100-year GWP for methane ranging from 28-36 (e.g., IPCC, UN Framework Convention on Climate Change, US EPA) although this time horizon reflects a relatively strong discounting of future warming by much longer-lived CO_2.

Given this GWP, there has been extensive work over recent years to estimate leakage rates and other "unaccounted for" losses of natural gas from various locations, processes, and systems. Such work has included life cycle analyses of shale gas extraction ("fracking") (39-41), bottom-up measurements of natural gas distribution and transport infrastructure (42-44), system-wide scenarios of natural gas use (45, 46), and overarching meta-analyses (47). Estimates of system-wide leakage rates in the U.S. range from 1.1% to a maximum of 6% (in the implausible case that all atmospheric additions of methane were from the natural gas system), with mean leakage ranging from 1.9-2.6% (48, 49).

In the case of natural gas, methane leakage may occur anywhere in the system prior to the gas being burned (Figure 3.4).

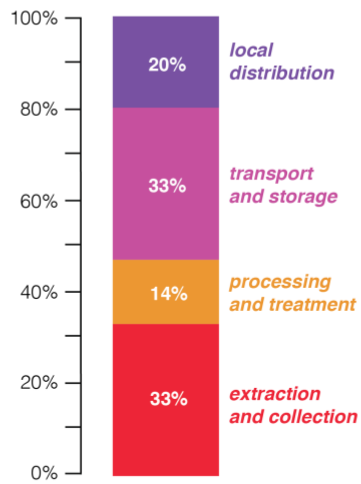

Figure 3.4. Proportions of methane leaked during different life cycle stages (50).

For methane derived from biomass rather than fossil sources, only extraction and collection processes would be substantially different. The research that has been done on fugitive emissions from anaerobic digesters suggests that leakage rates are comparable to or greater than those of fossil operations. For example, measurements at a Canadian facility estimated a leakage rate of 3.1% (51). Thus, we assume that concerns of leakage would persist regardless of whether or not methane is fossil-derived.

To achieve net-zero radiative forcing, leaked methane would need to be estimated and offset by other methods, for example by negative emissions technologies capable of removing CO_2 from the atmosphere (52). The equivalence of "carbon neutrality" and "net-zero radiative forcing" must therefore be evaluated, with implications for the cost of achieving university goals via increased use of biogas. Managing UC's biogas development to achieve the desired overall net impact on GHG emissions will require assessment of fugitive emissions alongside emissions avoided by capturing methane from manure or landfills that were previously open to the atmosphere.

Although some of the most recent studies indicate that leakage rates vary according to the age of related infrastructure (i.e. older pipes tend to leak more) (53), there is not yet comprehensive, region-specific data available by which we might assess differences in leakage if biogas is procured in Louisiana, Wisconsin, or California. Thus, estimates of leakage in this report are based on a nationally-averaged, system-wide range that is, in turn, drawn from numerous studies (48).In a survey of 24 other universities with carbon neutrality goals, only Cornell University explicitly accounted for methane leakage in their greenhouse gas inventory. Doing so quadrupled their baseline CO_2 emissions (54).

3.5 The Cost of Biogas

3.5.1 Cost Estimates

The basic costs for biogas production include capturing, conditioning and compressing. The degree to which the gas needs to be cleaned or conditioned after collection depends on both its original source and the intended end-use. Thus, the ultimate cost of the gas is largely dependent on the degree of processing needed to make it a useful fuel for its intended purpose. In the case of direct pipeline injection, the cost of transporting the fuel must also be considered.

Federal and state incentives support switching to renewable biogas as a substitute for fossil-derived natural gas by encouraging the development of biogas supplies and helping to directly lower prices. Another factor influencing biogas costs is both national and state carbon pricing policies to reduce GHG emissions. For example, a presumed carbon price of \$20/$MTCO_2e$ could equate to an added price premium of \$1.06/MMBTU that parties are willing to pay for biogas.

The supply of biogas is dependent on the capital cost of production, availability, energy yield, and any potential cost for the base feedstock. These factors, in turn, collectively determine the overall Levelized Cost of Energy (LCOE) for each source type. The availability of a particular biogas source is then dependent on the LCOE. Figure 3.5 shows the combined potential in billion cubic feet per year for four biogas (or Renewable Natural Gas) sources versus their cost of production in \$/MMBTU (55).

Using actual capital and operating costs, a supply function was developed showing that there is a clear correlation between price point and biogas supply. In other words, as the price consumers are willing to pay for biogas rises, there is increased interest by producers. This is especially evident in the long-term, where there is more time for supply to react to price signals. As prices rise and remain high, there will be more interest in production. Whereas, if prices fall for a sustained period, producers will leave, and supply will decline.

Current market pricing for biogas, when cleaned for pipeline injection as a substitute for fossil natural gas, ranges from \$7 to \$15 per MMBTU depending on the process used to derive the biogas. However, the EPA has recognized biogas, when processed to standards for pipeline injection and compressed to be used as a transportation fuel, as “Renewable Compressed Natural Gas” (R-CNG). This designation makes the biogas eligible to generate “Renewable Identification Numbers” (RINs) under the Renewable Fuel Standard Program (56). Use of biogas as a transportation fuel is now driving parts of the market, increasing the cost \$5-9 per MMBTU, which may be reflected in the higher costs seen in the recent UCOP solicitation.

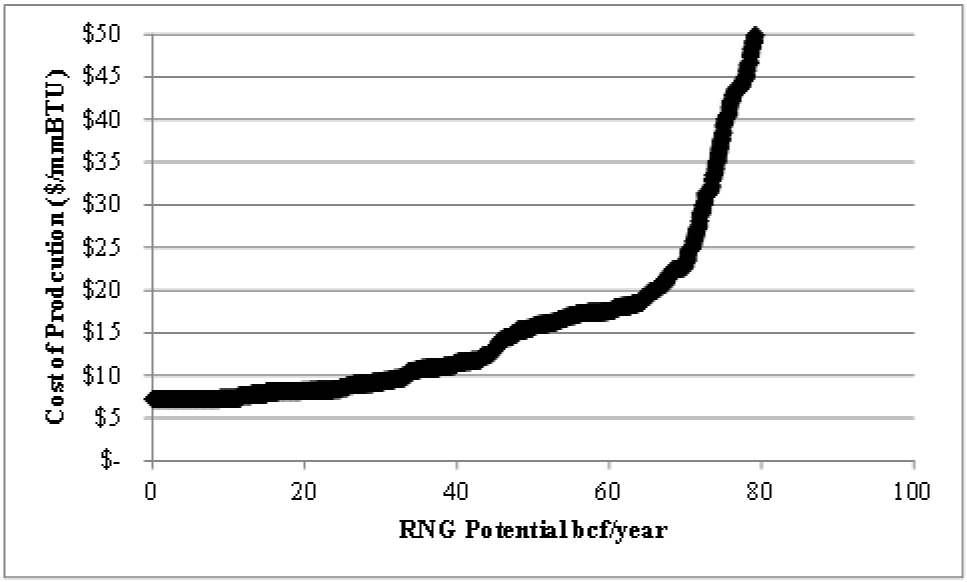

Figure 3.5. Potential for biogas (or RNG) sources (diary, waste water treatment plants, municipal solid waste and landfill) vs. cost of production. Source: (55).Note: data reflect California costs and resource amounts, which are estimated to be about 33% higher than the U.S. average.

There seems to be a wide range of estimates regarding the overall availability and potential U.S. market penetration of biogas. The estimate could rise if lignocellulosic biomass resources are used, increasing total supply to 4.2 trillion cubic feet per year, or enough to supply about 15% of total U.S. demand (34).

3.5.2 Recovering and Allocating Costs

Prior to 2025, the estimated $21 million capital cost and all operating expenses for the Louisiana and Wisconsin projects will be recovered through third-party sales of the biomethane. After 2025 the costs will be recovered via commodity charges to the campuses per existing agreements between the campuses and UCOP's Energy and Sustainability unit. The net cost to the campuses, in combination with the Shreveport project, is expected to be in the low $7/MMBTU range. The current arrangement with the campuses allocates the biogas volumes and cost proportionately based on current natural gas use.

3.5.3 Biogas as A Hedge Against Natural Gas and Cap-and-Trade Costs

The process for directing biomethane to the campuses is the same as directing it to other, higher-valued markets (i.e., transportation fuels). The environmental attributes for biomethane currently have significant value in other markets. Because the driving force for the university's biomethane program is to comply with the Carbon Neutrality Initiative's 2025 target, the university is proposing to sell all or part of the biomethane attributes for some period before 2025. At the beginning of 2025 the university intends to supply its campuses with the biomethane production to meet its carbon neutrality goals. This will generate revenue at the outset of the project and lower the net cost of biomethane to UC campuses after 2025 for the life of the project.

In this way purchase and operation of the biomethane facilities effectively provides a 20-year financial hedge on both natural gas prices and the cost of the university's compliance obligations under

California's Cap and Trade program. However, because the value of the environmental attributes of the biomethane is the difference between the price to produce the biomethane and the price of natural gas, it is much more effective to compare the estimated cost of the environmental attribute to the cost of California carbon allowances.

The contracted price of biomethane limits the university's exposure to volatility in these markets. The university, however, is still exposed to other market risks. In particular, natural gas and carbon prices may not progress along the estimated upward trajectories, resulting in the university "overpaying" for biomethane for the duration of the project life. However, the university is initiating this project at a time when natural gas prices are at historically low levels, and true price of carbon compliance has not influenced energy markets. If the university can accept the initial pricing, the comparison to market pricing is anticipated to improve over the next 20 years.

As mentioned previously the aggregated costs associated with the procurement of biomethane will be recovered from all campuses and medical centers through a commodity charge structure. Campuses and medical centers will be charged by the Office of the President for the biomethane they consume, in lieu of carbon-based natural gas and Cap and Trade compliance instruments. The current arrangement with the campuses proportions the biogas volumes and cost based on current natural gas use. With each new tranche of biogas, those supplies would be locked in. This approach provides the campuses with more certainty about the volumes of biomethane they will receive, allowing the campuses to optimize their energy use and procurement decisions.

3.6 Review of Biogas Use by Other Universities

We reviewed biogas integration at 25 U.S. universities that have set carbon neutrality targets (See Appendix B). Our findings reveal a variety of approaches to integrating biogas into campus operations. They do not, and are not intended to, proportionately reflect all universities using biogas across the U.S.

Nine universities that currently use biogas primarily procure it from offsite but nearby sources, such as wood waste from mills, forest management, and landfills. A few universities are attempting to grow their own willow plots to serve as supplemental, on-site sources of fuel (Middlebury College, Colgate University, and SUNY College of Environmental Science and Forestry). All of the schools using biogas view it as a long-term solution for their campuses' greenhouse gas mitigation. Half have already achieved carbon neutrality. Two of the surveyed schools have biogas projects underway, according to their most recent climate action reports. Seven schools are openly considering future use, and one of these schools (Duke) is considering a CHP plant that will be fueled by purchased biogas from nearby swine farms.

Stated reasons by the other seven campuses for explicitly avoiding or limiting biogas use include lack of suitable material to supply campus needs (Loyola and Macalester) and missed opportunity to gain rights to a local landfill (UMass). At Bowdoin, space and transportation constraints limit biomass technologies on campus, but the college may reconsider this option if they can find a biomass fuel source with a sufficiently high energy density (57). In addition to the problems of limited biomass suppliers and declining costs of natural gas, the University of Montana had a particularly compelling case for canceling the construction of a new biomass heating plant in 2011: the city of Missoula has a history of poor air quality, and the university faced strong opposition to the proposed plant's emissions.

Appalachian State University does not include biogas as part of its carbon neutrality solution, but it initiated its NEXUS project in 2013 to research applications of biomass technology in sustainable agriculture. Cornell rejected biogas as a stand-alone heating and powering solution due to small maximum sustainable yield on local land, although it is still evaluating the feasibility of using biomass to supplement other renewables. It is clear in all these cases that biogas was considered only as a local option and not as a nationally available commodity.

3.7 Scalability Beyond the University of California

As noted above, the potential national biogas resource is significantly smaller than current natural gas consumption (35). Figure 3.6 illustrates the magnitude of difference between current natural gas consumption and technical biogas potential at the national and state levels. UC's current natural gas consumption is also shown. The relative magnitudes indicate that biogas can only play a small role in long-term decarbonization nationwide. Although, in the near-term, early institutional adopters of biogas will be able to offset their fossil gas use with biogas.

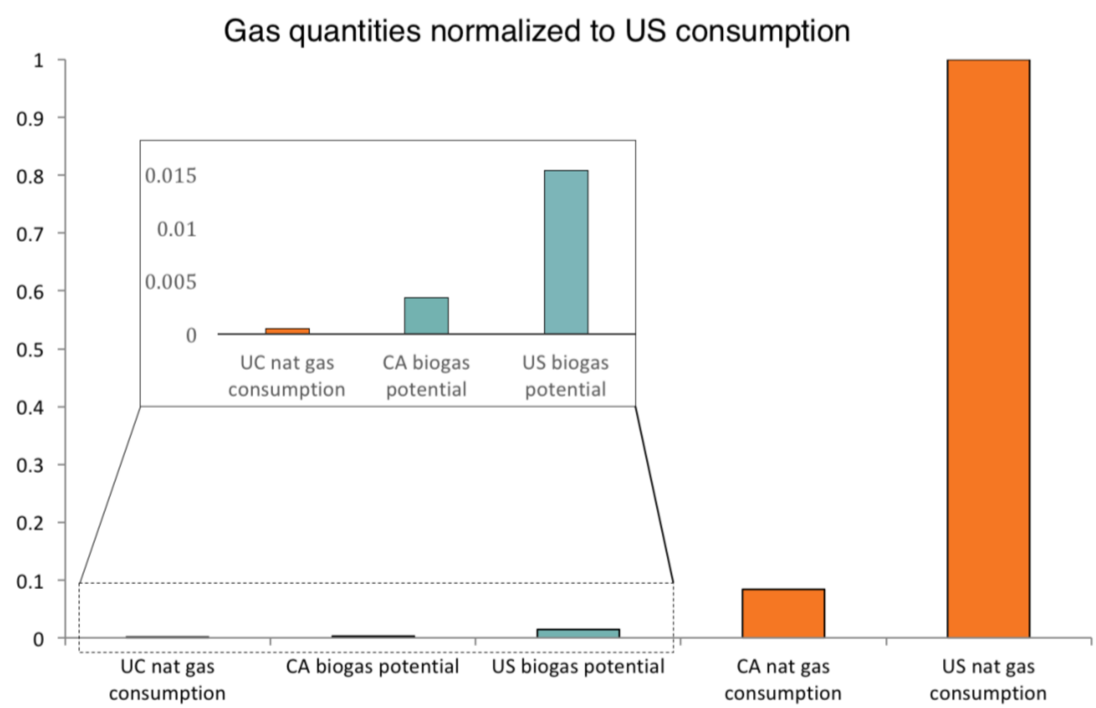

Figure 3.6. Gas quantities normalized to U.S. consumption. Source: (35). Inset panel shows the first three bars on a finer scale y-axis so that the values can be read.

3.8 Encouraging California Biogas Development

The academic resources of the UC system, coupled with its organizational experience in the development of biogas projects, could provide a valuable model for helping stimulate biogas production in California, which has the most abundant potential biogas resources in the U.S. (34). It has been suggested that UC consider mobilizing its faculty and related resources to facilitate in-state biogas production. Their first task would be to identify in-state project development opportunities that would benefit from the university's collective scientific and engineering capabilities, and which would otherwise not be viable without UC involvement. Second, UC could help with development, engineering and environmental impact review (EIR) costs. While challenging, this approach could accomplish two goals: (1) in-state biogas project development with local economic benefits, including job creation, and (2) more efficient use of in-state biomass resources.

California policy currently emphasizes biogas as a transportation fuel. Although UC could use biogas for transportation, since any institutional GHG reductions are of value, one objective of such an endeavor would be to make biogas available for a wide range of applications. Student involvement in research, implementation and policy-related efforts would provide opportunities for real-world teaching and result in a better public understanding of the opportunities and constraints on organizations pursuing carbon neutrality.

3.9 Considerations for Managing Biogas at Large Institutions

Decisions on how to use biogas will significantly impact management of the natural gas infrastructure. Many large institutions, like the University of California, have numerous sub-entities, similar to UC's campuses that operate semi-autonomous energy facilities. Each of these facilities is managed with an assumed output and a maintenance and retrofit schedule that cannot necessarily be changed quickly without incurring significant costs. Clear and timely communication of institutional-level biogas policies will be essential for smooth operation of such facilities. In particular, there are a few aspects of multi-campus biogas planning that need to be communicated, including use categories, timeline and internal allotment.

3.9.1 Use Categories

UC or other institutions procuring biogas need to make clear whether the biogas is intended to offset all categories of natural gas use, or only specific cases. For example, is the biogas to be used strictly for CHPs or can it also be used for individually-fired gas boilers? Given the energy efficiency and other benefits derived from cogeneration, there may be some justification for preferential allocation of the limited biogas resource to this use. Also, thought needs to be given to whether biogas should be directed to new construction or only to facilities that are reliant on natural gas as of some initial date. Lack of predictability and clarity on these distinctions may lead to sub-optimal decision-making on the part of individual campus facilities teams.

3.9.2 Timeline

Institutions need to decide whether biogas will be used as a short-term bridge fuel or as a long-term resource. If the institution chooses to use biogas as a bridge fuel, then it can be used as a buffer during a long-term transition away from all gas infrastructure. On the other hand, a plan to use biogas for the foreseeable future does not inherently motivate a switch away from fossil natural gas. In particular, cogeneration and large central plant facilities will likely keep operating and possibly even be expanded.

As an example, UCLA has an existing natural-gas-fired cogeneration plant that produces electricity and steam for the entire campus including its Medical Center. To meet Office of Statewide Health Planning and Development (OSHPD) requirements for medical facilities, UCLA plans to build a new standalone central plant to supply steam and chilled water for the UCLA Medical Center. The addition of this new natural gas connection is seen as a cost-effective means for meeting a mandated requirement. It is possible that an alternative approach would have been taken if UCLA was told that biogas supplies were only guaranteed for a limited time.

3.9.3 Internal Allotment

When biogas is purchased as an offset, and not directly produced on site, there are many questions involving who does the purchasing, for whom, at what cost, and over what timeline. The University of California, like many organizations, has chosen to centrally manage biogas contracts. This has given rise to questions of internal apportioning and cost transferal.

To manage risk, the acquisition of biogas has initially been set at a level below all of the campuses' natural gas needs. Consequently, a set of principles is needed for deciding how biogas costs and offsets are distributed among the campuses. The University of California is currently planning on allotting biogas allowances based on each individual campus's proportion of total systemwide natural gas use at the time of the initial biogas purchase agreement.

At the moment, the University of California is not envisioning a trading scheme for internal biogas allotments, but, hypothetically, this would improve the economic efficiency of reaching net zero carbon. Certain campuses, such as those with older steam systems or fewer previous investments in efficiency retrofits, will be able to more cheaply reduce and electrify loads than other campuses. This relative cost would be accounted for if the campuses could buy and sell biogas permits from each other. Of course, implementing an internal cap and trade system would itself come with overhead management costs.

Finally, the actual cost seen by the individual campuses for biogas is not obvious. Typically, biogas will be purchased in long-term contracts with some pre-specified price structure. UC could choose to pass these costs on to the individual campuses either as fixed long-term averages, scheduled changing values, or dynamically floating values that account for uncertain investment costs in further biogas acquisitions. The relative uncertainty each campus sees will affect localized decision making on optimal energy planning.

3.10 Concluding Remarks

Biomethane has a role in reducing GHG emissions, although biogas cannot fully replace natural gas as a long-term supply because of the low quantities available. Given these limitations, biogas is well suited as a fuel for highly efficient systems that are not easily electrified, particularly during the transition to comprehensive electrification. UC's combined heat and power plants are good candidates for biogas until they reach end of life.

In obtaining biogas, ideally, UC might favor locally-sourced, fugitive-emission-reducing methane supplies to meet its most critical natural gas needs. However, in-state supplies are currently significantly more expensive than out-of-state projects. UC's researchers can work to address these issues to support more affordable California biogas. In the meanwhile, UC's strategy to initially lock-in 20-year contracts for approximately 50% of needs eight years out from the Carbon Neutrality goal provides a balance between securing ability to drive down emissions, minimizing cost impacts, and leaving open the possibility of even more beneficial arrangements to round-out the decarbonization portfolio.

Chapter 4.
Electrify End Uses Presently Served by Natural Gas-fired Equipment

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4.0 Electrification

The third major action that can be taken to reach carbon neutrality is to replace conventional natural gas use with carbon-free electricity (58). In tandem with UC-wide and California-wide efforts to reduce emissions from the electric power system, electrification has already begun on several UC campuses, and UC has committed to procuring green energy, including its opening of an 80-megawatt solar power installation to supply roughly 10% of UC's total electricity usage and 20% of direct purchases.

The basic premise of electrification is that carbon-free electricity would be used to provide the same services as those currently powered by natural gas. This can be accomplished either through district systems, such as campus-wide or partial-campus steam or hot water with a central or distributed physical plant, or building-specific boilers providing energy services such as space or water heating. Some current high temperature uses of natural gas, (such as ovens or Bunsen burners), would be inefficient to meet with electrification and might instead be provided by localized gas-fired equipment.

To pursue electrification, the first step is to understand where and for what purpose natural gas is combusted within the UC campuses. This includes space heating and cooling, domestic and process hot water, cooking, sterilization, and other process uses. Once these end-uses of natural gas have been identified, quantified, and mapped onto the sources and distribution modes listed above, the next step is to investigate electric technologies that could be used as substitutes. Finally, electrification options would be prioritized based on size of the opportunity, practicality, and efficiency of the electric substitute, in the context of infrastructure renewal planning.

A key premise of an electrification strategy is the availability of carbon-free electricity. Thus, our analysis assumes that the University will be able to obtain carbon-free electricity through some combination of on-site self-generation, development of off-site generation, and purchasing of increasingly available 100% renewable supply options through the electric grid. Note that this approach will eventually require purchase of both renewable electricity and storage of such as the percentage of renewable energy on the utility grid network increases.

4.1 The Defining Problem for Electrification: Heat

The defining problem for electrification analysis is the use of electricity to provide heat at a wide range of temperatures. Two methods of generating heat are typically considered: resistance heating and heat pump technologies. Resistance heating -- flowing electricity through a resistor -- is the simplest way to turn electricity into heat at any temperature required on a university campus. However, electric resistance is a costly form of heating, much more expensive than fossil fuel-based or even de-carbonized bio-fuel combustion. The much more efficient alternative is to use electricity to move heat from a lower temperature to a higher temperature via an electricity-driven (e.g., motor-driven) “heat pump.” At moderate temperatures such systems move three units of useful heat for each unit of electrical energy (work) used. This ratio is called the coefficient of performance (COP). Challenges to widespread adoption of heat pump technologies on UC campuses are upfront cost, complexity, and limitations on the ability to provide very high temperatures. The trade-off between increased operating cost for resistance heat and higher upfront cost and temperature limitations for heat pumps underlies much of the discussion below.

4.2 Classification of Electrification Applications

As shown in Figure **4.1**, the distribution of natural gas usage across the 10 University of California campuses clearly demonstrates that the majority of UC's natural gas consumption is in combined heat, cooling, and power (CHP) applications, suggesting that carbon-free electrification would need to address both the heating being supplied by these CHP plants and the carbon-based electricity that they are providing. It must be noted that this distribution of gas use varies significantly between campuses. Moreover, more detail is needed to better characterize the uses of natural gas for applications other than CHP. Such characterization needs to include the temperature of the heat required, since temperature is a key determinant of how to achieve electrification—high temperature applications being much more difficult to accommodate with heat pumps.

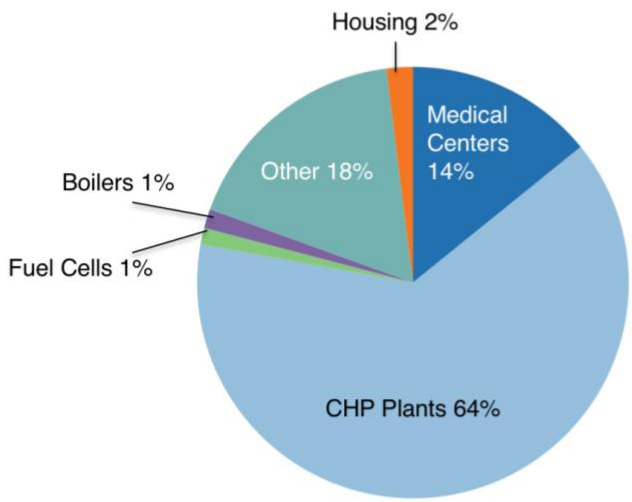

Figure 4.1. Natural gas usage across UC campuses, based on 2015 data from UCOP EnergyCAP purchased utility database, a systemwide program that processes and tracks utility bills. CHP includes a small amount of supplemental boiler use in the same plants, UC San Diego data were separated into the 'Fuel Cells' and 'Boilers' categories. Additionally, San Francisco, Santa Cruz, Riverside and Merced campuses have no 'Housing' specification. These campuses' housing usage therefore appears in the 'Other' category.

The flowchart in Figure 4.2 provides a general classification structure for electrification opportunities on UC campuses. Each of these three situations presents different opportunities and challenges for electrification. Starting on the left side of the figure, current installations are broken into three categories:

1. Campuses with central steam or high-temperature water distribution systems
2. Campuses with low-temperature water distribution systems
3. Campuses or portions of campuses that use local (e.g., single-building) natural gas combustion for heating

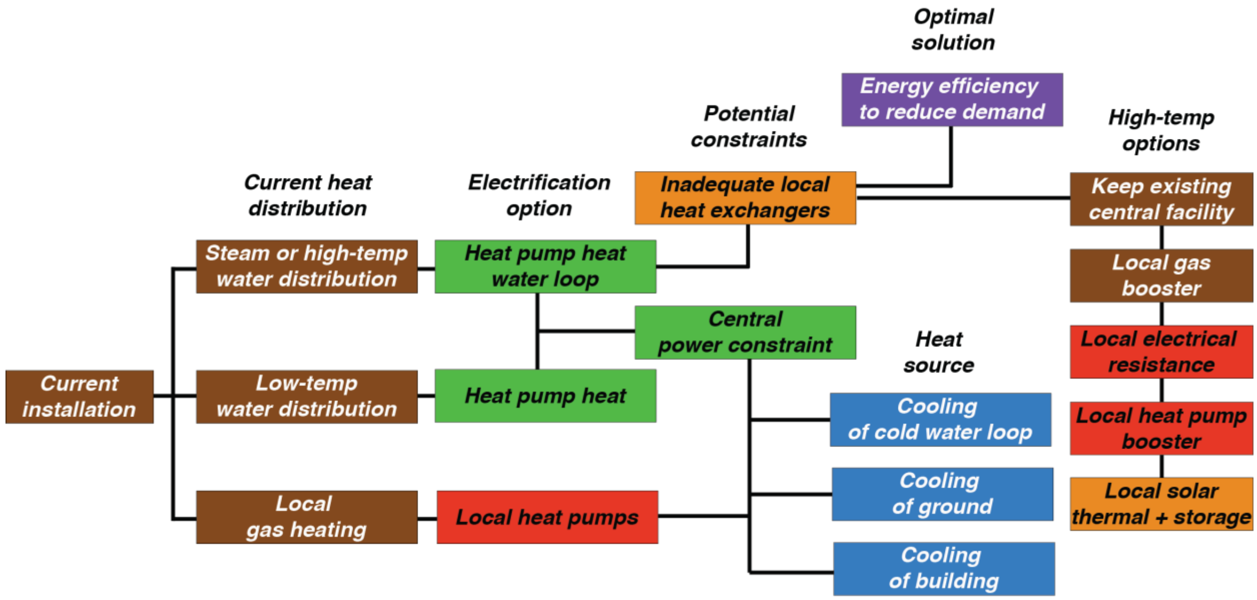

Figure 4.2. Classification of electrification opportunities for building heating on university campuses. Nodes are colored according to whether they involve natural gas combustion (brown), central electrification (green), local electrification (red), cooling (blue), energy efficiency (purple), or other miscellaneous options (orange).

4.2.1 Heat Pump Applications

In the first two electrification options (shown in green in the third column from the left), the key issues (other than cost) that must be addressed are: 1) the feasibility of bringing in adequate electrical power, and 2) the source of the heat to be extracted by heat pumps. Concerning the latter, the heat could be extracted from the ground, the air, or other available thermal reservoirs such as wastewater or cooling loop systems (e.g., heat-recovery chillers). Extracting heat from the ground is more energy efficient than air-source heat pumps, and therefore has lower operating costs, but it entails higher upfront costs, and can be constrained by a lack of appropriate ground from which heat can be extracted. In cases where a central cooling loop exists or is needed, extracting heat from the cooling loop can be the option with highest overall efficiency (heating plus cooling, e,g. heat recovery chillers), even though the temperature differential seen by a heat pump connected to a cooling loop can sometimes be larger than the differential with the soil or ambient air (i.e. when the cooling loop is at a lower temperature than the air or ground).

The third electrification opportunity, local, building-level heat pumps (shown in red in the third column from the left), has the same options for sources of heat, potentially even including extracting heat for a given building from a central cooling water loop. Building-level heat pumps could also extract their heat from the building itself, where there are both heating and cooling needs in the same building. However, this is not always a viable stand-alone option because heating and cooling loads within a building may not be not consistently balanced.

4.2.2 Space Heating with High Temperatures

Special considerations apply to steam or high-temperature water distribution systems. Electrifying high temperature water systems typically cannot be done with commercially-available heat pumps (i.e., heat recovery chillers) alone, because conventional heat pumps cannot produce steam or high-temperature water.[9] Additional complications may arise if these systems are converted to lower-temperature water because both the size of building heat exchangers and heat transport capacity of the distribution network are based on a larger temperature differential. Although the heat exchanger problem could be addressed by changing to larger heat exchangers, that is an expensive and disruptive alternative and does not address the capacity of the distribution network.[10] There are however a number of other options available, the best of which is to reduce building loads through energy efficiency (i.e., at lower loads the heat exchangers and distribution network can operate with lower water temperature). Chapter 2 of this report shows a natural gas savings potential of 29%, most of which is for space heating. Much of that potential could be available for high-temperature systems. Assuming that the fractional savings is the same for all space heating applications, including high-temperature distribution systems, very rough estimates of the impact of energy efficiency on heat exchanger sizing and distribution capacity for space heating can be produced. It is worth noting that considerable effort is currently underway in Europe and Japan to develop high-temperature heat pumps that can produce temperatures comparable to those being used in high-temperature distribution loops. The COP gets lower as heating side temperatures increase, potentially decreasing the benefit for large systems where only a fraction of the end-uses require high temperatures.

Assuming that energy efficiency is not enough, the right column of Figure **4.2** presents other options for addressing high temperature heat needs. In the first option on this list, the existing central facility is maintained and the high temperature distribution loop is augmented with one or more of the local temperature boosting options that follow. These local temperature-boosting solutions would be applied where the central distribution system interfaces with the building or at the end use within the building. To achieve the university's decarbonization objectives, any supplemental gas heating would need to be accomplished with biogas. When choosing among these options, some key considerations are the availability of space (e.g., the space to add a concentrated solar collector and storage tank) and electricity supply (the possibility of having to increase the capacity of the electrical service to the building). An important prerequisite to implementing any high temperature solution would be a careful analysis of actual heating temperature requirements at the individual building level, which could reveal that, in some cases, the high temperatures are unnecessary. This aspect of the process is not captured in Figure **4.2**.

4.2.3 Other High-Temperature Applications

In addition to building heating needs, there are many other local applications and uses of steam, high temperature water, or natural gas combustion that require high temperatures. UC Berkeley compiled a list of "orphan" gas and steam devices in buildings targeted for electrification (See Table 4.1). There are a variety of challenges associated with electrifying these "orphan" loads, and some can be especially challenging. For example, in older buildings, space and system constraints may limit the feasibility of

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[9] This assumes that steam and/or high temperature hot water are needed, however, in many cases, they are just being used as a heat source where a lower-grade heat source would also suffice.

[10] In some buildings, building level heat exchangers are oversized, so the main issue is to select a properly sized heat exchanger for the new system. This could mean a change from a steam-hot water HEX (often a large shell and tube with many auxiliary components) to a compact hot water-hot water HEX (plate and frame) which is a much smaller and simpler system.

replacing equipment such as cage washers or steam generators with an electric option. In addition, some grant-purchased equipment or end uses operated by contractors (e.g., kitchens), may not be easily converted to electricity due to contractual reasons. Other complications could include legal ownership of the equipment, residual equipment life, or resistance to research equipment changes.

Table 4.1. "Orphan'" Steam and Gas End Uses (Compiled by UC Berkeley)

Steam Uses	Gas Uses
Autoclaves	Kitchens/cooking
Absorption chillers	Kilns
Animal care/cage washers	Bunsen burners
Bottle/rack washers	Residential wall heaters, hot water
Dish washers	Laundry facilities/dryers
Library humidification	
Clean steam generator	

The variety of gas-supported heating options, including requirements for high temperature water, are presented in Table 4.2. as an aid to better understanding all of the gas uses today and how they can be electrified. The table attempts to summarize practical methods of electrifying existing end uses—that is, methods that are physically possible with current commercial technology. Electrification options are shown for the four major, campus-level and building-level systems (high temperature water, steam, low-temperature heating water and chilled water), in addition to what those systems do in the buildings. If a system is not presently used for a particular end use (e.g., high-temperature water not used for space cooling) then the box has "Not Applicable." Note that electric steam boilers are a form of resistance heating. The table does not include high-temperature heat pumps, which could potentially be used as an alternative to heat pump water heater and resistance heating.

4.3 Electrification Opportunities

The diversity of existing gas-fired heating applications and related infrastructure, and the range of options for electrification, mean that there are many ways to incorporate electrification into planning for carbon neutrality. Instead of trying to address every solution, we describe four principal opportunities for electrification, in order of increasing difficulty. These opportunities exist, to varying degrees, for every UC campus and most other institutional users of natural gas. The four principal electrification opportunities are:

1. New construction
2. Stand-alone existing buildings
3. Disconnection of existing buildings from central physical plant[11]
4. Electrification of the central physical plant

[11] Central physical plant = A plant that is a primary source of district heating, cooling or electricity for other buildings on the same facility, and which provides a substantial fraction of such services to multiple buildings (modified from US EIA glossary)

Table 4.2. Matrix of Existing Energy Uses and Electrification Options

	Existing Energy System (Central or Distributed)			
Required Product or Service (End-Use)	High Temperature Water	Steam	Low-Temperature Heating Water	Chilled Water
Building Heating Water <140 °F	Heat pump chiller or water heater (1)	Heat pump chiller or water heater (1)	Heat pump chiller or water heater (1)	Not applicable
Building Heating Water >140°F	Heat pump water heater + resistance heating	Heat pump water heater + resistance heating	Heat pump water heater + resistance heating	Not applicable
Industrial Hot Water >140°F	Heat pump water heater + resistance heating	Heat pump water heater + resistance heating	Heat pump water heater + resistance heating	Not applicable
Domestic Hot Water <140°F	heat pump water heater	Heat pump water heater	Heat pump water heater	Not applicable
Steam Autoclave (small)	Electric steam boilers central to building or Electric autoclave	Electric steam boilers central to building or Electric autoclave	Not applicable	Not applicable
Steam Autoclave (larger)	Electric steam boilers central to building or Local electric steam boiler	Electric steam boilers central to building or Local electric steam boiler	Not applicable	Not applicable
Space Cooling	Not applicable	Replace local absorption units, and steam driven chillers with electric chillers	Not applicable	Replace central absorption units with electric chillers
Equipment Cooling	Not applicable	Replace local absorption units with electric chillers	Not applicable	Potential to adopt heat pumps to recover heat

Notes:

1. Heat pump chillers would have the potential to recover energy to a chilled water system depending on synchronicity of use or availability of storage technology.

It should be noted that the simplest way to electrify would be to replace every gas-fired heater currently in use with an electric resistance heater. However, we have not considered that option due to the high costs stemming from the inefficiency of resistance heating for this type of application. There are applications within each of the four opportunities where electric resistance is appropriate, (e.g., providing second-stage heating for high temperature applications), and therefore included.

4.3.1 Electrification of New Construction

The most cost-feasible and technically feasible application of electrical heating for space, water, and food preparation is in new construction, where the cost savings that stem from elimination of gas distribution and metering systems contribute to what can be neutral first costs for all-electric buildings. A recent cost study conducted for UC found all-electric new construction to have first costs -6% to +1.5%

relative to gas-served equivalents—generally within the uncertainty of cost estimation practices. This includes efficient equipment or envelope options to control the potentially higher operating cost of electricity relative to gas. Energy costs for all-electric new construction are estimated to be -14% to +8% relative to gas-served equivalents, again within the uncertainty of the analysis—e.g., energy price assumptions[12] (16). In new construction, various design innovations and features may be employed to reduce energy costs. Building technology being explored includes innovations that could be particularly applicable to controlling the energy cost of electric heating, such as phase-change materials that enable lightweight frame construction to function as a thermally massive structure.[13]

4.3.2 Electrification of Existing Stand-Alone Buildings

The next electrification opportunity is in existing, gas-heated buildings that are not connected to a central plant. An advantage of stand-alone buildings is that the electrification decision can be made on a building-by-building basis, and the most attractive opportunities are buildings with aging equipment. Replacing gas-fired equipment with electrical heating equipment becomes more cost competitive at the end of the gas-fired equipment's life, when there is no economic value for the old gas-fired equipment. This is in contrast to an early-replacement scenario, in which case the economics are affected by the residual value (i.e. useful lifetime) of the equipment being replaced. Moreover, capital replacement budgets are typically available for use at the time of equipment replacement. At that time, other considerations can make electrification more attractive, including avoiding increased costs for new gas-fired equipment that meets current pollution criteria. Also, the potential incremental operating costs associated with switching to electricity are smaller when compared with the higher operating costs of aging inefficient space and water heaters. Finally, at replacement time, oversized equipment can be replaced with equipment sized for the actual loads rather than the loads that were assumed by building designers decades before, reducing both first and operating costs.

HVAC conversions — space heat and domestic hot water — can typically be achieved with conventional technologies, such as heat pumps, but high-temperature laboratory applications pose special problems. The primary issue is cost, both first cost and operating costs, so finding solutions that simplify replacement or provide additional features is paramount. For example, "mini-split" cooling and heating systems, which use refrigerant lines to distribute heating or cooling to one or more indoor units from a single outdoor unit, are becoming more popular in the U.S. UC Davis recently retrofitted a "multi-split" system that included variable refrigerant flow and heat recovery, and they are now monitoring its performance. One intriguing comparison of university buildings in Beijing (59) found that the highly decentralized control afforded by mini-splits resulted in buildings consuming 3-5 times less heating and cooling energy than comparable U.S. buildings. In the case of retrofits, mini-splits can be installed without costly removal of the existing system.[14]

4.3.3 Disconnecting Existing Buildings from Central Energy Facility

The third opportunity for electrification involves removing selected buildings from the district system and converting them to stand-alone, all-electric operation (sometimes referred to as "pruning"). The

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[12] High price premiums were assumed for both de-carbonized electricity and de-carbonized gas.
[13] By incorporating a material into the structure that changes phase at approximately room temperature (e.g. paraffin or certain salts), the daily temperature variations in a building can be minimized, reducing the need for heating in the morning and cooling in the afternoon.
[14] It is also important to keep in mind that significant heating takes place during the summer as a means of controlling ventilation, moisture and temperature simultaneously using reheat.

most attractive buildings to prune from the central system are at the end of distant branches. Such buildings often drive central system steam pressure requirements and hydronic pressure differential set points (pumping energy use scales with pressure differential). Many campuses have pruned buildings from central systems and, instead of making them all-electric, they have installed stand-alone, gas-fired space and water heating. UC Berkeley did this for a group of residence halls in the 1990's. As an alternative, the pruning process could involve installation of electric heat pumps. In limited circumstances, and only after extensive conservation measures had been implemented, resistance heating would be installed. One practical requirement for pruned buildings is the availability of sufficient space and electrical infrastructure capacity to install new electrical heating equipment.

Every campus with a central plant has opportunities to achieve electrification through pruning, although the pruning potential varies widely between campuses. Pruning needs to be coordinated with downsizing or operational management of the central plant because extensive pruning will ultimately lead to a significant reduction in heating demands, which could cause the central plant to operate less efficiently and produce more emissions. Less efficient plant operation would reduce net savings if operation is on a steep part of the system's performance curve.

4.3.4 Electrification of Central Physical Plant

The fourth and final pathway is to electrify central physical plants, and there are several possibilities here. The conventional solution would be to transition from gas-fired heating at the central facility to a heat pump (in this application often implemented as a heat-recovery chiller). This approach is often associated with transitioning to lower temperature water distribution, due to delivery temperature restrictions on heat pumps (implications of the transition to lower-temperature distribution are discussed above). Should the current development and testing of high-temperature heat pumps produce commercially viable technologies, the transition to low-temperature water could potentially be avoided (although high temperatures will still include energy penalties). An option is to use heat drawn from a central electric chiller loop to warm the heating water loop (e.g., heat-recovery chiller). This could be done at the central facility, or possibly as a hybrid central-local solution. One central-local solution would be to use a single central loop of chilled water to deliver cooling to the buildings, and also serve as the heat source for heat-pumps located in the buildings.

The hybrid system is particularly interesting for campus-style buildings, due to their relatively common simultaneous heating and cooling loads. A traditional temperature control strategy in air-conditioned buildings is to cool and dehumidify a mix of outside air and return air to the building at a fixed temperature (often around 54°F). Zone space temperatures are then controlled by first delivering the right volume of air to the zone and then reheating that air (to avoid overcooling) with hot water heating or resistance electric heat. This system is called Variable Air Volume with Terminal Reheat (VAV). In laboratory and some medical buildings, for air quality management reasons, this system supplies a certain minimum flow of air (typically changing the entire volume of the air in the building every 10 minutes) and uses 100% outside air. If heat gains in the space are small (as they often are), this amount of cooled air can result in large reheating loads in the summer and throughout the year. The largest load on the heating system in such cases is the cooling system. By using heat pump (i.e., heat recovery) chillers, one can improve performance of an electric option.

It is likely that a long-term solution for a multi-building campus will employ more than one of these approaches. In fact, even those that do not currently have a central plant may opt to connect some but not all buildings in a heating loop to reduce capital costs and improve efficiency through scale, as larger heat pumps are more efficient than smaller ones.

Electrifying a central system poses significant practical issues:

- The incumbent plant may be CHP, which has been a highly efficient and extremely cost-effective source of electric power, heat, and sometimes cooling.
- New central plants are capital intensive and potentially disruptive to operations.
- Central plants have long lifespans (30 to 50 years and more), and conversions risk leaving stranded assets, so this option may more appropriate for the oldest central plants.
- Distribution pipes can easily become undersized after transitioning to lower temperature. Pipes carrying lower temperature water typically require twice the flow capacity of high-temperature pipes for the same heating capacity.[15] Thus, the transition must be coupled with aggressive reductions in loads on the building side. Hot water storage might also be employed to address this issue.

Because of these challenges, campuses that have CHP plants and/or central heating and cooling loops may need to consider electrification in the context of opportunities (e.g., aging steam system replacement) or other infrastructure planning (e.g., plant retirement). In the interim, renewable gas use in the CHP plant may be preferred for decarbonization.

4.4 Case Studies and Application Examples

The strategy of electrification to achieve decarbonization is in its infancy, so there is little experience to draw upon. However, most of the specific modifications employ familiar technologies and engineering procedures, although not necessarily applied to these specific situations. A few technologies have not been fully vetted and the costs reflect no economies of scale. Nevertheless, electrification is occurring at UC and elsewhere. Below we describe examples in each of the four categories discussed previously: 1) New construction, 2) Stand-alone existing buildings, 3) Disconnection of existing buildings from central energy facility, and 4) Electrification of central energy facility. Finally, we address the electrification of high-temperature applications. This is not intended to be a comprehensive description; instead, we wish to illustrate the range of solutions and extent of experience at UC.

4.4.1 New Construction

Although all-electric buildings have been constructed in locations around the world for decades, buildings incorporating exceptionally high efficiency features are less common. Combined with on-site PV, such buildings sometimes even achieve net-zero electricity consumption and no carbon emissions.

Large, all-electric office buildings similar to those required by UC are already operating in California with net-zero electricity consumption. The Delta Products Corporation headquarters building in Fremont is an example of an extremely efficient, all-electric building achieving net-zero grid electricity with the assistance of associated PV (60). This was achieved despite unexpectedly large new demands caused by electric vehicles. The costs of achieving this level of performance were not available.

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[15] The impact of the cost of a new distribution system is less of an issue for an older steam plant, which may also have an existing steam distribution system that is aging and in need of replacement.

The West Village residential complex at UC Davis is another example of a moderately efficient, all-electric design combined with rooftop PV to achieve near-net-zero grid electricity use. West Village has been occupied since 2013 and has used PV to supply more than 80% of its electricity requirements. While the design had higher upfront costs than conventional construction, incentives and recurring energy savings lead to a payback in less than 10 years.

This year, UC Irvine began negotiating with a private contractor for construction of a net-zero energy residence hall complex. Their initial design strategy was to first maximize energy efficiency and then use solar energy to meet the reduced energy demands of the complex. However, many of the energy features considered turned out to entail a much greater marginal cost per kilowatt-hour saved than it would cost to procure more solar power. For these reasons, they are pursuing a limited set of less expensive upgrades and an all-electric design.

All-electric laboratories and research facilities are more challenging to design because heating systems need to address the high thermal losses caused by ventilation of fume hoods and other specialty equipment. Nevertheless, Lawrence Berkeley National Laboratory (LBNL) was able to design its new Integrative Genomics Laboratory to eliminate use of natural gas without significant additional cost by employing heat recovery chillers along with airside heat recovery and an air-source heat pump for backup space conditioning. The use of a centralized natural gas-fired water heater was replaced with small electric booster heaters close to the actual points of demand.[16]

4.4.2 Conversion of Stand-Alone Existing Buildings

Most UC campuses have some number of stand-alone, gas-supplied buildings that operate independently of central energy facilities, though the proportion of such buildings varies widely across campuses. Complete conversions of such buildings to electricity are extremely rare, especially now that natural gas prices are near historical lows. UC (and all other property owners) have little economic incentive to move from an inexpensive heating fuel to a more expensive one. The few conversions that do occur are motivated by strategies other than de-carbonization, such as short term equipment failures or unusual requirements. However, some partial conversions are being tested. These cases provide both technical experience and more realistic estimates of costs. At UC Davis, the Facilities department recently replaced a gas rooftop system that serves a small office building (3,465 sq. ft.) with a Variable Refrigerant Flow heat pump. At the same time, a Dedicated Outdoor Air System was installed to provide better control of fresh air delivery and increased efficiency. An evaluation of energy savings and cost-effectiveness is now underway.

4.4.3 Disconnection of Existing Buildings from the Central Energy Facility

Disconnecting or "pruning" buildings located on the periphery of a central energy system can offer significant benefits. In some instances, the central system can incur high losses serving those distant buildings, and occasionally buildings have been disconnected from the central energy system for economic or operational reasons. In the past, the central service was replaced by gas heating and

[16] Replacing a central, gas-fired water heater with smaller, point-of-use electric heaters is an increasingly common strategy for office buildings because more efficient faucets and equipment have substantially cut hot water consumption.

independent AC systems. For decarbonization to occur, such buildings must receive heat pumps and other electrical equipment instead.

UC has little experience disconnecting existing buildings from thermal networks and installing electrical heating systems. UC Davis plans to disconnect one building soon, but will continue to use gas to supply hot water. However, the connections will be designed to simplify replacement of the gas water heater with electricity in the future.

4.4.4 Electrification of Central Energy Facility

Electrification of an entire central energy facility is technically complex, invasive, and expensive. For systems that employ steam, the intermediate step of conversion to hot water is required before insertion of heat pumps to replace the gas-fired boilers. As noted above, existing pipes often lack the thermal capacity when the temperature is lowered. Much of the experience with this strategy exists outside of UC.

In Europe, central energy facilities more typically circulate hot water, which makes electrification via heat pumps more straightforward. These conversions are already underway or in planning stages in Switzerland, the UK and elsewhere. The use of high-temperature heat pumps is also being explored for these applications, as are various strategies for capturing and distributing waste heat.

The Swiss university, ETH, has set a decarbonization target of 2035. As part of their overall strategy, at Campus Hönggerberg, they have implemented Anergy Grid, an efficient heat-recovery and underground storage system, which is projected to halve CO_2 emissions from campus heating and cooling (61, 62). The system employs geothermal probes and thermally isolated underground storage systems. This design enables the system to respond to different heating and cooling needs, especially during the seasonal transition periods. The underground storage is connected to buildings and underground storage fields with a spiderweb-like ring-line network. Multiple heat pumps for processing low-temperature heat are dispersed around the campus. When designing new buildings, the maximum supply temperature permitted for heating is an exceptionally low 86°F, and for renovations a maximum of 95°F. Most of the heat and cooling are expected to be collected seasonally but, during peak periods (winter/summer), heat pumps in the buildings provide redundancy for the heat and cooling supply.

In 2015, California's Stanford University replaced its aging natural gas CHP and district steam system with electrically powered heat recovery chillers providing both chilled and heated water to an existing chilled water loop and a new heated water loop, also employing both chilled and heated water storage (63, 64). The project, which is expected to cut campus emissions by 68%, cost $485 million. The campus now supplies 93% of its heating load from this recovery system. Certain research buildings need direct steam access, so small steam boilers and a limited steam distribution system were installed to meet this demand.

UC Santa Barbara plans to employ a distributed heating electrification approach in previously independent gas-heated buildings that are served by the campus's district cooling system. The purpose of this project is to provide energy-efficient, heat-pump-produced hot water for buildings that currently use old, natural-gas-fired, local boilers. The network of cooling-loop-integrated heat pumps will help UCSB comply with equipment-level NOx emissions limits. The new "distributed plant" will include electric-motor-driven heat pumps, which will operate when there are simultaneous heating loads in a building and cooling loads on the district system.

4.4.5 Electrification of High-Temperature Applications

Applications that require high-temperature steam present a key barrier to removal of gas boilers. Such applications include animal cage cleaning, autoclaves, and other high-temperature processes. UC — and all institutions — have little experience electrifying these applications in an economical and non-disruptive way. For example, Stanford ultimately installed separate gas-fired boilers and a limited steam distribution system to meet these needs. Operating cost aside, electric boilers have been available for a century and are available from miniature to more than 50 MW of input power. There is considerable industrial experience with these units, which could be tapped to support conversion.

4.5 Recommendations

4.5.1 Acquire experience in electrification at various scales and for diverse end uses.

There are few examples of completed, comprehensive electrification projects, although there is more experience with electrification of specific end uses or situations. The absence of information limits our ability to broadly evaluate the potential for electrification at UC. Thus, our overarching recommendation is that UC acquire experience in electrification at various scales, from end use to central energy facilities, and in hot and cold climates.

4.5.2 Further investigate energy supply costs and infrastructure capital costs of electrification.

A key decision factor for choosing between electrification and the purchase of biogas (the pace of electrification) is a comparison of the estimated future pricing of carbon-free electricity versus biogas and the impact of storage and time of use on these prices. The capital costs of electrification also require additional study, especially the potential need to augment electrical infrastructure or incorporate energy storage as peak loads increase.

4.5.3 Pursue greater integration of high energy efficiency and all-electric approaches in both new construction and retrofit.

The most cost-feasible and technically feasible application of electrical space, water, and food preparation heating is in new construction, where the cost savings stemming from elimination of gas distribution and metering systems can offset the somewhat greater costs of additional efficiency needed to control operating costs with electrification. Thus, ensuring that new construction employs a combination of energy-efficient design and efficient electrical equipment should be a high priority. Integration of a high-degree of energy efficiency can also help control the costs of retrofit electrification.

4.5.4 Experiment and learn from targeted electrification retrofits of equipment in existing buildings.

The electrification of gas-combusting space heating, water heating, and cooking equipment in existing buildings becomes more cost-feasible as these capital equipment assets approach the end of their useful life. Individual UC campuses need more local experience with site-specific technologies. For that reason, we recommend that campuses initiate small, “learning” projects, targeting certain buildings or end uses near end-of useful life of gas-using equipment.

4.5.5 Develop campus-specific plans and timelines for electrifying central plants, starting with pruning buildings where the economics are favorable

The larger challenge is to fully or partially electrify central plants. These assets (which represent the majority of UC's natural gas use) are costly to build or retrofit, but achieve significant energy and cost efficiencies (especially when operated as combined heat and power plants).

Potential pathways to electrifying central plants are heavily dependent on campus context. The most important factors include the age of the plant, the condition of the existing steam or hot water distribution system, the balance between heating and cooling needs, and the percentage of buildings needing high-temperature water or direct steam for existing uses. The campuses may wish to begin by identifying target buildings for pruning where the economics are most favorable.

4.5.6 Accelerate research and discovery of electric replacements for high-temperature applications

Finding practical and economic electrical replacements for high-temperature applications, possibly including high-temperature heat pumps, should be a priority. This is an obstacle faced by all universities around the world, so national task forces would be appropriate. UC could easily take a leadership role and thus contribute to its own and the nation's solutions.

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Appendix A

The energy efficiency cases are modeled on conditions at, but are not exact representations of, 14 UC campuses and medical centers that have various combinations of the following characteristics:

- **Campus Type:** CHP or Non-CHP, with or without a Medical Center
- **Gas/Electricity Ratio***:* Low, High, Very High
- **Electricity Price***:* Very Low, Low, High, Very High
- **Energy Efficiency Improvements to Date***:* Minimal, Low, Moderate, High or New Campus
- **2009-2012 Debt Burden***:* Minimal, Low, Moderate, High

Definitions

The following terms are used in Tables A-1 through A-4.

Annual Energy/EE Debt Service Budget. The combined budget for:

- Purchased energy utilities
- 2009-2012 loan cohort debt service
- New debt service

Biogas Premium. Representing the fraction of gas use for which the premium for biogas can be afforded within the combined energy and energy efficiency debt service budget.

2028 Annual Energy/EE Debt Service Surplus. The combined energy and energy efficiency debt service surplus resulting from full roll-off of the 2009-2012 loan cohort in 2028.

Gross Debt Service Ratio (DSR). The debt service ratio for the energy efficiency portfolio before payment of biogas premium is considered. Net DSR is 100% with biogas premium.

New Debt. The amount of new debt required to fund the new energy efficiency portfolio.

Seed Funding. The amount of initial capital required to fund projects that produce savings for reinvestment. (Capital is not preserved as full avoided energy expenditures are re-invested.)

New Gas / Electric Energy Efficiency (EE). The amount of current energy use avoided through new energy efficiency. For CHP cases this percentage applies to supplemental gas and electricity purchases only. The percentage of use at the buildings is within potentials or campus plans. For "gas," the percentage can be high because the base includes CHP thermal output. For electricity, the percentage can be high because some campuses appear to already be incorporating new construction loads into EE planning and CHP load projections.

Appendix A-1: Table of Non-CHP Cases

	Case A	Case B	Case C	Case D
Campus Type	Non-CHP	Non-CHP	Non-CHP	Non-CHP
Gas/Electricity Ratio	Low	Low	Low	High
Electricity Price	Low	High	Low	Very Low
Energy Efficiency Improvements to Date	Moderate	New Campus	Minimal	Moderate
2009-2012 Debt Burden	Moderate	Minimal	Minimal	High
Annual Energy/EE Debt Service (1) Budget now-2025	~$12 million	~$4 million	~$15 million	~$24 million
Biogas Premium now-2025 (2)	Partial	Full	Partial	Partial
Biogas Premium 2025	Full	Full	Full	56%
Biogas Premium 2028	Full	Full	Full	Full
2028 Annual Energy/EE Debt Service Surplus (1)	~$0.8 million	None	~$0.2 million	~$0.6 million
Gross Debt Service Ratio (Elec)	62% (4)	21% (4)	70%	70%
Gross Debt Service Ratio (Gas)	62% (4)	70%	70%	70%
Net Debt Service Ratio (3)	100%	100%	100%	100%
New Debt	~$8 million	~$3 million	~$22 million	$25 million
New Gas Efficiency	24%	10%	20%	25%
New Electric Efficiency	10%	13%	21%	12%

Notes:

1. Only 2009-2012 loan and new loan debt service included.
2. Might be deferred to 2025 to mitigate risk.
3. Energy cost reduction is reduced by biogas premium.
4. Based on projects in 2017-2021 Plan

Appendix A-2: Table of Non-CHP + Medical Center Cases

	Case E	Case F	Case G
Campus Type	Non-CHP + Medical Center	Non-CHP + Medical Center	Non-CHP + Medical Center
Gas/Electricity Ratio	Low	Low	Very High
Electricity Price	High	High	High
Energy Efficiency Improvements to Date	Low	Minimal	Minimal
2009-2012 Debt Burden	Minimal	Minimal	Minimal
Annual Energy/EE Debt Service (1) Budget now-2025	~$7 million	~$7 million	~$9 million
Biogas Premium now-2025 (2)	Full	Full	Partial
Biogas Premium 2025	Full	Full	79%
Biogas Premium 2028	Full	Full	79%
2028 Annual Energy/EE Debt Service Surplus (1)	`~$0	~$0	~$0
Gross Debt Service Ratio (Gas)	70%	70%	70%
Gross Debt Service Ratio (Elec)	70%	70%	70%
Net Debt Service Ratio (3)	100%	100%	100%
New Debt	$11 million	$11 million	$17 million
New Gas Efficiency	17%	14% (4)	25% (4)
New Electric Efficiency	22%	21% (4)	28% (4)

Notes:

1. Only 2009-2012 loan and new loan debt service included.
2. Might be deferred to 2025 to mitigate risk.
3. Energy cost reduction is reduced by biogas premium.
4. Lower EE potential considering new higher EE hospital

Appendix A-3: Table of CHP Cases

	Case H	Case I	Case J
Campus Type	CHP	CHP	CHP
Gas/Electricity Ratio	Low	Very High	High
Electricity Price	High	High Elec Price	Low
Energy efficiency Improvements to date	Moderate	High	Moderate
2009-2012 Debt Burden	Low	High	Low
Annual Energy/EE Debt Service (1) Budget now-2025	~$6 million	~$11 million	~$16 million
Biogas Premium now-2025 (2)	Partial	Partial	Partial
2025 Biogas Premium	Full	35%	15%
2028 Biogas Premium	Full	Full	36%
2028 Annual Energy/EE Debt Service Surplus (1)	~$0.4 million	~$0	~$0
Gross Debt Service Ratio (Gas)	47% (8)	70%	70%
Gross Debt Service Ratio (Elec)	47% (8)	70%	70%
Net Debt Service Ratio (3)	100%	100%	100%
New Debt	$9 million	$18 million	$15 million
New Gas/Thermal Efficiency	8% of total 62% of non-CHP (4)	14% of total 58% of non-CHP (5)	4% of total 29% of non-CHP
New Electric Efficiency	22% of total 51% of purchases (4)	15% of total 92% of purchases (5)	7% total 39% of purchases

Notes:

1. Only 2009-2012 loan and new loan debt service included.
2. Might be deferred to 2025 to mitigate risk.
3. Energy cost reduction is reduced by biogas premium.
4. Current pace 2017-2021 plan (implies integration with new construction planning)
5. 2017-2025 plan limited by electricity purchases (implies integration with new construction planning)
6. 2017-2021 plan (implies integration with new construction planning)
7. 2017-2021 plan plus deep gas/thermal efficiency
8. Based on projects in 2017-2021 plan

Appendix A-4: Table of CHP + Medical Center Cases

	Case K	Case L	Case M	Case N
Campus Type	CHP + Medical Center HEE	CHP + Medical Center HEE	CHP + Medical Center HEE	CHP + Medical Center
Gas/Electricity Ratio	High	Very High	Low	High
Electricity Price	High	High	High	Very High
Energy Efficiency Improvements to Date	Low	Moderate	Moderate	Minimal
2009-2012 Debt Burden	Minimal	High	Moderate	Minimal
Annual Energy/EE Debt Service (1) Budget now-2025	~$45 million	~$27 million	~$18 million	~$9 million
Biogas Premium now-2025 (2)	Partial	Partial	Partial	Partial
2025 Biogas Premium	86%	29%	52%	13%
2028 Biogas Premium	86%	84%	74%	13%
2028 Annual Energy/EE Debt Service Surplus (1)	~$0	~$0	~$0	~$0
Gross Debt Service Ratio (Elec)	70%	70%	70%	70%
Gross Debt Service Ratio (Gas)	55% (9)	70%	70%	70%
Net Debt Service Ratio (3)	100%	100%	100%	100%
New Debt	$128 million	$28 million	$38 million	$12 million
New Gas/Thermal Efficiency	21% of total 36% of non-CHP (8)	22% of total 76% of non-CHP (5)	8% of total 67% of non-CHP (6)	6% of total 67% of non-CHP (7)
New Electric Efficiency	23% of total 75% of purchases (8)	4% of total 24%of purchases (5)	18% of total 39% of purchases (6)	4% of total 39% of purchases (7)

Notes:

1. Only 2009-2012 loan and new loan debt service included.
2. Might be deferred to 2025 to mitigate risk.
3. Energy cost reduction is reduced by biogas premium.
4. 2017-2021 plan
5. 2017-2025 plan with deeper electricity EE
6. 2017-2021 plan with deeper electricity EE
7. Limited to non-CHP gas and electricity purchases
8. 2017-2021 plan plus deep gas/thermal efficiency
9. Based on projects in 2017-2021 plan

Appendix B

Summary of Universities Surveyed

The following is a summary of the 25 universities surveyed for their integration of biogas as a solution for achieving carbon neutrality.

University	Region	Carbon Neutral Target Year	Biogas Status	Biogas Source	Reason for Excluding Biogas Use
Appalachian State University	Southeast	2050	Not using	N/A	Focusing on solar thermal energy, wind energy, and carbon offsets.
Arizona State University	Southwest	2025	Under consideration	N/A	N/A
Bowdoin College	Northeast	2020	Not using	N/A	Space and transportation constraints at Bowdoin's Central Utility Plant.
Colby College	Northeast	2015	Using	Low-grade wood chips and forest waste offsite (within 50-mile radius)	N/A
Colgate University	Northeast	2019	Using	Onsite landscaping wood waste, offsite wood chips (within 75-mile radius)	study on Colgate willow plots found that they were not sustainable biomass fuel source
College of the Atlantic	Northeast	2007	Using	Regionally sourced wood pellets	N/A
Colorado State University	Southwest	2050	Using	Offsite wood waste from forest fire mitigation projects and pine beetle kill areas around Fort Collins, Colorado	N/A
Cornell University	Northeast	2035	Under consideration	N/A	N/A
Dickinson College	Northeast	2020	Not using	N/A	Using carbon offsets in addition to converting their dual-fuel Central Energy Plant to run primarily on waste vegetable oil instead of natural gas and #2 fuel oil
Duke University	Southeast	2024	Under consideration	North Carolina swine farms or other operations that release methane.	N/A
Green Mountain College	Northeast	2011	Using	Locally sourced wood chips from forestlands in Rutland County, Vermont	N/A

University	Region	Carbon Neutral Target Year	Biogas Status	Biogas Source	Reason for Excluding Biogas Use
Loyola University Chicago	Midwest	2025	Not using	N/A	Focusing on carbon offsets due to limited opportunities for renewable fuels.
Macalester College	Midwest	2025	Not using	N/A	No suitable biogas material due to issues with storage, supply, unpleasant odors, and high operational expenses. Additionally, contracts are not available with local biogas producers to refine their products for direct injection into Macalester's existing natural gas pipelines.
Middlebury College	Northeast	2016	Using	Wood chips from Vermont and NY (within 75-mile radius)	N/A
Portland State University	Northeast	2040	Under considera tion	N/A	N/A
Southern Oregon University	Northwest	2050	Under considera tion	Offsite, regional woody biomass (within 50-mile radius)	N/A
SUNY College of Environmental Science and Forestry	Northeast	2015	Using	Wood pellets from Schuyler, New York	N/A
University of Colorado-Boulder	Southwest	2050	In transition	N/A	N/A
University of Florida	Southeast	2025	Under considera tion	N/A	N/A
University of Illinois- Urbana Champaign	Midwest	2050	Under considera tion	Onsite and offsite dedicated energy crops or agricultural waste	N/A

University	**Region**	**Carbon Neutral Target Year**	**Biogas Status**	**Biogas Source**	**Reason for Excluding Biogas Use**
University of Massachusetts-Lowell	Northeast	2050	Not using	N/A	Biogas shortage due to missed opportunity to gain rights to the renewable produced by nearby landfill. The landfill has also since been converted into a solar panel lot by the city of Lowell, which entirely eliminates this cost-effective option for the university.
University of Minnesota-Morris	Midwest	2020	Using	Agricultural fuels (corn stover, perennial grasses, wood) from regional farms (within 60-mile radius)	N/A
University of Missouri	Midwest	2050	Using	Regional wood waste from mills and forest clearing and management	N/A
University of Montana	Midwest	2020	Not using	Local forests	Public opposition surrounding air pollution, declining price of natural gas, difficulty in securing a supplier.
University of North Carolina Chapel Hill	Southeast	2050	In transition	Landfill gas and woody biomass	N/A