FEATURE

Stanford University's "fourth-generation" district energy system

Combined heat and cooling provides a path to sustainability.

Joseph C. Stagner, PE, Executive Director, Sustainability and Energy Management, Stanford University

Stanford's new Central Energy Facility uses renewable electricity as a primary fuel source to heat and cool the university. The facility's net-positive-energy administration building is equipped with a 176 kW rooftop solar array.

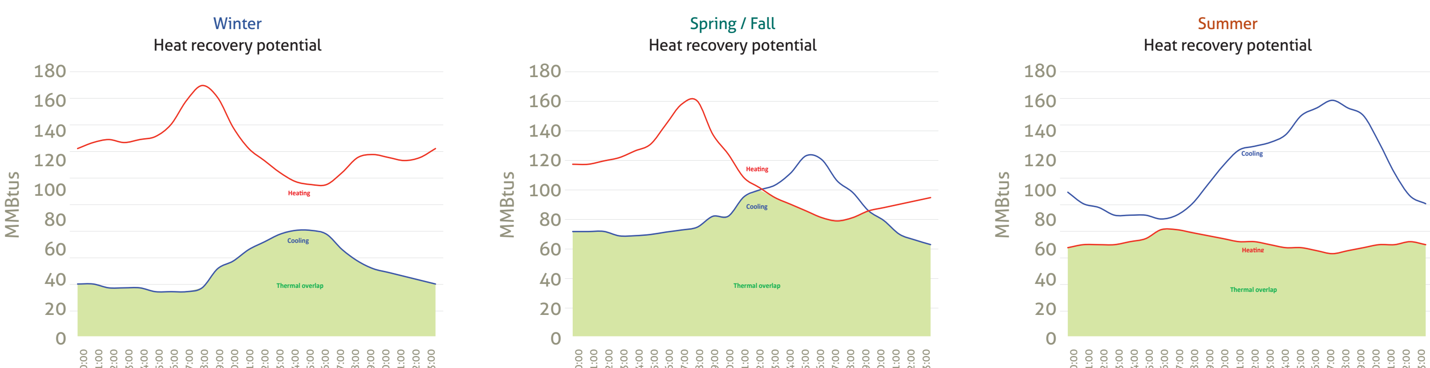
Stanford University is at the heart of one of the birthplaces of innovation, California's Silicon Valley, but you won't find one of its latest creations in lines of code, on a printed circuit board or in a miracle genome. It's in plain sight on the university campus in the form of an attractive architectural interpretation of Stanford's rich history and technological innovation. What's under the hood is even more eye-catching.

In 1987 Stanford took a giant step forward in efficiency and environmental stewardship with the installation of a 50 MW natural gas-fired cogeneration plant to provide electricity, steam and chilled water for its campus. Three decades later, the Cardinal Cogeneration plant has been replaced by the new $468 million Stanford Energy System Innovations (SESI) project, which has taken Stanford into the 21st century with an even more efficient system that immediately reduces campus greenhouse gas emissions by 68 percent, decreases total campus water use by 18 percent and is expected to save the university hundreds of millions of dollars over the next three decades compared to other options. Shifting from gas cogeneration to grid electricity may be contrary to current trends, but heat recovery and renewable power are the keys to economic and sustainable energy for Stanford University.

HEAT RECOVERY

The cornerstone of SESI is the recovery of waste heat from the campus district chilled-water system to meet building heating and hot water needs. This opportunity was

Figure 1. Typical daily heating and cooling profiles and thermal overlap by season, Stanford University, 2008.



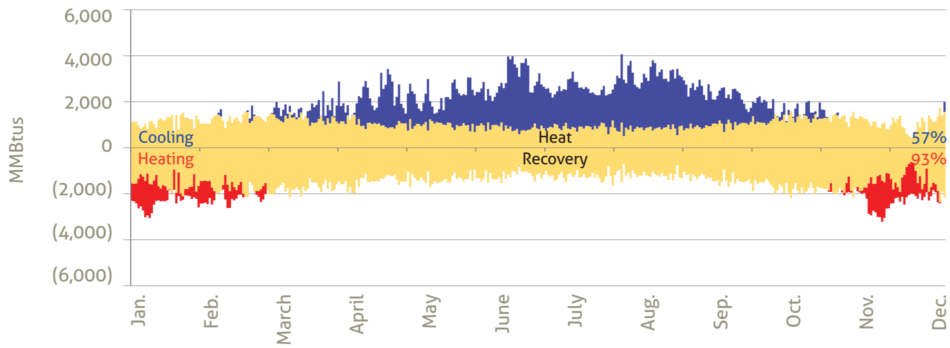
Source: Stanford University.

discovered in 2008 upon the review of hourly energy production data by Stanford's Utilities engineering staff as they began exploring options to replace the university's aging gas-fired cogeneration plant, scheduled for decommissioning in 2015.

With cooling occurring mostly in summer and heating in winter, the opportunity for heat recovery was assumed to be modest until Stanford engineers compared the simultaneous delivery of heating and cooling from the cogeneration plant over all hours of the year (fig. 1). The large thermal overlap that was revealed opened up a major new opportunity for improvement in the efficiency, economics and sustainability of the university's energy system – namely, a heat recovery-based heating and cooling system that could be powered by renewable electricity instead of natural gas.

Viewed on an annual basis, the thermal overlap and corresponding opportunity for heat recovery totals 75 percent, with 93 percent of campus heating and hot water needs able to be met by recovering 57 percent of the waste heat from the chilled-water system as shown in figure 2.

Figure 2. Annual heat recovery potential: heating and cooling overlap, Stanford University, 2016.



Source: Stanford University.

COMBINED HEATING AND COOLING

Stanford refers to its new heat recovery system, which began operation in March 2015, as "CHC" (combined heating and cooling) in contrast to the more widely known SHP (separate heat and power, e.g., gas boilers, electric chillers and grid electricity) and CHP (combined heat and power, e.g., gas-fired cogeneration) district energy options. Key features of the CHC system include replacing steam production and distribution with hot water; large heat recovery chillers (heat pumps); both hot and cold water thermal energy storage; and advanced "model predictive control" energy management software.

GETTING INTO HOT WATER

Since standard heat pumps can't produce temperatures high enough for steam production, the new CHC system uses hot water, with large reductions in heat distribution line loss and O&M cost compounding the base savings from heat recovery to help justify the switch. To determine required hot water supply temperatures for the new system, engineers examined campus building HVAC designs and performed winter operational tests. It was determined that temperatures of 160 degrees F would suffice most of the time, with 170 F potentially required for periods of extreme cold, followed by return hot water temperatures of 130 F to 140 F. It was noted that a lower hot water supply temperature of 150 F could be used if several laboratory building HVAC systems were modified; however, since those changes could not be made in time for SESI commissioning planned for March 2015, and to provide flexibility in future operations, it was decided that the CHC system would include the ability to provide the higher temperatures. Chilled-water system temperatures were unaffected by the change.

OPTIMIZING DESIGN AND OPERATION

Developing the CHC design required determining how such a system should be configured and operated to meet loads so that its economics, efficiency and environmental impacts could be compared with those of SHP and CHP options. Stanford could not find commercial energy management software for modeling a CHC system so it developed the patented Central Energy Plant Optimization Model (CEPOM) itself for this purpose.

CEPOM incorporates model predictive control to look at least 168 hours (seven days so as to always include weekends) into the future at any given time to predict hourly system energy loads and grid electricity prices and then produce the optimal hourly dispatch plan for the central energy facility over that period to meet projected loads at the lowest possible cost.

Using this tool, the performance of different CHC system configurations was modeled for an entire year and used to optimize the heat pump, chiller and hot water generator fleets along with hot and cold water thermal energy storage tank sizes to meet the forecasted loads. This design process was performed for multiple years from 2015 to 2050 to develop an optimal plant design and expansion plan to meet campus energy loads over the long term.

Given the usefulness of CEPOM for conceptual planning and detailed design, Stanford realized that it could also be used for actual real-time system operation if it could be translated into an industrial platform and integrated with the base energy plant operating control system. Before investing in migrating CEPOM from Excel spreadsheet to an industrial software platform, Stanford retained consultants to study whether such a software program was commercially available; their conclusion confirmed

Stanford University's new Central Energy Facility.

Natural gas-fired hot water generators are highly efficient at 85 percent higher heating value but are used only part-time from November through February to supply less than 10 percent of annual system heat.

System Snapshot: Stanford University

	Hot water system	Chilled-water system
Startup year	2015	1960s
Number of buildings served	300	360
Total square footage served	12 million sq ft	11 million sq ft
Central plant capacity	2.2 million MMBtu/year, max peak 300 MMBtu/hr	75 million ton-hr/year, max peak 25,000 tons/hr
Number of heat pumps	3 (heat recovery chillers)	3 (same heat pumps as serve hot water system)
Number of boilers/chillers	3 hot water generators	4 chillers
Fuel types	Electricity, natural gas	Electricity
Distribution network length	22 miles	25 miles
Piping type	Preinsulated welded steel	Welded steel, PVC
Piping diameter range	2 to 36 inches	2 to 42 inches
System pressure	65 psi	68 psi
System temperatures	150 F-170 F supply/130 F-140 F return	42 F-44 F supply/56 F-58 F return
System water volume	6 million gal (including thermal energy storage)	18 million gal (including thermal energy storage)

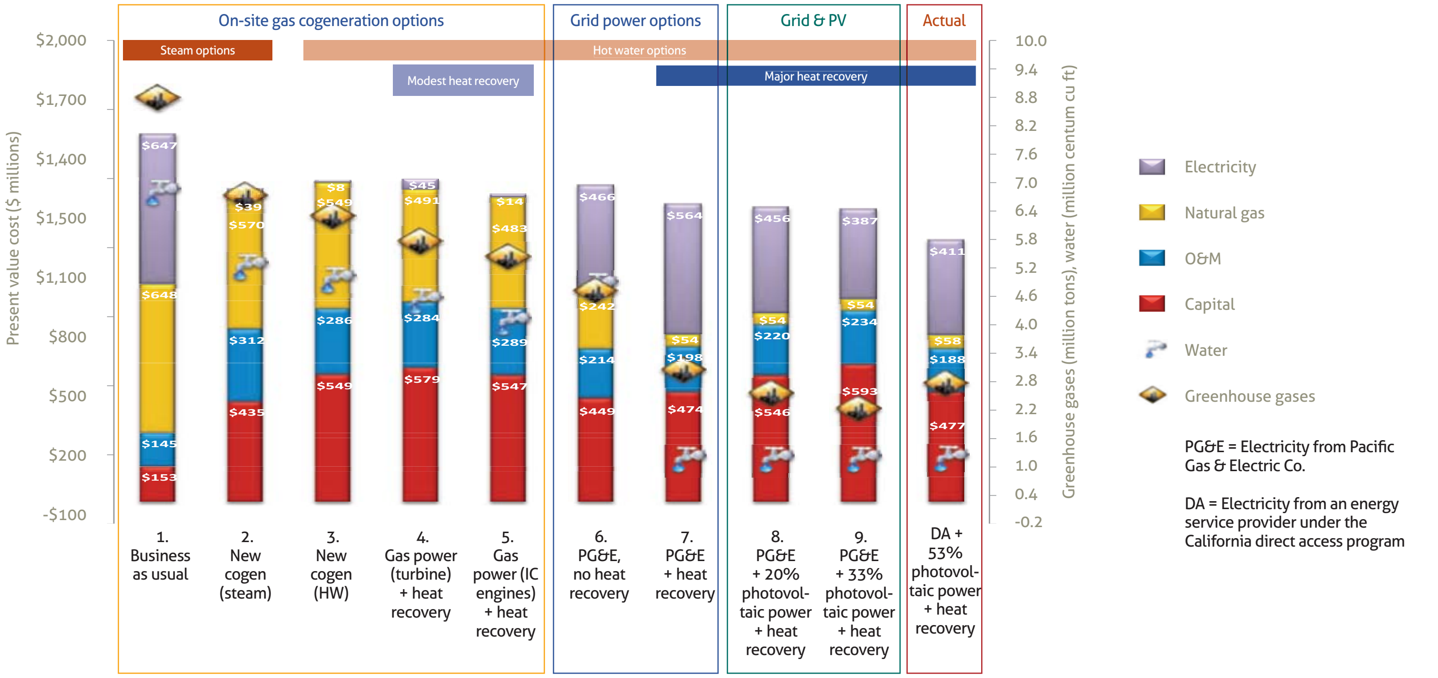
Source: Stanford University.

Stanford's own earlier assessment that it was not. Stanford then partnered with Johnson Controls Inc. (JCI), which had already been selected to provide the base energy plant control system, to do this. The resulting program developed by JCI in 2014, known as the Enterprise Optimization Solution (EOS), was deployed to provide real-time optimization and dispatch control of Stanford's new energy system. EOS also includes a planning module that replicates and improves upon CEPOM for system planning and design.

CENTRAL ENERGY FACILITY

An optimal design for the new Central Energy Facility was developed by Stanford using CEPOM between 2010 and 2012. It improves the reliability of the campus district energy system through simplification by eliminating gas and steam turbines, steam and ice production from the process. This also allows for a much smaller plant staff and greatly reduced O&M cost. The design includes the following

Figure 3. Comparison of energy supply replacement options, Stanford University, 2011 with August 2015 update. (Update added for the selected CHC option after the system had become operational, showing actual additional savings achieved through low-cost, long-term solar power purchases.)



Source: Stanford University.

initial equipment plus room for expansion through 2050:

- 7,500 tons heat pumps (three 2,500-ton units)
- 12,000 tons chillers (four 3,000-ton units)
- 180 MMBtu gas hot water generators (three 60-MMBtu units)
- 14,500 tons cooling towers
- 90,000 ton-hr cold water thermal energy storage (two tanks totaling 9.5 million gal)
- 600 MMBtu hot water thermal energy storage (one 2.3 million-gal tank)

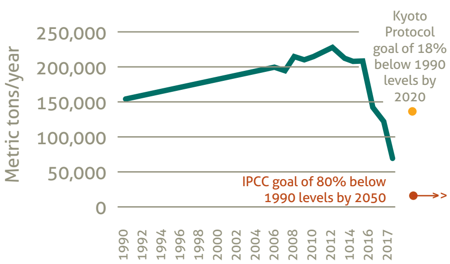
CHC VS. SHP VS. CHP

Prior to proceeding with CHC, Stanford also developed SHP and CHP system options and compared all using a total lifecycle present value cost analysis including fuel, O&M and capital costs. Long-term gas and electricity prices, inflation and discount rates have a large impact on the comparisons; so to assure objectivity, multiple sources for these were utilized, including consultants, the U.S. Energy Information Administration and Stanford faculty. Assumptions for these and other key factors were then developed for the analysis, including sensitivity bands. Multiple internal and external peer reviews of the models were also performed, and the comparison of long-term energy supply options for Stanford was completed in 2011 and presented as shown in figure 3. The best gas-based option was a hybrid internal combustion engine and heat recovery scheme that presented long-term costs similar to that of CHC. Given the better sustainability performance of the CHC option and the long-term flexibility it provides in energy sourcing by using electricity instead of gas, Stanford selected the combined heating and cooling option.

SUSTAINABILITY

Construction of the CHC system was approved by Stanford's Board of Trustees in December 2011, and construction began in October 2012. That same year, Stanford achieved "direct access" to California electricity markets and in April 2014 executed long-term power purchase agreements with SunPower Corp. for the development of 73 MW of on- and off-campus photovoltaic solar power generation. (SunPower and its partners own and operate these PV projects.) The 5 MW of rooftop panels on campus buildings, including a 176 kW system at the new Central Energy Facility, and the 68 MW off-site at the Stanford Solar Generating Station located near Mojave, Calif., will be operational by the end of 2016 and supply around 53 percent of Stanford's electricity. This reduces the cost of the CHC option by another $156 million, as shown in the August 2015 cost update in figure 3, and boosts SESI's initial 50 percent greenhouse gas reduction to 68 percent. Greenhouse gas reductions will grow to at least 73 percent as the remainder of Stanford's power from the general grid is cleaned up under state renewable portfolio standards, which advance to 50 percent by 2030. (See Stanford's green-

Figure 4. Greenhouse gas emissions trend, Stanford University, 1990-2017. (Graph reflects actual emissions through 2014 and estimated for 2015-2017.)



Source: Stanford University.

house gas emissions trends in figure 4.) In addition, SESI saves at least 18 percent of the university's drinking water supply by greatly reducing the use of evaporative cooling towers for heat rejection.

IMPLEMENTATION

After project approval was granted in December 2011, the task of designing and building the new system in time to meet the March 31, 2015, planned shutdown of the cogeneration plant was a monumental challenge. Components of the $468 million SESI project include the new Central Energy Facility; a 100 MVA, 60 kV high-voltage substation located on the edge of campus one-half mile from the existing cogeneration plant; 22 miles of new hot water piping; conversion of 155 buildings to receive hot water instead of steam; extension and tie-in of existing chilled-water and high-voltage distribution systems to the new Central Energy Facility; and demolition of the cogeneration plant.

As the largest single construction project in Stanford history – with more than two years of disruption touching all areas of the campus – SESI required the full support of the campus community, adept project management and fully committed equipment suppliers and contractors for success. In a remarkable achievement, the project was completed on time and under budget. The new system was started up March 24, 2015, and the cogeneration plant was shut down simultaneously. Over its first year of operation, SESI has exceeded expectations in service reliability and quality with no interruptions in energy supply or significant building heating or cooling problems. Annual energy and O&M costs were $9.9 million, or 21 percent less than anticipated in the 2011 pro forma due to lower-than-expected electricity cost and a 2 percent underrun in O&M cost.

THE LARGEST SINGLE CONSTRUCTION PROJECT IN STANFORD HISTORY, SESI REQUIRED FULL CAMPUS COMMUNITY SUPPORT, ADEPT PROJECT MANAGEMENT, AND COMMITTED SUPPLIERS AND CONTRACTORS.

"FOURTH-GENERATION" DISTRICT ENERGY

In its recently released report, *District Energy in Cities – Unlocking the Potential of Energy Efficiency and Renewable Energy*, the United Nations Environment Programme envisions an evolution from 2020 to 2050 to "fourth-generation" district energy systems. These systems of the future will rely far more on waste heat recovery, heat pumping from ground and water bodies, and renewable energy than on the use of fossil fuels for powering, heating and cooling buildings in order to achieve needed greenhouse gas reductions. UNEP has found that optimizing production, use and delivery of thermal energy for heating and cooling buildings is an essential and often overlooked segment of energy use in cities. Moving to fourth-generation district heating and cooling will enable the use of low-grade thermal energy as a means to reduce regional greenhouse gas emissions. Low-carbon technologies such as heat recovery, deep lake water cooling and thermal storage are valuable strategies to facilitate effective deployment of district energy in cities, communities and campuses. Where waste heat recovery, ground and water body heat exchange, and renewable energy cannot meet the entire energy needs of a district energy system, CHP systems, especially those using sustainable fuels, may also be valuable elements in a district energy system optimized for economics, efficiency and sustainability. These are also the findings of the International Energy Agency in its *Technology Roadmap: Energy-efficient Buildings: Heating and Cooling Equipment.* Stanford's new district energy system may be one of the first large examples of that evolution in a university setting. It has enabled the university to achieve huge reductions in greenhouse gas emissions and exceed state, federal and international goals several decades early and has opened the path to 100 percent reductions in the future.

TRANSFERABILITY

Stanford conducted a review of thermal load studies done by campus utilities engineers at several major universities including in the Midwest and Northeast – very different climates than that of the university in California. All indicated a 50 percent or more annual overlap in heating and cooling and a greater-than-expected opportunity for a renewable electricity-based heat recovery system, ratifying the findings of Stanford, the IEA and UNEP. At first this seems counterintuitive given the extremely cold winters in the Midwest and Northeast; however, the studies reveal that much of the opportunity for heat recovery occurs in the summer and shoulder seasons, which makes sense given that the lower 48 states have a net environmental heat surplus for half the year.

During that time there is no need to generate additional heat, and heat recovery can typically meet 100 percent of heating and hot water needs in most locations. The magnitude of heat recovery potential in the colder half of the year varies by location, but it is present everywhere year-round and not to an insignificant degree. In colder climates, large-scale ground source heat exchange, such as is implemented at Ball State University, offers a great complement to heat recovery by utilizing the same equipment that is used for heat recovery from campus buildings. Ground source heat exchange can boost annual sustainable heat supply from 50 percent up to almost 100 percent via building heat recovery alone.

While such systems are probably technically feasible in most locations, the economics and sustainability must be analyzed over the long term, given the capital required to make the transition and the projected long-term cost and carbon-intensity of the local electricity supply. The optimal time for making such a transformation is probably when major components of an existing district energy system are near or past their useful lives so as to minimize stranded assets. Stanford's analysis of potential new district energy system schemes revealed that at balanced power, heating and cooling loads, an electricity-based system with moderate amounts of heat recovery and/or renewable power supply in the mix could result in lower overall emissions than new high-efficiency natural gas alternatives even in higher-carbon-intensity regional grids. Currently, the probability of adequate supplies of cost-competitive, sustainable combustion fuels or small-scale carbon capture and storage appears slim over the next decade or more. Given that fossil fuel boilers and cogeneration units typically last 30 years and beyond, this means that any such new equipment installed in the coming years may foreclose an institution's ability to achieve significant greenhouse gas emissions to levels prescribed for minimizing the consequences of climate change. Therefore, when opportunities for major changes in a district energy system present themselves, a transition to an electricity-based system should be seriously considered.

SESI has been recognized at local, state, national and international levels for its innovation and sustainable design. Its various honors include the state of California Governor's Environmental and Economic Leadership Award, the *Engineering News-Record* (ENR) Editor's Choice Best of the Best Projects 2015 award in the United States, the Alliance to Save Energy's Energy Efficiency Visionary Award and, most recently, ENR's Global Best Green Project Award for 2016.

Joseph C. Stagner, PE, *is executive director of the Sustainability and Energy Management Department at Stanford University, where he is responsible for advancing sustainability in campus operations through leadership of the university's Office of Sustainability and Facilities Energy Management; Utilities Services; and Parking and Transportation Services departments. Prior to joining Stanford in 2007, Stagner served on the facilities management team at the University of California, Davis, for 14 years and spent 10 years in various engineering roles on nuclear, geothermal, coal and hydroelectric projects with the Pacific Gas & Electric Co., Sacramento Municipal Utility District and Morrison Knudsen Co. Stagner led development of SESI and created the Central Energy Plant Optimization Model software. He earned a bachelor's degree in civil engineering from the University of Florida and is a registered professional engineer in California. He can be reached at jstagner@stanford.edu*