

STANFORD ENERGY SYSTEMS INNOVATION (SESI): LEADING THE WAY TO A SUSTAINABLE ENERGY FUTURE

I think that innovators are by nature optimistic. You have to believe there's a better way to do something. If you're a pessimist, you'll never even try.

— Joseph Stagner, Executive Director of Sustainability and Energy Management, Stanford University

On a cool spring morning in April of 2017, Joseph Stagner stood in front of a panel of wall-mounted computer monitors in the control room of Stanford's central energy facility, reviewing how much energy and water the university had saved in the last two years since launching "SESI," the university's cutting edge grid-tied heat recovery energy system. Later that day, Stagner, Stanford's Executive Director of Sustainability and Energy Management, would be leading a SESI facility tour for trustees from a prominent east coast university, and he wanted to have the most current system performance data at his fingertips. Short for Stanford Energy System Innovations, SESI was built to meet campus heating, cooling and electricity needs through the year 2050. Powered largely by renewable electricity and designed to reduce Stanford's greenhouse gas emissions by 68 percent and water use by 18 percent, SESI not only had a much lighter environmental footprint than the fossil-fuel burning cogeneration plant it replaced, but was also expected to save the university \$300 million in electricity, heating and cooling costs during its first 35 years of operation.^{1,2}

SESI represented one of the most comprehensive energy supply transformations of its kind, and visitors from all over the world had been coming to Stanford to see how it worked. An eternal optimist, Stagner was hopeful that he could inspire and persuade his guests that day to pursue a heat-recovery energy solution of their own. Of course there would be challenges to overcome in the planning, financing and implementation of a large-scale capital project such as this, but Stagner believed these could be surmounted with hard work and political will. The United Nations Environment Program, International Energy Agency and U.S. National Laboratories all agreed that widespread adoption of modern district energy solutions like SESI was imperative if the world was going to meet the daunting but urgent goal of limiting global temperature increase to less than two degrees Celsius.^{3,4,5} Stagner was eager to see universities, businesses and cities

¹ Stanford University Energy and Climate Plan, Revised September 2015, Third Edition.

² The \$300 million savings reflects the difference between the present value cost (PVC) of building and operating the new SESI facility and the PVC of extending the life of the existing cogeneration plant. The PVC calculation includes initial capital costs plus 35 years of operating and maintenance costs, financing costs and fuel purchases.

³ *District Energy in Cities: Unlocking the Potential of Energy Efficiency and Renewable Energy*, United Nations Environment Programme, 2015.

⁴ *Technology Roadmap - Energy-efficient Buildings: Heating and Cooling Equipment*, International Energy Agency, 2011.

do their part to achieve a sustainable energy future, and he was ready and willing to provide assistance in any way he could.⁶

In Pursuit of Sustainability at Stanford

Stagner joined Stanford in late 2007 to lead the university's Department of Sustainability and Energy Management, a new department that reflected the strong voices for sustainability coming from deans, directors, faculty and students at various university institutes and schools, from managers in Stanford's Land, Buildings and Real Estate division, and from Board of Trustee members who had been calling for increased sustainability efforts for several years. Creation of the department came on the wings of the construction of Stanford's first high performance 'green' buildings, such as the Yang and Yamazaki Environment and Energy Building.

Stagner and his team were tasked with reviewing the university's energy, water, buildings and transportation systems and identifying ways to operate them more sustainably. Stagner admired the university's commitment to learning and improvement. "Whether it was the students prompting the administration, or members of the administration prompting themselves, Stanford had the resolve to take a fresh approach and see if there was a better way to do things," he said. "That was the first ingredient in Stanford's success - a desire to want to know if there's a better way. The second was to then expend the effort and the upfront resources to take a hard look."

Stagner also liked the university's organizational approach to tackling sustainability challenges. "Stanford realized that all these greenhouse gas emissions were coming from infrastructure, for the most part, and that they therefore needed the people who understood the infrastructure to devise the solutions to fix it. Not faculty or staff without any direct experience in buying or using energy," he said. "Stanford got it. They said, 'Look, the people who are going to fix this are the people who own the smokestacks. I mean, who else? They know the business. They know what they're doing. They've got to tell us if there's a better way to do it than having a smokestack.' Stanford understood where the accountability and the subject matter expertise lay, and they organized their efforts around that. That predated me, but that's why I came here," Stagner explained.

While Stagner and his team would examine all of the university's major systems in parallel, they had good reason to make energy their top priority. Not only did Stanford's energy supply system carry huge operating costs of about \$80 million per year, it also accounted for 90 percent of campus greenhouse gas emissions and 25 percent of water consumption.⁷ (Exhibit 1 on page 22 provides a breakdown of campus greenhouse gas emission sources from 2006 - 2014.)

Stanford's primary source of heat and power at that time was an onsite cogeneration plant owned by Cardinal Cogen Inc., a wholly owned subsidiary of GE Power Systems. *Cogeneration*, or

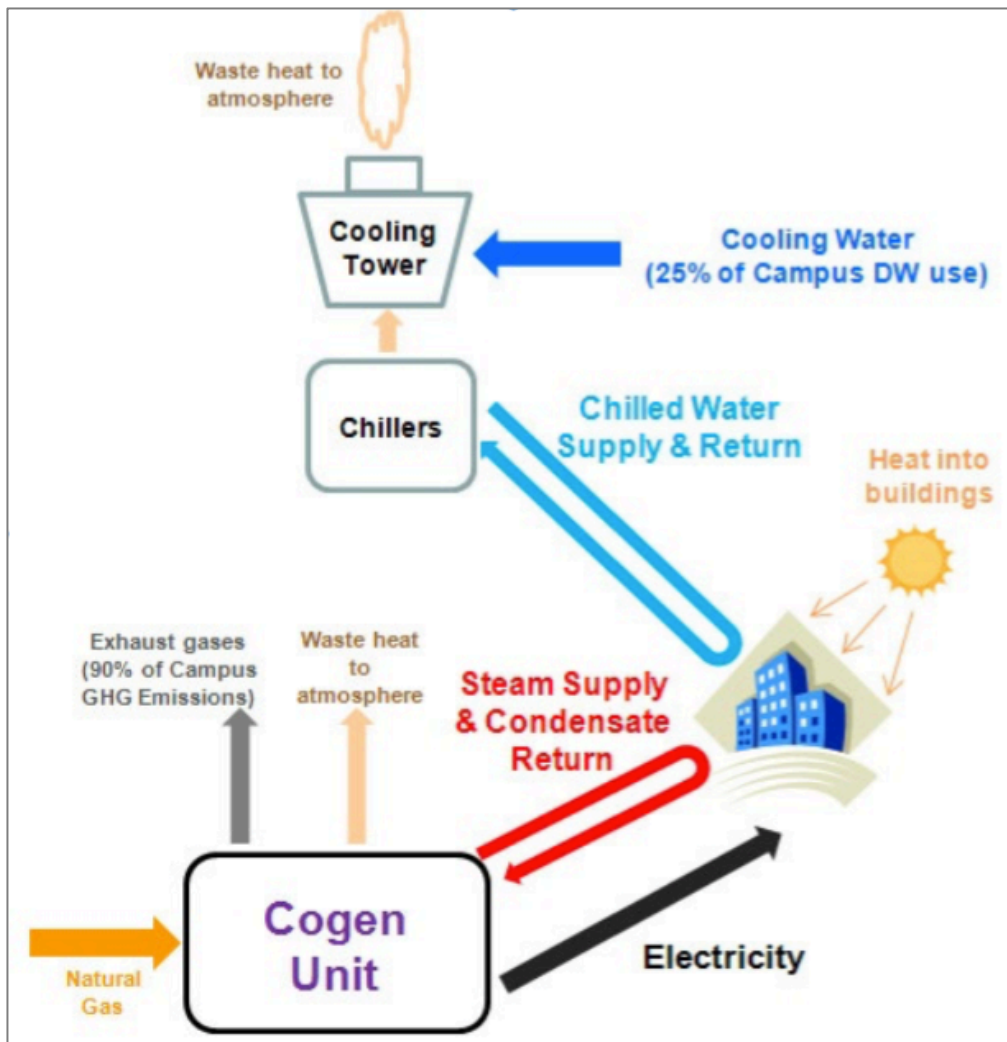
⁵ Williams, J. H., B. Haley, F. Kahrl, J. Moore, A. D. Jones, M. S. Torn, H. McJeon (2014). *Pathways to deep decarbonization in the United States*. The U.S. report of the Deep Decarbonization Pathways Project of the Sustainable Development Solutions Network and the Institute for Sustainable Development and International Relations.

⁶ Unless otherwise noted, information and quotes in this case come from interviews with Joseph Stagner, Executive Director of Sustainability and Energy Management at Stanford University, held on March 20 and 27, 2017.

⁷ Stanford University Energy and Climate Plan.

cogen for short, also referred to as *combined heat and power*, uses a power station to generate electricity and heat concurrently. The Stanford *cogen* plant, considered state-of-the-art when it began operating in 1987, consisted of a 'combined cycle gas turbine' that produced electricity via both a massive natural gas-fired turbine generator and a secondary steam-driven turbine generator. Exhaust heat from the gas turbine combustion process was captured to generate steam, which was then used to drive steam-powered chillers or delivered around campus via a network of underground steam pipes to provide heat to Stanford's buildings. Excess steam was used to drive the steam turbine generator and produce additional electricity. "The challenge with natural gas-fired power plants," Stagner explained, "is that, even today, they're only 50 percent efficient, so half the fuel that you burn turns into heat instead of electricity. Typically, that waste heat is discharged into the atmosphere via evaporative cooling towers, consuming huge amounts of water in the process. Cogeneration is a major improvement because it co-locates a natural gas-burning power plant with buildings that need heat. So instead of discarding the waste heat, you can put it to good use."

Figure 1: Schematic illustration of a cogeneration system



Source: Stanford University

Stanford purchased its energy from Cardinal Cogen under a long-term contract that was set to expire in March 2015, at which point the plant's turbine would be 28 years old. Per the contract, the turbine was due for a major overhaul in 2012 to keep it running smoothly. "When I came on board, there was no reason to know or believe necessarily that we would end the contract, or, if we renewed the contract, what the terms or the methods of energy supply would be," Stagner said." A combination of factors led us to think we might want to do a five-year extension, using the existing equipment. Or maybe Cardinal would propose a 15-year deal and they'd invest some capital to keep things running. It could have been any range of things that happened, but we knew, with the contract ending, and with some components of the plant being fairly old, it was probably our best opportunity to make a change. The stranded assets, if you will, would be at their lowest point in years. We knew there could be a major opportunity to change horse mid-stream here. But that's all we knew."

In the not too distant future, Stanford would need to decide whether to renew the contract with Cardinal Cogen or pursue a different path - possibly one that would require major capital improvements and infrastructure changes. When the time came for Stanford's leadership - the president, provost and board of trustees - to make that important decision about Stanford's energy future, Stagner wanted them to be well informed about their options. Their decision would have major implications, both financial and environmental, that the university would have to live with for decades to come.

Envisioning Stanford's Energy Future

In 2008, as Stagner's team set out to discover the best ways to meet the university's future energy needs, they put out a call for help, inviting faculty, staff, students and community members to bring ideas forward or help with the analysis of ideas. "We wanted to seek all the available knowledge from around the planet and bring it to bear to start to craft a solution. There was no pride of ownership," Stagner explained. "You have to be willing to say, 'Bring me all your best ideas, world. Whoever they come from, I don't care. I'm looking for the best, and we want anybody that's interested to help.' That was the attitude we took."

The initial brainstorming process yielded dozens of ideas ranging from tidal power (which the City of San Francisco was pursuing under the Golden Gate Bridge at the time), to wave power, geothermal, lake source and ocean source cooling, solar, wind and more. "We wanted to know," Stagner explained, "could this or that energy solution work for Stanford? Should we dive deeper or not? Should we dismiss lava power right off the bat because we don't have a volcano nearby? The overall approach was to invite all ideas and be completely open. Then we'd apply a filter for practicality to Stanford, with a very liberal bias to not restrict things that didn't initially seem promising." An idea would have to be completely outrageous, like volcanic power, for example, to not make the list.

Once all the ideas were up on the whiteboard, Stagner's team grouped them by like technologies and similar aspects, then organized all the volunteer analysts into small "Sustainability Working Teams", or SWTs. Stagner recruited subject matter experts to serve as team leads and made sure that each team included a Stanford Utilities engineer with enough knowledge of energy systems to help keep the conversations grounded in reality. For example, senior energy engineer Scott

Gould, a solar and wind expert, would lead the solar energy SWT, investigating and critiquing solar technologies ranging from standard rooftop applications to massive utility-scale projects in the desert to concentrated solar power systems that used mirrors and lenses to direct a large area of sunlight onto a specific spot. Gould would reach out to specialists, like Sally Benson at Stanford's Global Climate and Energy Project, to identify the latest research findings, production trends and innovations. Meanwhile, a different engineer would lead the SWT tasked with assessing water technologies, such as wave power, tidal power and other hydro solutions.

Although Stagner didn't necessarily expect that Stanford would pay a lot of additional money in order to pursue the most environmentally-sound energy solution that could be devised, he suspected the university might be willing to pay a little extra in order to be more sustainable. "Let's see what technologies are available. Let's devise all the best systems we can. Let's model their performance and costs to see what the tradeoffs might be. Let's bring the board options. That was the approach," Stagner explained. "The conventional thinking was that it would cost more to be sustainable, but we didn't want to assume that and instead were open to the possibility that it might actually cost less." Stagner's job was to provide that menu of options, have them peer reviewed, and let the board of trustees decide what Stanford should do.

In order for Stanford to make a well-informed decision, Stagner's team would need more information about how energy was produced and used at Stanford. They already knew the total amount of cooling, heating and electricity the university used on a monthly basis under its contract with Cardinal Cogen, but those figures didn't paint a clear enough picture for Stagner. He wanted to see the daily energy production and usage patterns and the differences between weekdays and weekends, when no classes were held. As a matter of fact, he wanted the data down to the hour so that he could see the diurnal patterns. If, for example, the university wanted to consider wind power as part of a new energy supply solution, would that make sense given the energy usage patterns on campus and the highly fluctuating nature of wind energy? And how would wind stack up against other "variable renewable energy" sources such as solar or tidal power? To answer these types of questions and determine an optimal system design for Stanford, the hourly data were essential.

There was one other reason why Stagner suspected that the seasonal and hourly data on Stanford's heating and cooling needs would be important: "You think, conventionally, that you heat your buildings in winter and cool them in summer, right? That's what we do at our house," Stagner said. "But since Stanford is a massive university with complex uses ranging from biology labs to Olympic-sized swimming pools, and with the seasons we have here, I knew that there might be some overlap when we're cooling some parts of campus and heating other parts of campus at the very same time. I had it in my mind that we might be able to do something with that overlap." Stagner knew a little bit about *heat pumping* - extracting waste heat from a space that needs cooling and transferring it to another space where heat is needed, but he didn't have a clear picture in his mind of how it might work at Stanford. "I wanted to see the data," he said, "and maybe that would tell me."

Stagner would also need that same detailed energy data to determine the best configuration of thermal storage technologies for Stanford. *Thermal storage* - capturing and temporarily storing energy in the form of heat or cold for use at a later time - would almost certainly play a role in

any new energy system at Stanford. The approach was not new to Stanford. Since 1999, the university had been operating an ice plant, using chillers to generate ice late at night when energy rates were lowest and then piping the melted-ice around campus during the day to provide air conditioning, augmenting the cooling capacity of Stanford's older chilled water plant.⁸ Detailed energy data could enable Stanford to fine-tune its existing cold storage system or maybe even devise a better thermal storage solution that included heat storage.

In late 2008, as the SWTs were immersed in their due diligence, Stagner asked the utility engineers at the cogen plant to collect the necessary data. Over the course of a whole year, how much electricity, steam and chilled water was the plant producing, not just in the aggregate, but for every hour of the day? Stagner's request was met with resistance. "They grumbled and griped, 'Boy, it's going to be so tough to get this,'" Stagner said. Though the plant equipment didn't actively track production by the hour, the engineers ultimately determined that they could construct a reasonable set of data manually by using paper strip charts and other information logs. Stagner asked them to proceed with the work, explaining why the information was important. "They fought long and hard. They said, 'It will take six months and lots of labor to do this.' And I said, 'Yes, but I think we need it. You never know what will be revealed.'" To Stagner's dismay, when the engineers came back several months later, the data set they provided only included every Wednesday of the year. "They gave me 52 Wednesdays," he said, "and so again I insisted that we needed every hour of every day."

Finally, in September 2009, the engineers came through with the full year's worth of hourly data, enabling Stagner and his team to compare the campus heating demand with the campus cooling demand and determine the degree of overlap. "If you looked at January 1st, hour one," Stagner reported, "you saw that we had a heating demand of 100 units and a cooling demand of 10 units. Okay, heating was bigger than cooling. That was to be expected in January. But there *was* some cooling, because in times of high humidity like rainy winter days you have to dehumidify air to maintain general comfort in occupied spaces and to protect sensitive research and computing equipment, artworks, etcetera. There are certain research and computing processes that generate high amounts of heat and must be cooled, even in winter."⁹ In that one hour on January 1st, Stanford was effectively collecting 10 units of waste heat and throwing it away - via cooling towers - at the same time that it was burning fuel to make 100 new units of heat. This begged the question: Why couldn't the university reuse the 10 units of waste heat and make just 90 units of new heat?

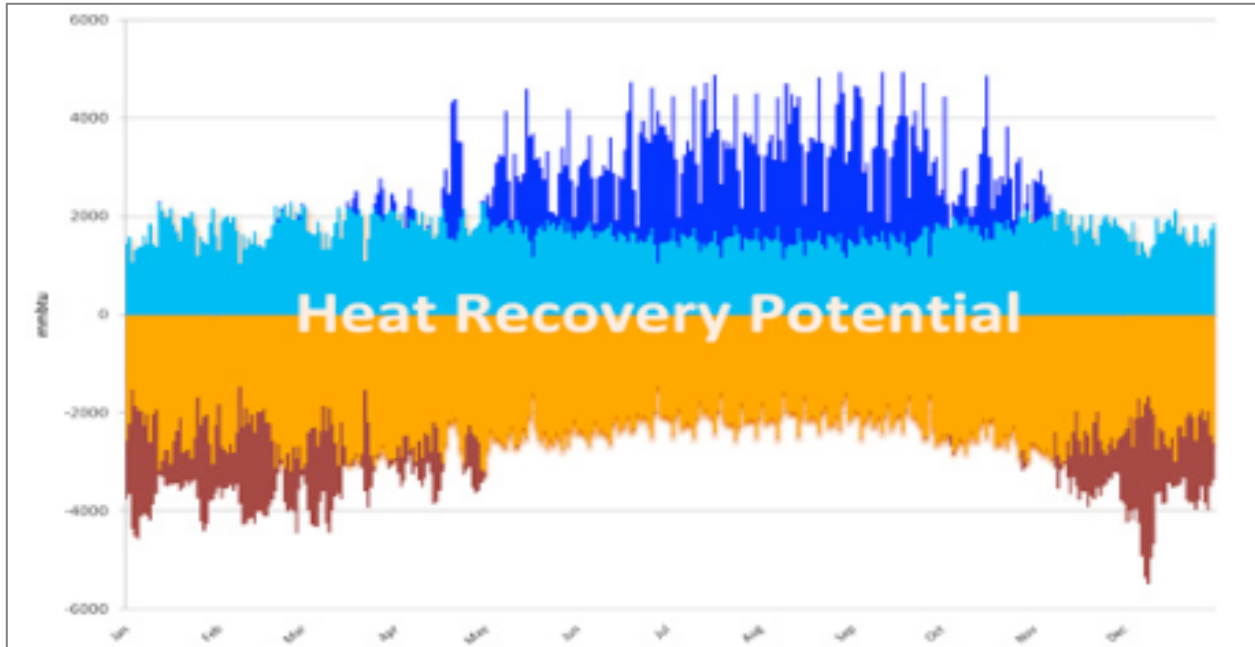
Stagner anticipated that the overlap of heating and cooling needs across campus would amount to 5 or 10 percent, or maybe 15 percent at most, over the course of the year, making heat pumping a small but potentially viable part of an energy solution for Stanford. The actual result came as a shock. "When you compare the data for every hour of the year, it turns out there's a 75 percent overlap," Stagner explained. When he saw that number, Stagner realized that *heat recovery* - using heat pumps to extract unwanted heat from buildings for reuse - could turn out to be the

⁸ Marissa Klein, "What You Don't Know about the Ice Plant," *Stanford Alumni Magazine*, July/August 2007, https://alumni.stanford.edu/get/page/magazine/article/?article_id=32125 (April 27, 2017).

⁹ Cooling a space in a building is achieved by sending out a cold fluid via pipes to collect unwanted heat and bringing it back to be discarded via a cooling tower. The process effectively involves extracting unwanted heat and sending it away.

dominant feature of a new energy system. "That was a game changer," he said. (Exhibit 2 on page 23 shows heat recovery potential at Stanford by season.)

Figure 2: Heat recovery potential at Stanford



Overlap of simultaneous heating and cooling demand on campus throughout the year (2015)

Source: Stanford University

"The major improvement that heat recovery provides," Stagner explained, "is that it takes advantage of free energy that already exists in the system. All these buildings on campus have energy going into them. The sun is imparting energy. The human body is imparting energy. Electricity that feeds into lights and machines is eventually converting into heat energy. Our buildings have all of these heat sources, and that's the extra energy we can bring to the table through heat recovery. We missed all of that with our cogen plant."

If a robust heat recovery system could be devised and the economics made sense, Stanford could have an opportunity to cut way back on its fossil fuel use and greenhouse gas emissions, reducing its environmental footprint by leaps and bounds. As excited as he was by this possibility, Stagner remained cautious. "Before we started shouting from the mountaintops 'Look what we found!' we had to be sure that the data were reliable and not some really crazy mistake leading us down the primrose path," he said. "We asked ourselves, 'Can we tie this new heating and cooling data back to the Cardinal Cogen monthly bills? If in January we're paying the company for X amount of chilled water, heating and steam, and if we add up our hourly heating and cooling production data for the month, does the result match?' Well it does. The engineers checked that and it matched." Yet, even after reconciling the data with the bills, Stagner wasn't completely satisfied. The numbers were correct, he agreed, but they only spanned one year, from September 2008 to August 2009. Was that a regular year, Stagner wondered? "We can't base

everything on just one year, so let's start looking at additional years and make sure we've got a representative data set here," he instructed his team.

Once Stagner and his colleagues had verified that there was a reliable 70 percent heating and cooling overlap across multiple years of data, they set out to see if they could use this information to Stanford's benefit. They had a lot of questions: Is there a heat pump out there that can recover the unwanted heat from our buildings so that we can use that heat rather than dispose of it? Does anybody in the world make that machine? How big a machine do we need, and what are its performance characteristics? Can it generate enough heat for the campus so that we don't have to burn any fossil fuels? Will we need a custom design? Or does this machine not exist, and the idea dies right now?

Through "good old-fashioned detective work" of internet research and talking to people in the industry, Stagner and the engineers at the cogen plant identified a number of heat pump manufacturers, but for the most part the units they made were too small. In theory, Stanford could aggregate dozens of small units to achieve the necessary scale, but the approach would create huge operating inefficiencies. Only two companies in the world made heat pumps large enough to meet Stanford's heat recovery needs. One was based in Europe and not set up to sell or service equipment in the United States. That left only one choice: York, a well-established American company that offered a few different models. "These were proven units, not experimental, and the company gave us all the data we needed on sizes, performance, efficiency and costs," Stagner said. He hoped he might later find other companies that could make a competitive unit and give Stanford some more options, but for the time being, he was satisfied that at least one viable equipment source existed.

Stagner and his team soon came to realize, however, that the existing heat pump technologies had a major shortcoming: they weren't capable of delivering the hot water temperature and pressure required to convert waste heat into steam - a serious problem given that the miles of underground steam pipes Stanford used to heat the campus were not suitable for water conveyance. Converting the entire campus from steam heating to hot water heating would be time consuming and disruptive, not to mention costly. More than 20 miles of larger diameter pipes would need to be added, and the steam connections at 155 buildings around campus would need to be changed out. While others might have abandoned the heat recovery concept at this juncture, Stagner stayed the course. "A whole new piping network. Now that's a major undertaking," Stagner admitted. "We'll of course have to examine what it would take to do the conversion, but I'm not going to assume that it's impossible or that the university won't do it. Let's set that aside while we run the numbers and see if we can devise a hot-water based heat recovery system that pencils out," he said. If Stagner could show that a heat recovery system would outperform the current cogen system financially, environmentally, or both - and this was a big if, then it would be up to Stanford's leadership to decide whether the investment in new infrastructure and the associated disruptions in campus operations were worthwhile.

In addition to heat pumps, a new campus energy system designed for heat recovery would require other major pieces of equipment including boilers, chillers, hot water storage and cold water storage. The big question was how to arrange these components into an integrated district energy system that could not only deliver optimal results for Stanford in the short term, but also

accommodate campus growth five, ten, twenty and thirty years into the future, while providing flexibility to integrate new, more efficient technologies that might emerge.

Determining the optimal configuration of equipment was complicated for a number of reasons, and as far as Stagner could tell, no one had solved this type of puzzle before in a way that he could replicate for Stanford. While it was fairly common for district energy systems - such as those serving college campuses, cities, airports and military bases - to rely on chilled water for cooling, and increasingly common to see them deploy cold water storage solutions for increased system efficiency, there were few if any examples of computerized optimization of cooling system operations. System operators had no way to accurately determine which pieces of chilling equipment to run at certain time and how much cooling to draw from or add to thermal storage at each hour of the day in order to minimize operating costs given the hourly changes in electricity rates. The necessary tools to optimize their system operations simply didn't exist.

The heating part of the equation was even more difficult to solve. Most district heating systems relied on steam, rather than hot water, for heating, and offered no heat storage capacity, in part due to the technological challenges of storing steam, but also due to the perception that there was no need to do so: since steam was produced by burning natural gas, and gas pricing did not vary diurnally the way electricity pricing did, conventional belief was that the best approach was simply to burn gas and generate steam as it was needed.

To Stagner, it was clear that designing the most appropriate new district energy system for Stanford could only be achieved by optimizing all three of the system's major subsystems - the heating, the cooling and the power. While optimizing each subsystem individually would be difficult enough, creating an overall optimization plan for an integrated district energy system encompassing all three subsystems would prove to be a challenge of a whole different magnitude. Internet and other research indicated that it simply hadn't been done before.

"If you sit down and try to figure that out by hand, you'll find out fast that it's impossible. It's too complex. There are too many moving parts," Stagner said. "So I started doing internet searches and calling different energy optimization software companies, and I asked, 'Has anybody tried modeling out a complex system like this before?' I found a little bit of dabbling into it, but no other software product or other tools that I could use." Stagner then asked engineers at GE Energy Systems if they would collaborate with Stanford to develop the software, but GE's management declined, unwilling to put up the research and development money for the effort, even though they could potentially recoup their costs and make money on the investment by selling the software to others. Knowing he couldn't ask Stanford for millions of dollars to "chase this potentially wild goose," Stagner decided that the only way an engineering model was going to get built was if he did it himself. "I got the old computer and Excel and just worked on it," he said.

Stagner had always been an optimist, approaching life with the outlook that there could always be a better way to do something. "You need that optimism to take on something like this," he said. "And you need two other things: the ability to zoom to 10,000 feet and see the big picture of what you're trying to achieve, as well as the willingness to dig into the minutiae, the extreme detail. This involved much of that. I said, 'I'm going to find a better way for Stanford. That's why

they hired me. I'm not going to disappoint them. I've got to find something.' And then, you can't just ask a bunch of engineers to start chasing down your big ideas for you, because they'll never have the passion, they'll never understand why, and they won't dig as deep. I've never been able to find someone to do that for me. Those people are rare - the ones that have enough interest and passion to go off on a task and come back with something better than you even imagined, something that just blows you away. So you have to be willing, I think, to roll up your sleeves and get into that minutiae yourself when it's called for."

As he plugged away at his Excel model, Stagner's intellectual curiosity kept him motivated. "I felt like we were onto something quite significant," he said, "when I saw that potential overlap and I ran some initial calculations that indicated an integrated heat recovery system could be far more efficient than cogen or the other technologies our SWTs were exploring. All I had to do was model the system to see if it was really true. I perceived that it was, looking at it logically from other angles, and I said to myself, 'I've just got to prove it. I've got to show how heat recovery could work.'" Thanks to the engineers at the cogen plant, Stagner now knew the actual loads - how much heating, cooling and electricity were used - for every hour of the 2009 fiscal year. He also knew what it took for the cogen plant to meet those loads - the amount of fuel and water that were used, the greenhouse gases emitted, and how much Stanford paid to Cardinal Cogen. Stagner would take those same actual loads from 2009 and plug them into his model to see if a heat recovery system could have performed as well as or better than the cogen plant. "And if it's better," Stagner said, "then we've got something here. We'll still have to worry about converting the campus from steam to hot water, but showing that this can work is step one."

Step one turned out to be a major test of will for Stagner. "It took more than half a year, nights and weekends, just trying to figure out how to do this. My wife almost divorced me because I'd be at home on the weekends for 16 hours on the computer like a mad scientist, but she put up with me. I've got to tell you," Stagner said, "there were so many times that the thing just would not work. When you find your first bug, bugs one through 20 let's say, well that's just part of the process. There are going to be bugs to work out. Then you get to that point where it feels like every time you fix a bug, another one pops up, and you just wonder if you're ever going to get it right. You think, 'Oh my god, this code has grown monstrous. I'm at bug number 36. I'm tired. I give up.' But you just have to have faith that there's a way. It's just logic. It's just math. There's got to be a solution. And if I eventually get stuck, well, I'll find some help to get me through the last bit, but I'm not giving up. I'm just too curious. I've got to know if we can do this."

Beyond what the model could do for Stanford, Stagner believed that the tool he was developing could have far-reaching benefits, enabling universities around the country to improve the performance of their existing heating and cooling systems. "You see utilities engineers using these seat-of-the-pants rules," he said, "like running their electric chillers between 9pm and 6am in the summer to recharge their cold water storage tanks because those are the hours when the electricity tariffs are lowest. But that's not the optimal solution. There are all these other variables that need to be taken into consideration. That's what kept me going - not only the desire to understand whether this new heat recovery system would be good for Stanford, but also to help others run their systems more optimally. All sorts of good things could come from it," Stagner said.

With the Cardinal Cogen contract expiring in March of 2015, and knowing that it could take at least three to five years to build a new energy system, Stagner felt some pressure to work quickly. "Five years is a normal, comfortable time for a system build out. Three is rushing it," he explained. "And some of our utilities guys were saying to me, 'Joe, we're not going to be able to change out the steam pipes for hot water pipes in less than seven years. We'll need to do a chunk every summer, have all these outages, convert people. I don't know how you can do that in less than seven years.'" Stagner envisioned that the conversion could be done faster if the university tackled it all at once, even as others insisted that the administration would never allow it. "It was the usual thing where there were a lot of personalities that were more pessimistic and cautious, and then there were the more optimistic personalities. I really think that innovators are by nature optimistic. You have to believe there's a better way to do something. If you're a pessimist, you'll never even try," he said.

After eight long months of persistence, Stagner finally had a functioning model. The Central Energy Plant Optimization Model (CEPOM), as it was later named, used a variety of inputs to determine the best mix of equipment and the equipment operation schedule that would meet Stanford's electricity, heating and cooling loads at the lowest possible cost. These inputs included hourly electricity, heating and cooling demand forecasts, hourly electricity price forecasts, and the performance characteristics of the specified energy production and thermal storage equipment. Utilizing estimated hourly energy needs for an entire year, based on the actual energy demands observed for the campus in prior years, CEPOM could lay out the optimal equipment operation plan for every hour of the year. The model also calculated and summarized the amount of fuel and electricity required to operate the equipment and the associated greenhouse gas emissions and water consumption, as well as the costs for the energy and water. If Stagner specified a mix of energy production and thermal storage equipment that was insufficient to meet the desired loads, the model would indicate the exact hours and magnitude of the deficiency, providing Stagner with important feedback that he could use to hone in on a better system solution. It would take hundreds of iterations, using different combinations and sizes of the five major system components, to arrive at an optimal system design.

A handful of enthusiastic students helped Stagner test the model to see how it held up under different scenarios. "What if you set the hot water storage tank to zero to indicate that we don't have a hot water tank?" he asked the group. "Will this model correctly model a system without a hot water tank? If you put in all different types of numbers for the other components and always keep the hot water tank at zero, does the system bust, or does it return results? And if it generates results, do they make sense, or do you get crazy outputs like negative numbers? Now, turn the hot water tank on, but put the cold water storage tank at zero and see what happens," he instructed.

Over the course of two semesters, the students methodically tried different combinations of equipment and ranges of values and reported their results. By March of 2010, Stagner felt confident that the model was fully debugged. To his elation, the model showed that it was indeed technologically feasible to design a heat recovery system that could meet Stanford's energy needs. "Everything was clearly laid out, step by step, hour by hour. You could pick any hour of the year at random, with its particular heating and cooling needs, and see how the system

worked. Or you could sum up all the hours and see the system's performance in aggregate," he said.

At that point, with the model showing that a heat recovery energy system was not only feasible but also quite attractive in terms of operating costs and environmental performance, Stagner hired two firms specializing in central energy plant design for universities - Affiliated Engineers and Jacobs Carter Burgess - to peer review the conceptual system design. If they both signed off on the engineering concepts, then and only then would Stagner go to his boss and say, "We've got something here, and I have proof." The two firms made some adjustments, downgrading certain equipment performance factors to account for manufacturer's optimistic claims, for example, but overall they concurred that the conceptual system design was correct from an engineering perspective. "I wanted to be able to pass that test," Stagner said, "because I just knew Stanford would have very smart people critiquing this from all angles. When I brought it forward, I would need to know more about it than anybody else could possibly know. Having the peer review to back up the system design gave me the confidence to stand by it."

Stagner had been keeping his supervisors at Stanford apprised along the way. Stagner's boss was Jack Cleary, Associate Vice President of Academic Projects and Operations for Land, Buildings and Real Estate (LBRE), who in turn reported to LBRE Vice President Bob Reidy. "When I first started sharing my ideas with [Reidy] back in 2009, his first reaction was, 'Joe, you're nuts. You've been here only a year and you think we should get rid of our cogen plant? I don't get it. Tell me why.' So I diagramed it out for him, and he felt it was promising enough to say, 'Okay, keep working on it. Maybe you're onto something here.' He could have said, 'Oh, that's ridiculous. Don't even look at it any more. We're never going to do that.' But he didn't. That's one of Stanford's greatest attributes - people who are optimists but also knowledgeable. I had the right leaders above me, who listened, and when I had the case fully proven, then Bob Reidy said, 'All right, you've proven it to me. Now I'm going to share it with the provost.'"

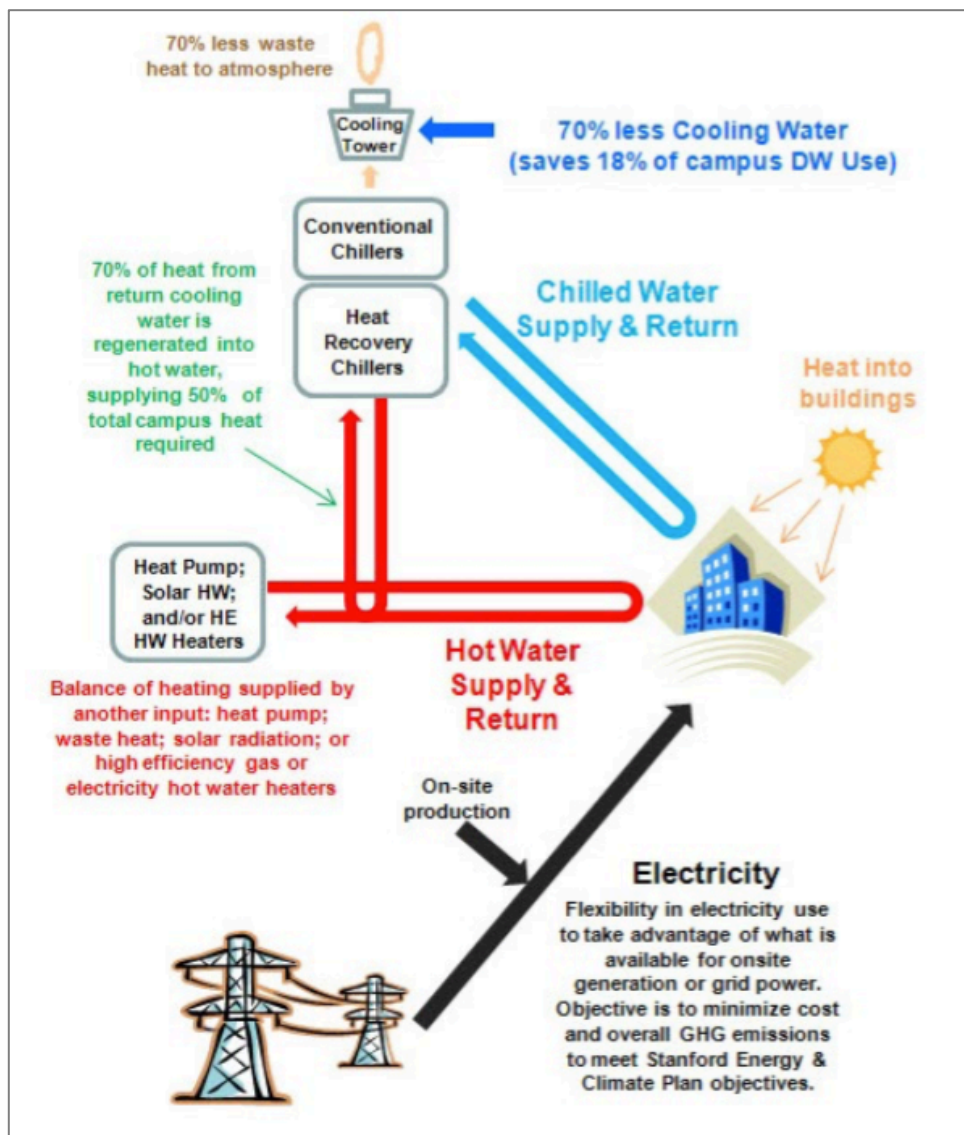
The report that Stagner submitted to Stanford Provost John Etchemendy and President John Hennessy for consideration was thick and full of detailed appendices. "I never expected them to read it," Stagner said. "I expected them, like most executives, to ask their subordinates to read it and then say, 'Is this thing true? I trust you, so if you say it's good I'll buy it.' But being the smart and inquisitive individuals they are, even though they must have tremendous responsibilities and schedules, they both took the time to read it in detail. They wanted to understand it, I think, both because they were intellectually curious and because of the huge scale of it. So hats off to them." To Stagner's amazement, Etchemendy even found an error in a chart in an appendix. "Wow, I thought, how did he know that that line should have intercepted here instead of there? It really invigorates you when you have leaders willing to engage and go the extra mile," he said.

At Etchemendy's and Hennessy's request, Stagner convened Stanford's energy faculty to tell them about the heat recovery concept and get their feedback. He presented to two-dozen experts from across the university, including faculty from the schools of engineering and earth sciences, the global climate and energy project, and more. When Stagner asked his audience for comments, 90 percent of those in attendance said the idea was very intriguing. They agreed that he was on to something. However, not everyone was convinced. Two prominent faculty members, one of whom was a Nobel Prize winner, were strong advocates of cogeneration and questioned Stagner's conclusion that heat recovery was a better solution. Though Stanford's

cogen plant had certainly been cutting edge for its time, Stagner felt that these professors were missing the point by assuming that nothing could be better. Eventually, when they sat down together to discuss the concepts and diagram out the details, Stagner found them to be more open in their thinking. "They realized that nobody had thought about all this free energy in the system, and that changed their minds, so much so that one of them now teaches about heat recovery in his own classes," Stagner said.

With the faculty on board, Etchemendy and Hennessy asked Stagner to commission additional peer reviews of the engineering model. If the university was going to consider a new energy system of this magnitude and expense, they wanted to be absolutely confident that the model was sound.

Figure 3: Schematic illustration of Stanford's new heat recovery system



Source: Stanford University

At that point, a new wrinkle emerged. "One of my subordinates who was here for 30 years managing the cogen plant, he too was convinced that gas-fired cogen was the only way to go, that there could be nothing better," Stagner said. "Even when we showed him the analysis, he was very combative, insisting that we had doctored the results." Frustrating as this was, Stagner tried to remain objective. "I would have changed horses in a minute if somebody showed it was the right thing to do, if there was proof," he said. "That has to underlie everything. Fairness and objectivity. You can't say to yourself, 'Gosh, I got this idea so far, I've got to stick with it no matter what happens.' You can't do that and be intellectually honest. It will haunt you." In an effort to diffuse the situation, Stagner acknowledged the engineer's cogen expertise and tasked him with leading a team to devise all the best possible cogen solutions. "We asked him to lay out all the possible natural gas-fired cogen scenarios, model them, price them, do everything," Stagner said. "His team gave it their best shot. When he saw that heat recovery was outperforming cogen, that led him to dig deeper and try even harder. They actually developed a hybrid system consisting of a smaller cogen combined with some heat recovery. We called it 'hy-gen.' To their credit, they tried really hard, and that solution they came up with turned out to be the best possible natural gas option."

Meanwhile, the SWTs had finished researching other available energy supply technologies and concluded that, with respect to providing heating and cooling, the two primary options already under serious consideration - heat recovery and cogen - were the best possible solutions. They further concluded that if Stanford should decide to move from a system, such as cogen, that was primarily reliant on natural gas to one, such as heat recovery, that was reliant on electricity, then the university should shift its electricity supply to renewables, not only for increased sustainability but because renewable options offered greater price stability (fossil fuel prices are known to swing wildly whereas renewable prices can be fixed under long-term contracts). Specifically, the SWTs suggested a combination of wind, solar and geothermal, since these were the most mature and best-value renewable energy technologies available to the university at the time, but they also emphasized that new technologies would almost certainly emerge in the years to come, and Stanford should closely track and consider new possibilities.

The next step was to model out the present value cost of the most promising energy systems, taking into account the upfront capital costs as well as the long-term operation, maintenance, fuel and electricity costs.¹⁰ To do this, the team would need to agree on a set of assumptions about the market price of gas and electricity over time. "You've got two competing fuels," Stagner explained. "You have a cogen option that uses natural gas, and you have the heat recovery plant option that uses mostly electricity. If you predict natural gas is going to be nearly free for 30 years, then the economics say go with that option. If you think natural gas is going to be horrendously expensive and electricity is going to be almost free, you go with that option."

Stagner called on professors from Stanford's Graduate School of Business and other campus finance professionals to help determine appropriate gas, electricity and labor cost escalators for the model. Forecasting electricity and gas prices was especially tricky. "Those markets are completely wild, but we had to pick something reasonable," Stagner said. Bureau of Labor

¹⁰ In economics, the present value cost of a project is the sum of all cash outflows associated with the project over a period of time, including initial capital costs, financing costs and operating costs, discounted to reflect the time value of money.

Statistics data showed that the price of electricity in the U.S. had increased 7 percent annually in the last 50 years, whereas the general rate of inflation had been roughly 5 percent. Energy was costing more over time. Armed with that information, the team decided to approach the energy forecasts three different ways. First, they looked at the 30- to 40-year energy price forecasts published annually by the federal Energy Information Administration. "It's the official forecast the government and others use. It's their best guess. They put many variables into it, but still it's tough to get it right for energy," Stagner said. They also asked a consultant with deep expertise in California's energy market to prepare a forecast, and hired a third specialized company to do the same. Stanford's team of experts then analyzed and debated the three different long-term estimates and came to an agreement. They also selected a discount rate to be used for present value cost calculations.¹¹ "We objectively fixed those variables before we started running the model, so that the results would be unbiased," Stagner said.

With the energy and financial modeling complete and peer reviewed, Stagner and his team turned their attention to laying out the most promising energy supply options for Stanford's leadership to consider. They developed comparison tables and the so-called *bars and bubbles chart* (see Figure 5 below) to illustrate the financial costs and environmental performance of each option relative to the business-as-usual approach of extending the existing cogen contract. Of the top eight solutions, four consisted of new cogeneration systems that would primarily use natural gas to meet campus energy needs, and the other four were grid-tied systems that would rely on heat recovery to varying degrees and primarily use electricity to meet campus energy needs. Though the initial capital costs of any of these new systems would be massive - in the range of \$435 to \$595 million, the model showed that, over the span of the next 35 years, all of the new options would cost less than the business-as-usual option due to their lower operating, maintenance and energy (i.e., natural gas or electricity) costs. The new options also offered superior environmental performance; their electricity and gas usage, greenhouse gas emissions and water consumption were all projected to be lower, and in some cases substantially lower, than those of the existing cogen system.¹² (Exhibit 3 on page 25 presents the various options and their advantages, disadvantages and costs relative to the business-as-usual approach.)

As the options became clear, Stagner and his team began vetting them more broadly. One of the first audiences was the University Cabinet – the deans, vice presidents and vice provosts who helped the president and provost run the university, and who were responsible for all the Stanford community members who would have to live through any major construction and pipe network changes. Around the same time, in late 2010, President Hennessy recruited six members of Stanford's board of trustees, including oil and gas executives Jim Coulter and Bob Bass and clean energy advocate Tom Steyer, to vet the ideas in detail prior to engaging the full board. "We had a good mix of both camps politically," Stagner said. "They did their homework and then reached agreement on a single solution."

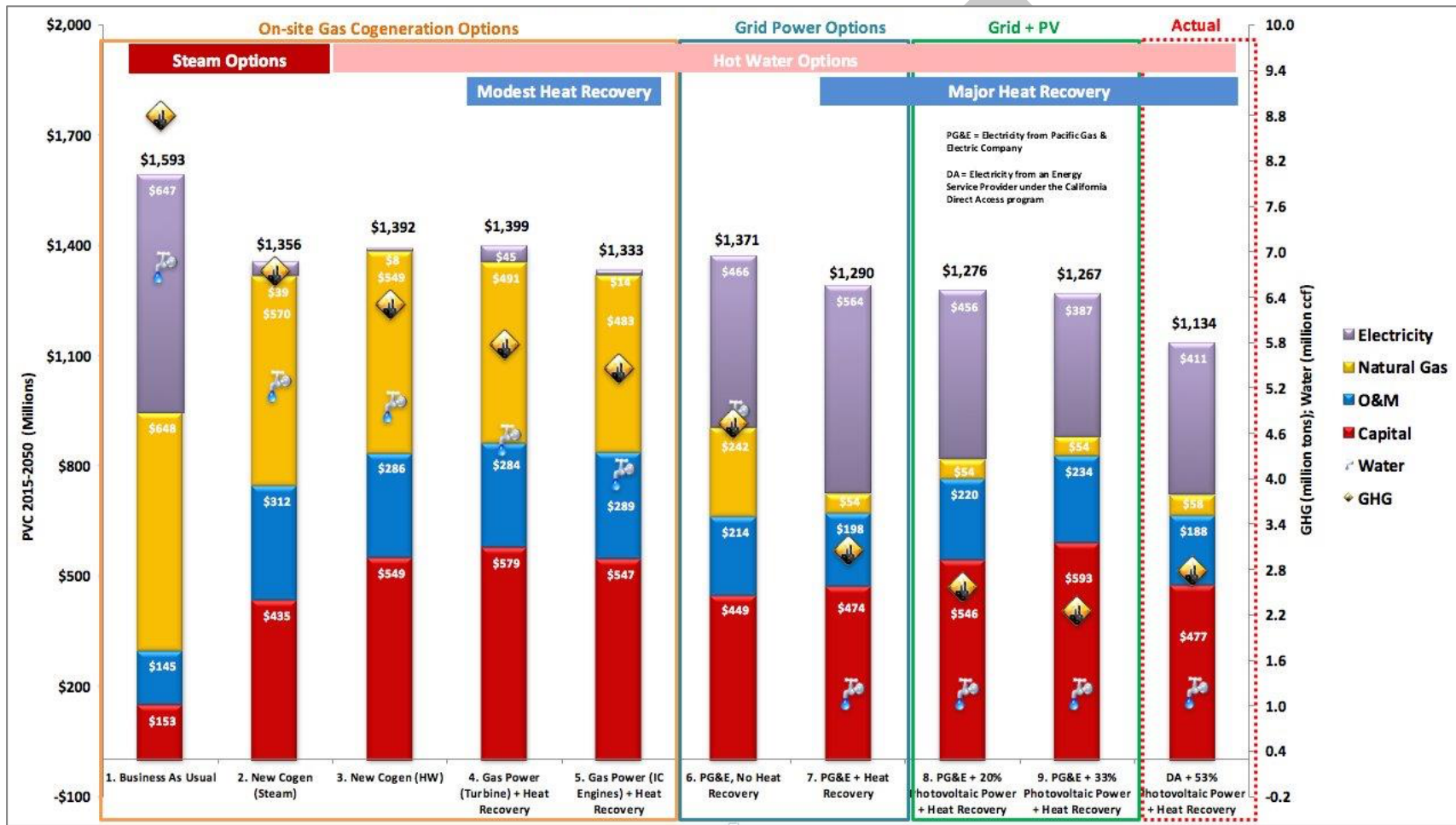
¹¹ Discount rate refers to the interest rate used to determine the present value of future cash flows. The discount rate accounts for the time value of money, which is the idea that a dollar today is worth more than a dollar tomorrow given that the dollar today has the capacity to earn interest. It should also account for the risk or uncertainty of future cash flows; the greater the uncertainty of future cash flows, the higher the discount rate. Source: Investopedia, <http://www.investopedia.com/terms/d/discountrate.asp> (May 26, 2017).

¹² Stanford University Energy and Climate Plan, Revised September 2015, Third Edition.

When the subcommittee made its recommendation to the full board in 2011, the trustees voted unanimously in support of a new *grid + heat recovery* system. Though the upfront capital cost of the system was estimated at \$474 million, SESI - as the project came to be known - was projected to save Stanford \$300 million over the 35-year life of the project relative to the business-as-usual approach and up to \$109 million relative to other base energy systems that the trustees considered. From an environmental perspective, SESI would be far superior to the existing system, cutting greenhouse gas emissions by 80 percent and water use by 70 percent, resulting in an overall reduction in campus greenhouse gas emissions of 68 percent and water use of 18 percent. Since the system would run on electricity from California's power grid instead of burning natural gas, Stanford's energy mix would become greener and greener over time as the state continued to shift to cleaner, renewable sources. Furthermore, if Stanford could successfully obtain "direct access" rights as provided for under state law, the university would have the option to purchase up to 100 percent of its energy from renewable sources.

In March 2015, after a three-year design and construction process, including 30 months to replace the steam conveyance system with new hot water pipes, Stanford brought SESI into operation and permanently shut down the cogeneration plant. That April, President Hennessy gave a press conference at the new central energy facility announcing SESI's successful launch. For the first few months, Stagner and his team operated the new plant manually, using the existing Excel model to inform their operating decisions. Meanwhile, Johnson Controls Inc. was putting the finishing touches on a more robust industrial-quality software platform - called "EOS" (short for enterprise optimization solution) - that Stanford could use to automatically control the plant equipment and ensure that the system was running at optimum efficiency. In November 2015, Stagner smiled as his team worked with technicians from Johnson Controls to deploy EOS for the first time, letting the integrated control system take over the operation of SESI much as a pilot puts his aircraft on autopilot.

Figure 5: Comparative costs, greenhouse gas emissions and water use of central energy facility replacement options



The life-cycle cost decision criteria, shown in bars, include: initial capital investment in red, operations and maintenance cost in blue, cost of purchasing electricity in purple, and cost of purchasing natural gas in yellow. The present value cost (PVC) of each energy generation option is shown in the \$ figure above the composite bar. Water use and GHG emissions are shown via icons. The Stanford Board of Trustees elected to pursue the grid power with heat recovery option. Chart updated August 2015 to include direct access scenario, which gives Stanford the option to purchase electricity from renewable sources.

Source: Stanford University

Figure 6: Aerial view of SESI

Source: Stanford University. Photo credit: Steve Proehl.

Beyond Stanford: Modern District Energy Systems around the World

While SESI offers an inspiring example of an integrated energy solution at the campus level, a variety of cities around the world - from Paris to Dubai - are leading the global transition to a sustainable energy future by deploying modern district energy solutions at an even larger scale.¹³ The United Nations Environment Program (UNEP) defines *district energy solutions* as those that "seek synergies between the production and supply of heat, cooling, domestic hot water and electricity, with the goal of optimizing energy efficiency and local resource use."¹⁴ Because cities account for 70 percent of energy demand and 40-50 percent of greenhouse emissions worldwide,¹⁵ collective leadership by cities to advance low-carbon, climate-resilient energy solutions is imperative. Fortunately, municipalities often play a primary role in managing physical infrastructure and providing services such as waste collection, transportation and energy and water utilities, making them uniquely positioned to pursue integrated energy solutions that go beyond the scope of any single city department. Integrated systems thinking and adaptation to local conditions are key ingredients to success. An energy solution appropriate for the desert city of Dubai, for example, where the average high temperature in summer exceeds 100 degrees Fahrenheit¹⁶ and air conditioning represents 70 percent of electricity use, is likely to look very

¹³ *District Energy in Cities: Unlocking the Potential of Energy Efficiency and Renewable Energy*, United Nations Environment Programme, 2015.

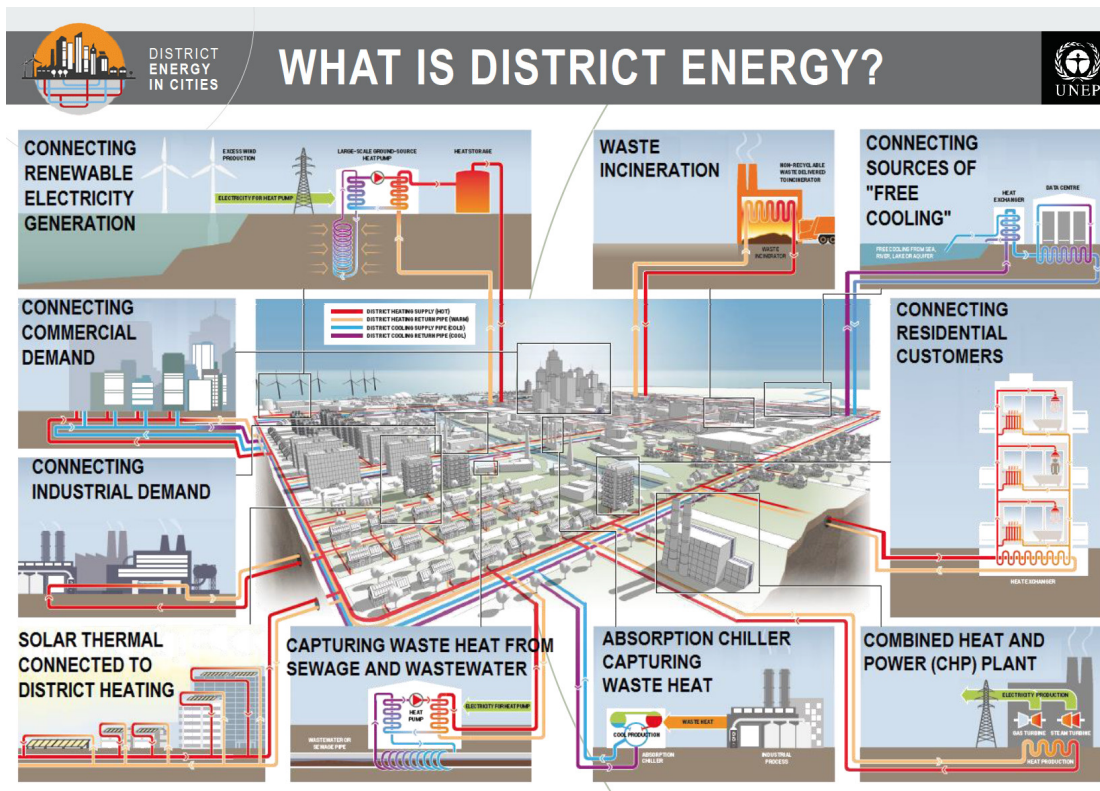
¹⁴ United Nations Environment Programme. "District energy: a tried and tested answer to modern urban energy problems," October 2016, www.unep.org/ourplanet/october-2016/unep-work/district-energy-tried-and-tested-answer-modern-urban-energy-problems (May 26, 2017).

¹⁵ Seto et al., 2014, in "District Energy in Cities: Unlocking the Potential of Energy Efficiency and Renewable Energy," UNEP, 2015.

¹⁶ "Climate: Average Maximum Temperature °C (1984-2009)," Dubai Meteorological Office, October 5, 2013. <https://web.archive.org/web/20131004223556/https://services.dubaiairports.ae/dubaimet/MET/Climate.aspx> (May 27, 2017).

different than an optimal district energy solution for Frankfurt, Germany, with its more temperate climate.¹⁷

Figure 7: Illustration of a modern district energy system at the city scale



Source: United Nations Environment Program

The city of Paris, France, which first turned to district energy in the 1920s as a way to mitigate pollution from coal, provides a shining example of what is possible when systems thinking and local resources are creatively deployed.¹⁸ Today Paris is home to Europe's first and largest district cooling network, which utilizes the river Seine as a major source of cooling as it bisects the city. To meet the city's heating needs, the Paris district heating company utilizes a variety of renewable and recovered heat sources including geothermal, waste-to-energy and heat recovery from sewage and industry. The district system, which is on track to secure 60 percent of its energy from renewable or recovered sources by 2020, serves all hospitals plus half of all social housing and public buildings, including the Louvre Museum, offering strong social benefits as well as environmental. The economic benefits are also positive, as district energy provides cheaper and more renewable heating and cooling for customers, €10 million in fees and

¹⁷ According to UNEP's 2015 "District Energy in Cities" report, Dubai's heavy demand for air conditioning led the city to develop the world's largest district cooling network, which is expected to meet 40 percent of the city's cooling demand by 2030 as the network expands. Through district cooling, Dubai is halving the amount of electricity it uses for cooling, while also reducing its consumption of fresh water - a priority in the region - through use of treated sewage effluent. Frankfurt, meanwhile, is on track to source 100 percent of its energy from renewable sources by 2030, completely eliminating its reliance on fossil fuels. Its district energy solutions include improved energy efficiency and using waste heat to balance out the variability in its renewable energy sources.

¹⁸ *District Energy in Cities*, UNEP, 2015.

dividends to the city, and estimated annual benefits of €19.5 million. Efforts like those underway in Paris are an important step toward fulfilling the United Nation's Sustainable Development Goal #7, which calls upon its members to "ensure access to affordable, reliable, sustainable and modern energy for all."

Despite the tremendous potential of modern district energy systems to provide affordable and reliable energy and drastically reduce greenhouse gas emissions, a variety of barriers make their widespread adoption extremely challenging. Barriers include simple lack of awareness about district energy and its many benefits; lack of data on city-wide heating and cooling consumption; lack of holistic planning policies that integrate energy and other systems; lack of capacity to coordinate and implement integrated solutions; unproven commercial viability or inadequate financial incentives for private actors in some markets; and high project development costs.

Lily Riahi, research director and author of UNEP's extensive 2015 report on district energy in cities, explained the challenge as follows: "Switching to modern district energy requires innovative local planning that integrates energy and land-use, and coordination across multiple city sectors such as energy, transport, housing, waste collection and wastewater treatment. Because it's new to many cities, it takes time, and many local governments worldwide do not have the capacity, accounting tools, or a clear mandate from their national governments to intervene in the sector," Riahi said. Through its District Energy in Cities Initiative, UNEP works with local and national governments around the world to improve their policies and planning processes in the hopes of facilitating investment and accelerating the development of district energy solutions. Cities that can get past the barriers stand to reap a range of social, economic and environmental benefits including waste reduction, better air quality, reduced greenhouse gas emissions, power grid resilience and local jobs in the green economy.

Inspiring Change

Back at Stanford, Stagner was ready for his visitors to arrive. He sincerely hoped this facility tour, one of the dozens he would lead in the months ahead, would inspire his guests to take the kind of meaningful action that was so desperately needed in every corner of the globe. If his guests were unprepared or unwilling to pursue their own district energy project, at the very least he wanted to make sure they left Stanford with a solid understanding of the steps they should be taking now to set themselves up for success in the future - everything from data collection, to advocating for clean energy policies and greener electrical grids, to simply starting the conversation and sharing ideas with key decision makers.

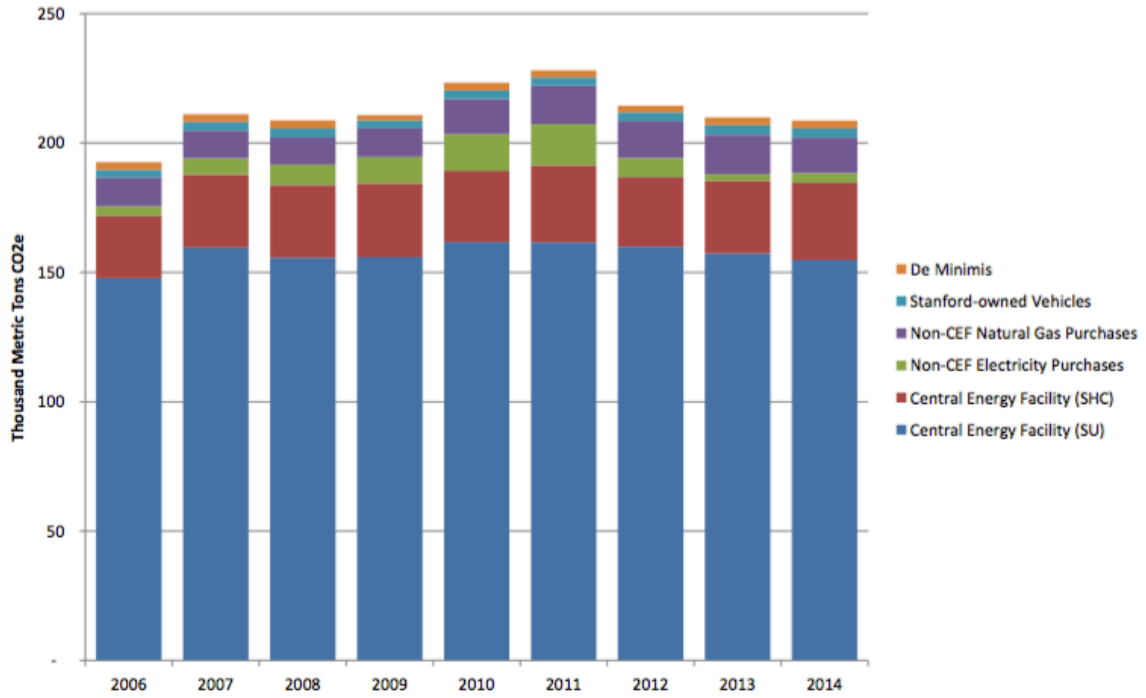
Stagner was convinced that heat recovery held widespread promise for college campuses across the country. Energy analyses conducted for universities in Massachusetts, North Carolina, Illinois and California all showed that it was possible to meet 50 percent of annual campus heating and hot water needs through waste heat. Yet progress toward system implementation was slow. "People are afraid," Stagner explained. "Everybody comes away thinking this is the greatest thing since sliced bread. They're excited. A few have gone home and looked seriously at developing their own systems, and it's been proven in detail that the heat recovery concept could work there too and be just as beneficial as it is here. But then they get hung up on the thought of how much work it takes to transform a system. Well, it's true, you're not going to have profound

change without hard work. People need to accept that. But it's only two and a half years of hard work for something that will last a century. And we will help. We can show them how. For the most part, there are no technological reasons why they can't do this. It's mostly that people are fixed in their ways."

Though frustrated by the slow pace of change, Stagner was quick to highlight a handful of recent successes. Ball State University in Indiana had installed a large-scale ground source heat exchange system and converted its campus from steam to hot water. Cornell University was also making progress, having installed a major lake source cooling system. District energy systems were also gaining ground in a handful of applications outside of academia. "The military is one place where we've seen movement," Stagner said. "A lot of their bases will be around a long time, just like university campuses, so they're willing to make investments. Then you have airports. San Francisco and Dallas-Fort Worth are both working very hard to be progressive. And there's movement toward district energy in the corporate sector by those who believe both in the moral and business reasons for sustainability. But obviously there are many others who don't think that way."

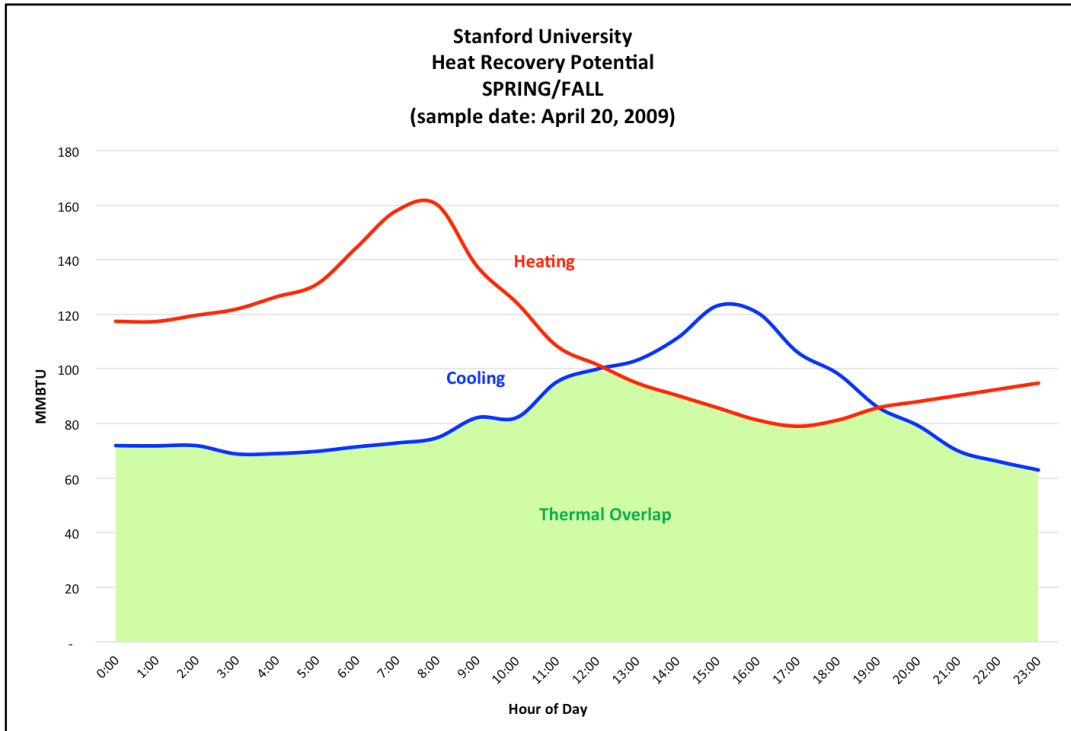
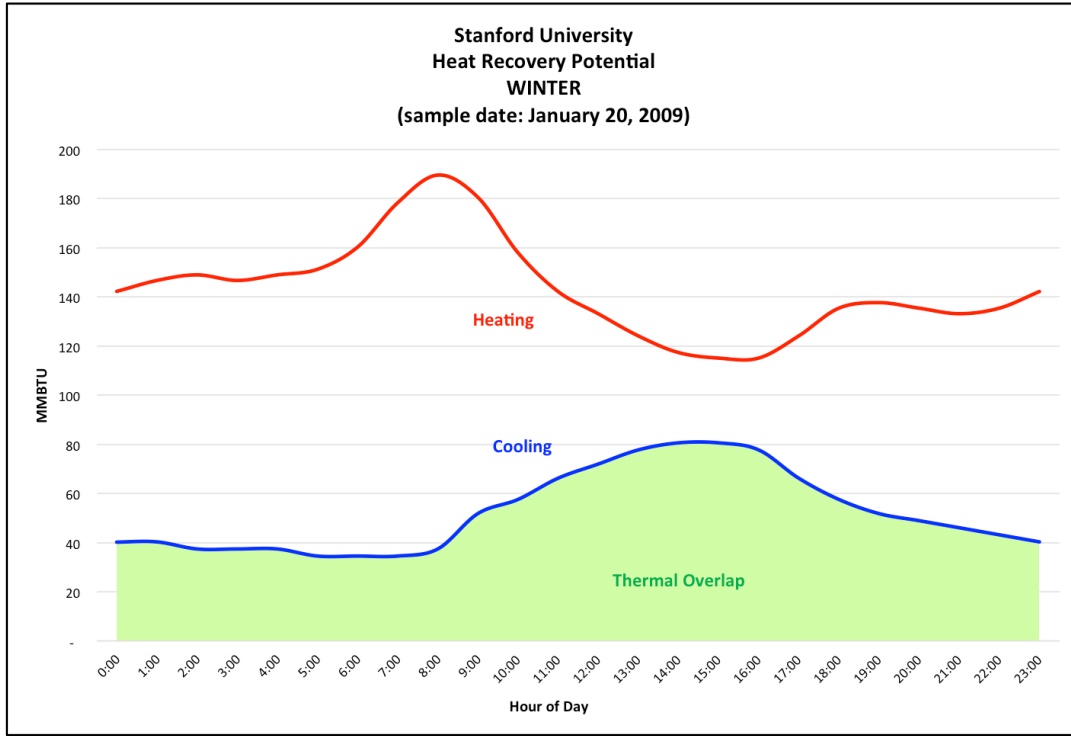
In Stagner's view, the biggest obstacle to progress was lack of political will. "Half of our country is still of the mindset that there's really no problem to solve. Or they believe that what we're proposing will be bad for the economy, that it will kill jobs," Stagner said. "Some will say, 'Look, if I move from gas to electricity, that just makes things worse because our grid is on coal power here. If the state never cleans up my grid electricity, this approach will produce more greenhouse gases than the gas we're using now.' But do you really think for the next 50 years they'll continue to burn coal? You've got to work with the state until they recognize that electrification and cleaning up electricity is the strategic way forward. There are five big things for which electrification may not be the solution for achieving sustainability and reducing greenhouse gases: airplanes, ships, semi-trucks, steel production and cement production. It's really challenging to get the GHGs out of those five. But the rest of the world - the other 80 percent that includes buildings, cars, trains, and most everything else - needs to electrify through efforts like this. It's very clear. You have to electrify everything in society that you can and clean the electricity. That is the only practical large-scale path forward."

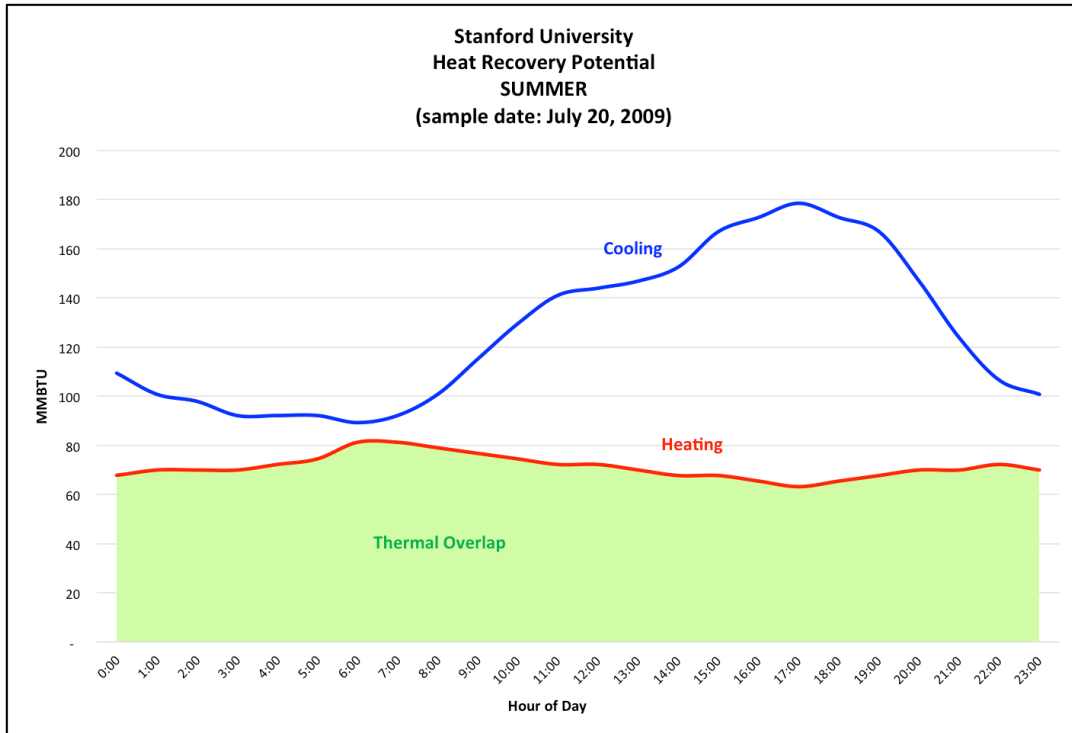
Exhibit 1: Annual Greenhouse Gas Emissions, 2006 - 2014



Source: Stanford University

Exhibit 2: Heat Recovery Potential on Stanford Campus by Season





Source: Stanford University

Exhibit 3: Stanford University Energy Supply Options - Comparison Chart

Option Category	Name	Description	Advantages	Disadvantages
Gas	On-site gas cogeneration options	These options explore burning fossil fuel on site to meet campus power and thermal needs.	Potential for low-cost long-term natural gas supply; 100% on-site power generation	Dependence of all campus energy on single fossil fuel source; lack of environmental sustainability
#1, with present value cost (PVC) of \$1.593 billion	Steam option—business as usual (BAU)	Extend current cogen operation to 2050 under existing third-party agreement	Lowest direct capital and O&M costs because third party owns and operates plant	Highest overall cost, GHG emissions, and water use due to third-party overhead and profit and lowest plant efficiency
#2, with PVC \$1.356 billion	Steam option—new cogen plant	Install new Stanford-owned and operated combined cycle gas turbine (CCGT) cogen plant	Lower capital cost than other new Stanford-owned cogen options because includes no new hot water system; lower GHG emissions and water use than BAU	Higher overall cost than high-efficiency hot water-based internal combustion (IC) cogen systems; only modest overall emissions and water use reductions
#3, with PVC \$1.392 billion	Hot water option—new gas turbine (GT) cogen	Install new Stanford-owned and operated CCGT cogen plant with hot water-based heat distribution system	Modest reductions in GHG emissions and water use over new steam-based cogen plant	No economic advantage over new steam-based cogen plant
#4, with PVC \$1.399 billion	Hot water option—new GT cogen with heat recovery	Install new Stanford-owned and operated CCGT cogen plant with hot water-based heat distribution	Slight emissions reduction, slight water use reduction over standard GT cogen with hot water,	Higher capital cost (\$579 million), higher overall cost than hot water-based GT cogen without heat recovery

		system and some heat recovery	due to modest amount of heat recovery possible	
#5, with PVC \$1.333 billion	Hot water option—GT cogen using internal combustion (IC) engines with heat recovery	Install new Stanford-owned gas-fed IC engine cogen plant with hot water-based heat distribution system and some heat recovery	Best overall gas-fed cogen option with additional modest GHG, water use, and cost reductions over GT-based cogen without heat recovery	High capital cost (\$546 million); higher GHG emissions, water use, and overall cost than grid + heat recovery (option #6)
Grid	Options using grid power for electricity instead of on-site cogen	These options explore combinations of grid power for electricity, an on-site thermal energy plant with optional heat recovery, and hot water-based heat distribution.	Optimality from overall economic, risk, flexibility, and environmental sustainability standpoints	Modestly higher up-front capital costs than retaining cogen with steam-based distribution
#6, with PVC \$1.371 billion	Grid, no heat recovery	Get electricity from grid; install new gas boilers, electric chillers thermal plant; install hot water-based distribution system	Better option than BAU; simpler ownership and operation than cogen plants; more long-term flexibility	No real improvement over gas-based IC cogen plant, more expensive investment and less water savings.
#7, with PVC \$1.290 billion	Grid + heat recovery	Get electricity from grid; install new electricity-based heat recovery plant and hot water-based distribution system	Best overall option, with relatively low cost, GHG emissions, and water use	Higher up-front capital cost (\$485 million) than retaining existing cogen with steam-based distribution, which is nanced, owned, and operated by a third party
Grid + On-site PV	Grid power options with on-site photovoltaic (PV) power generation	These options explore combinations of grid and on-site PV power for electricity, an on-site thermal energy plant with heat	Optimal environmental sustainability; lower capital costs	No economic advantage over new steam-based cogen plant

		recovery, and hot water-based heat distribution.		
#8, with PVC \$1.276 billion	Grid + 20% PV + heat recovery	Same as grid + heat recovery option but using same total capital that would be required by best cogen option to buy some on-site PV plant	Further improvement upon best overall option (grid + heat recovery) if total up-front capital equivalent to that required for best cogen option is allocated; ability to absorb PV power behind the meter	Higher up-front capital cost than base grid + heat recovery option; land use requirement
#9, with PVC \$1.267 billion	Grid + 33% PV + heat recovery	Same as grid + heat recovery option but allocating enough land and capital to meet full 33% California Renewable Portfolio Standard for electricity use via on-site PV	Further improvement upon best overall option (grid + heat recovery) if additional up-front capital and land are allocated; partial long-term power cost stability	Very significant land use requirement; possibility that exports of PV power to grid would be required in some hours

Source: Stanford University