

Introducing the Distributed District Energy System

Jonathan Bean, The University of Arizona

ABSTRACT

This paper explores the potential of a distributed district energy system (DDES). The potential for a DDES is explored in the context of a medium sized city located in Tucson, Arizona, a cooling-dominated hot and dry climate with an abundance of solar energy. First, existing school buildings retrofitted to reduce peak hourly cooling loads. The retrofit results in a surplus of cooling capacity from the existing air-to-water chillers during periods of occupancy and additional cooling capacity when the building is not occupied. Directly coupling the chillers to electricity generated by on-site photovoltaics allows a surplus of thermal energy to be generated, stored, and shared while eliminating most carbon emissions associated with cooling. Over time, schools are connected to commercial, residential, and industrial buildings to create the DDES. Depending on use and site, connected buildings can use, contribute, or store thermal energy via retrofit space conditioning systems, air-to-water heat pumps coupled to photovoltaics, and thermal storage. This topology, which can be optimized for different loop temperature and distribution strategies, addresses three key obstacles to conventional district energy systems by 1) allowing organic growth over time and 2) eliminating the first cost of a centralized plant, and 3) providing a pathway for retrofit and distribution in existing urbanized areas. In addition to increasing access to cooling by guaranteeing a minimum level of conditioning to all users regardless of ability to pay, the DDES approach described could also allow utilities to transition to a new business offering: building conditioning as a service.

Introduction

About district heating and cooling

Interest is surging in district energy systems. Centralizing the generation of heated or cooled water leverages economic and thermal efficiencies of scale, while newer systems make use of waste heat through redistribution and storage. In the U.S. and North America, district energy systems, including district heating, chilling, and cogen plants, have been deployed in dense urban areas (Tredinnick et al. 2015). These systems typically have a large, centralized plant that produces heated or chilled water circulated out to the loads and back to the plant through underground pipes. Buildings served by the district energy system have smaller mechanical systems than would be otherwise needed, reducing costs and saving space. While research shows that adopting district cooling could reduce peak demand by 50% compared to individual units in hot climates such as Kuwait (Alajmi and Zedan 2020), much of the recent literature on integrating cooling in district energy systems focuses on the addition of cooling to different types of district energy systems, rather than on the creation of new systems that prioritize cooling. Interesting recent developments include National Grid's trial of a district geothermal loop in Massachusetts (National Grid 2022), which has the potential to repurpose its

natural gas pipeline installation and maintenance capabilities, and the extraction of waste heat from sewage in Denver, Colorado, at the National Western Complex (Brasch 2021).

In the U.S., despite the advantages of district systems, the vast majority of buildings in urban, suburban, and rural settings are conditioned with individual mechanical systems, which are attractive because of low first cost, the lack of material infrastructure needed to support district systems, and lack of social, political, and economic precedent. Retrofitting existing cities or neighborhoods with district energy systems is difficult because of the first costs of the centralized energy plant. Furthermore, other research indicates the viability of district energy systems in low-density areas is limited by higher distribution costs, such as the cost of laying circulation pipe around other infrastructure, such as roads, sidewalks, and existing underground utilities, compounded by low energy costs and the lack of a carbon tax in North America (Reihav and Werner 2008; Nilsson et al. 2008).

Cooling as a Service

Cooling as a Service (CaaS) extends the potential of district cooling to deliver large economic, social, and environmental benefits by shifting the business model from the sale of cooling equipment to a subscription model for the provision of cooling services (K-CEP 2018). This has several benefits, including reducing the first cost for cooling users and encouraging service providers to choose and carefully maintain high-efficiency equipment. As climate change continues to increase the intensity, duration, and frequency of heat events, advocates argue that access to cooling in extreme conditions should be viewed as a basic human right. Furthermore, research shows that cooling contributes to the attainment of all 17 Sustainable Development Goals (Khosla et al. 2020). If CaaS solutions are implemented at district scale, they have the potential to reduce the number of compressor-driven air conditioning (AC) systems and the volume of refrigerant needed to deliver a given amount of cooling.

Evolution of District Energy

Research on district energy systems characterize shifts in “generations” of district energy. While the demarcations between the generations are subject to debate, the overall trend is for newer generations to incorporate multiple heat sources or heat sinks, optimize the flow of energy between buildings, and use distributed heat pumps, which allow the efficient utilization of reduced loop temperatures. This trend reflects a shift away from earlier models, which linked multiple users to a single, centralized source of energy. Lund et al. (2021) categorize these systems in four generations:

- first-generation, with high-temperature steam in concrete ducts, powered by coal;
- second-generation, with high-temperature water, powered by combined heat and power plants fired with coal or oil;
- third-generation, with a reduction in water temperature and the addition of new heat sources such as large-scale solar and biomass; and
- fourth-generation, incorporating thermal storage, bidirectional flow, and district cooling.

The potential for dynamic thermal flows has led to significant innovation and a proliferation of competing claims about fifth-generation district heating systems. While Lund et al. (2021) argue these innovations are best thought of as variations on the theme of fourth-

generation district heating systems, Buffa et al. (2019) define the simultaneous delivery of heating and cooling as a key characteristic of fifth-generation systems that allows for both increased efficiency and the “sector coupling of thermal, electrical, and gas grids in a decentralized smart energy system” (p. 508). While there is disagreement over terminology, there is agreement that these types of tightly integrated systems are well-suited to the challenge of wringing the most useful energy possible out of a district system.

Rezaie and Rosen (2012), following work by MacRae (1992), distinguish four densities suitable for district energy systems:

1. densely populated urban areas,
2. high-density building clusters,
3. industrial complexes, and
4. low-density residential areas.

In countries where district heat is available for single-family houses, research shows that there is the economic potential for more connections beyond the 48% of single-family houses in Denmark, 13% in Finland, 10% in Sweden, and 5% in the Netherlands currently served. This research did not define density levels, but a chart indicates that pipeline length per house for eight demonstration projects ranged from approximately 10m-70m. The upper end of this range correlates with typical North American suburban densities of 4-10 houses per acre. Pipeline length is a key metric because the labor required to excavate, place, and cover pipelines represents 75% of total construction costs (Nilsson et al. 2008). Even when the cost to construct a central plant is excluded from the calculation, the average initial cost of 13,800 € to connect new houses to an existing district system can be offset over time by the sale of energy. This finding, however, assumes relatively high energy use over time, which creates a business disincentive for the implementation of conservation strategies. Furthermore, the findings do not translate to areas where energy is relatively inexpensive. (Reidhav and Werner 2008).

Defining the Distributed District Energy System

A different way of thinking about the potential of district energy is needed. This approach would be suited for low-density suburban areas common in North America, would reduce the amount of capital investment required to launch the system, and should be able to grow organically from the scale of a single block to a neighborhood to an entire city. It should also be compatible with the regulatory and economic landscape in the US, where the implementation of climate plans and carbon reduction strategies appears is often framed as opposed to the profitability of energy providers.

This paper defines a Distributed District Energy System (DDES). Whereas other approaches to district energy draw from a centralized source of energy, such as a chiller plant, biomass boiler, or lake water, the energy that circulates in the DDES loop is generated by sources distributed in the loop. The majority of thermal energy is generated by air-to-water heat pumps driven by PV. Thermal energy storage is integrated into the loop to allow for peak shifting and sharing between different building types. The DDES can work to reduce energy consumption and carbon emissions at the scale of a few buildings in a single development, near each other on a street, in a neighborhood, or, if levels of participation are high enough, across an entire city.

This paper addresses the following questions:

1. What are the first principles behind a DDES, and why is it important to identify and define the principles driving decisions in a district energy system?;
2. What types of novel technical and social solutions can be advanced by a DDES?; and
3. What future research is needed to develop the DDES concept?

Approach and Structure

Most of the literature on district energy does not discuss the importance of local geography, settlement patterns, culture, or policies. For example, even in societies such as Sweden, where attitudes tend to the collective, the adoption of rooftop photovoltaic systems was limited by cultural norms: not everyone wants to stand out as a conspicuous conserver of energy (Henning 2005). Inspired by a foundational work in the field of cultural geography titled “Axioms for Reading the Landscape,” written by Peirce Lewis (1979), the next section of this paper aims to make clear the first principles underpinning the development of a DDES. Rather than a universally applicable prescription, the aim is to clearly articulate the reasons underpinning the following six key decisions:

1. shifting from conservation to reallocation;
2. using storage to shift loads and increase sharable energy;
3. preferring thermal to chemical storage;
4. reducing use of refrigerant;
5. respecting the grid; and
6. prioritizing compatibility with existing and future technology.

The next section draws from several entries to a design competition to illustrate how these first principles can help advance other goals, including 1) affordable housing, 2) establishing a subscription model for cooling, 3) creating a local market for advanced building components, and 4) piloting alternative methods of cooling. The intention is to show the potential of district energy in general and the DDES approach in particular as an infrastructure. Rather than a means to an end of energy conservation, district energy and the DDES approach can address complex sociotechnical problems. The following section takes a step in that direction by articulating the assumptions and goals underlying six first principles of a DDES.

This represents a different take on a central convention in much of the literature on district energy, which aims to define or redefine specialized terms. For example, Sulzer et al. (2021) argue that a common vocabulary is needed for the fourth generation of district heating and cooling, differentiating these networks from others by defining bidirectional mass and energy flows, the complex topology of emerging approaches, the use of low-temperature loops boosted by local heat pumps, whether a network is providing heat or cold versus heat and cold, the new terminology of “energy transfer station,” the location of pumps, the direction of flows within a network of pipes, and the recommendation that the term “prosumer” be applied to buildings that can both use and provide energy in a district system. Sommer et al. (2020) define a new topology, the reservoir network, which uses two three-way valves to switch the direction of flows and thereby allows multiple buildings with conflicting heating and cooling demands to use or expel heat to a single loop. These explorations are important and useful in driving technical development and standardizing concepts. Much work remains to be done on the definition and

optimization of DDES for different geographic, cultural, and economic settings. The aim of this paper, however, is to identify the principles underpinning the design of a particular district energy system.

The Distributed District Energy System (DDES): First Principles

Existing approaches to district energy systems characterize their components and operation. While this level of technical resolution is critical for the implementation of district energy, shifting the focus from technical innovation to systems-level outcomes can lead to new avenues and applications for district energy systems. This is in broad alignment with work on reducing energy consumption that adopts the perspective of social practice theory. A core assumption in that body of work is that energy itself is not consumed as an object; rather, energy is a means to an end. Efforts to reduce energy consumption must focus first and foremost on the broader practices in which energy is used (Guy and Shove 2014). This perspective also fits with the sociotechnical frame of analysis as defined by Moore and Wilson (2014), which highlights the agentic entanglement of buildings and technology. Therefore, rather than outlining specific components or technical qualities, the following six sections explicate the principles underpinning the development of a DDES .

Shift the frame from conservation to sharing surplus.

Conservation and efficiency have long dominated discussions about building energy use. The focus of nearly all existing building efficiency programs can be summed up in two words: use less. But while demonstrably effective in new construction, the pragmatic and economic constraints of utility business models have created an awkward marriage between mandates to promote energy efficiency and the need to grow a profitable business. Furthermore, the physical qualities of the existing building stock, combined with dominant economic models in the U.S. real estate industry mean that deep energy retrofits of existing buildings are difficult to justify. Often, when energy use is considered in building retrofit process, it is because of regulatory requirements, such as New York City's Local Law 99, or because a forward-looking building owner has decided to make an additional investment. If policies are to be effective at reducing systemic carbon emissions, then the impact of conservation efforts for new or existing buildings should be measured not in the abstract terminology of energy use intensity (EUI) or carbon reduction, but rather in by determining the share of existing building energy use that can be offset through conservation measures.

Tune thermal storage strategies to climate.

The need to deliver large amounts of heat throughout a long, dark winter has driven interest in seasonal energy storage in regions where district energy is used in heating-dominated climates. For example, in summer, excess heat recovered from cooling can be injected into the ground using a network of boreholes. In winter, this low-grade heat can be extracted and concentrated by a heat pump using fluid through the boreholes. The primary drawbacks of this method are the expense of drilling required to create the borehole field and the pumping energy necessary to inject and extract the fluid that carries the heat.

There is a different opportunity for energy storage in climates where there is a wide diurnal (day-to-night) swing in temperatures, often associated with high-altitude dry climates, especially in places where the typical building stock is poorly insulated or constructed with materials high in thermal mass. Buildings in these climate conditions are characterized by large daily swings in heating and cooling loads. These swings are amplified by occupancy patterns. In some situations, capturing heat gain during the day and effectively delaying the transfer of heat can function as well or better than additional building insulation. Inventor Harold Hay's roof pond systems were an early example of this approach: water in an open pond or contained in plastic bags, was left exposed to the night sky, which allowed radiative cooling. It was covered with insulation during the day so it could absorb excess heat from within the structure. Subsequent developments using the concept of thermodynamic arbitrage have used underground storage tanks to be subsequently. In the context of district energy, recent research has investigated the potential to use district energy to perform the thermal equivalent of night flush ventilation cooling (Haggard 2018). Both examples show the potential of load shifting, rather than load reduction, and point to the possibility to achieve significant carbon reductions in climates with large diurnal swings by using approaches that, strictly defined, are not conservation. Instead of large, centralized, or seasonal thermal storage, these types of approaches benefit from distributed, local thermal storage sized to cover the building's needs for one or a few days. Local storage eliminates the pumping energy required to store energy remotely and reduces the losses due to transfer and time.

Prefer thermal to chemical energy storage.

When district energy systems include storage, it is typically centralized, for example in a chiller plant or in a borehole field where thermal energy is stored. These approaches do not require the transformation of energy from one form to another and, thus, are inherently more efficient than storing energy in chemical batteries. However, distributing storage capacity around a district energy network has several potential advantages. First, it allows the storage capacity to grow in tandem with the size of the network, reducing uncertainty and potentially removing a built-in barrier to system growth. Enabling organic growth over time is especially advantageous if a district energy system is to be retrofit in an existing neighborhood. Second, distributing storage allows for stores of energy at varying temperatures. For example, storage near a building with very high cooling load could use phase change material to provide additional capacity, whereas storage near a building with a high heat load could be maintained at higher temperatures. Depending on the hydraulic design of the district loop and the distances involved, high-grade heat could also be sent to the storage location closest to where it is likely to be utilized. This extends some of the advantages of the Reservoir Loop concept while increasing the second law efficiency of the system. Third, distributed storage of thermal energy increases system resiliency by increasing redundancy. Fourth, distributed storage has the potential to have synergistic benefits. Oversized and carefully placed thermal storage tanks using water as a storage medium, for example, could potentially help to mitigate flooding and provide a source of graywater (Crosson).

Reduce use of refrigerant.

Many refrigerants currently used in cooling applications are large molecules that persist in the upper atmosphere for long periods of time, trapping heat and increasing the rate of climate change. The most commonly used refrigerant in AC systems, R134a, has a global warming potential (GWP) of 1300, which means it is 1,300 times worse than CO₂. Project Drawdown, which listed refrigerant management as the top climate mitigation measure in 2017, has issued a new analysis that separates the potential of alternative refrigerants from refrigerant management. In the two carbon reduction scenarios studied, both of the two categories— switching to less harmful refrigerants and better managing the rest— remained in the top 10 of 74 strategies identified (2020). Refrigerant use can be reduced in a DDES in two ways. First, refrigerant use can be reduced through the substitution of air-to-air for air-to-water heat pumps, which move heat out of a building using water, rather than with refrigerant. When heat is moved out of a building with refrigerant, which is how conventional split systems, minisplit systems, and variable refrigerant flow systems work, a lineset must connect each air handler on the exterior of a building with the heat pump compressor on the exterior of the building. These lines must be installed and sealed on-site during building construction and retrofit, and they are prone to leak to the atmosphere. Those in the industry report that annual leakage rates of 2-5% are not uncommon. The second way a DDES can reduce refrigerant use is through the reduction in the overall number of systems. Low-load buildings, especially homes, can easily have heating loads, and sometimes cooling loads, that are significantly less than the smallest minisplit system available. Therefore, the potential of a DDES to share energy between one or more super-efficient buildings and its neighbors could reduce the number of systems required to provide comfort. Furthermore, the provision of a DDES system at the right monthly cost, especially if maintenance is included in the service offering, could make it financially more attractive for an individual building owner to join the DDES network than to nurse along an old, inefficient, and leaky AC system requiring frequent top-ups of refrigerant.

Fit energy to use.

It is possible to discern three broad approaches in the current discourse. One espouses the value of micro-grids as a complete replacement for the conventional way of distributing energy. A second advocates for retrofit of the existing grid as a “smart grid,” pointing to the potential value of integrating services such as demand management and the need for a robust, nationwide grid to reliably distribute renewable energy across a broad region. A third vision of the future is articulated by advocates for electrification, who see a robust electric grid replacing most, if not all, other forms of energy. These visions frequently fail to distinguish electric loads from thermal loads in buildings. Because electric equipment, whether in a micro-grid or a national grid, must be sized to meet peak loads, there are cascading benefits from moving energy in a low-grade thermal form rather than a high-grade electrical form.

Compatible with existing technologies and systems.

The implementation of distributed district energy systems should not be tied to the widespread availability of new or future technology. The principles of design for disassembly

and recovery are helpful in this context. For example, the recognition that many residential and commercial buildings are conditioned by rooftop package units indicates that the deployment of DDES in existing urban areas should be designed to allow the smallest possible change of mechanical systems. Commercial rooftop units powered by electricity or gas should be replaceable 1:1 with new air handler units connected directly to the district energy system. If needed, local heat pumps can be used in these systems to boost capacity. Likewise, residential systems connected to the DDES should directly replace existing air conditioner air handlers and gas furnaces, with additional dehumidification capacity integrated into the system if needed in a given climate.

Case study: The SunBlock DDES as a catalyst for change

The principles of the SunBlock DDES, as outlined above, have been applied and tested by nine finalist teams from The University of Arizona that developed proposals for the 2019-22 Solar Decathlon Design Challenge competitions. In this international competition, which is sponsored by the U.S. Department of Energy (DOE), students design a building that meets the requirements of a “use less” paradigm: the DOE Zero-Energy Ready Building. Teams must make a building that approaches the DOE’s definition of net zero, which is “an energy-efficient building where, on a source energy basis, the actual annual delivered energy is less than or equal to the on-site renewable exported energy” (DOE and NIBS 2015) or the past several years, teams participating in the competition have regularly surpassed this goal, for example by designing low-load buildings that meet Phius targets, or with proposals for net-positive buildings. These types of proposals underscore a point forcefully made by Kiel Moe: that the impact of a building’s energy use does not stop at its boundaries (Moe 2017). Still, this definition reflects social norms embodied in utility bills, building codes, and other forms of regulation. The SunBlock DDES projects, along with other competition entries that suggested sharing energy between neighboring buildings or a larger district, can be thought of as bridging the requirements of the competition and existing norms with a different set of possible futures than that embedded in the competition’s requirements. Put another way, whereas the competition’s rules invited teams to imagine buildings that were less bad, the potential that a building could usefully share a surplus of energy with its neighbors opened up a range of previously invisible potentials. The following sections outline three of these potentials and directly connect the potential of district energy to discussions about equity and innovation.

More than affordable housing: providing cooling as a service.

The concept of Cooling as a Service (CaaS), outlined in the Kigali Cooling Efficiency Program’s “Chilling Prospects: Providing Sustainable Cooling for All” report, point to the potential of district cooling in poor and developing countries. While the need to increase equitable access to cooling will grow in nearly every country as the climate continues to warm, greater access to cooling is also needed in industrialized countries such as the U.S., where an ongoing shortage of housing has put focus on the pressing need to build more housing units.

Students Rachel Shultz, Elizabeth Franzen, and Hao Wang developed their proposal for The Loop as a comprehensive answer to Tucson, Arizona’s affordable housing shortage and the need to increase access to affordable, low-carbon cooling. Starting with a mostly vacant strip

mall originally constructed in the 1980s, they proposed renovating the existing buildings as loft-style apartments and adding a new, 3-story apartment building with fifty-seven units consisting of twenty-three studio, twelve 1-bedroom, seven 2-bedroom, and twenty 3-bedroom units. They reduced the building's energy use by making design choices to meet PHIUS+2018 energy use targets. They used WUFI software to model energy use and inform their design decisions. Using NREL's PVWatts tool, they estimated that the PV arrays proposed for the existing and new buildings would generate 454,757 kWh per year. This electric energy would be used to power a series of air to water heat pumps sized for maximum peak output. Sizing the system to significantly surpass the building's heat cooling load allows The Loop to contribute enough energy to cool 496 homes in the surrounding neighborhood (see figure 1).

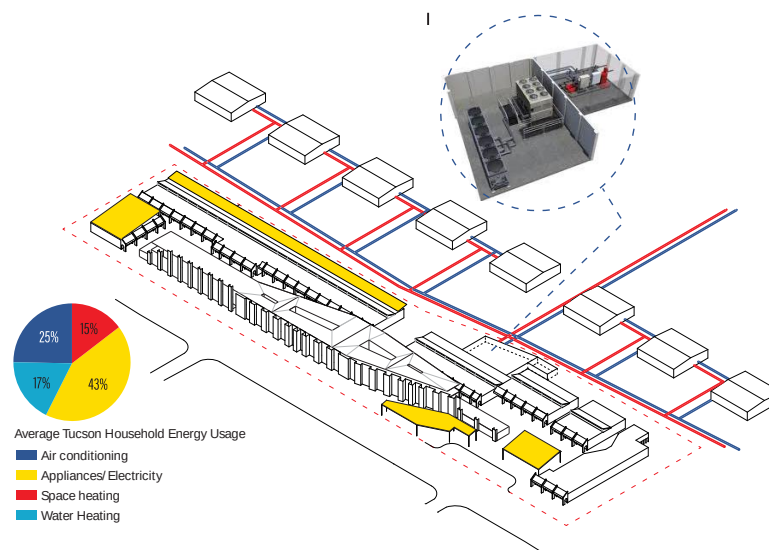


Figure 1: The Loop contains an oversized mechanical plant consisting of a conventional ice-enhanced air-to-water chiller. It is coupled to a heat exchanger to feed energy into a new district cooling grid serving single-family homes in the surrounding low-income neighborhood. *Source:* Elizabeth Franzen, Rachel Schultz, and Hao Wang. Student work, The University of Arizona.

The students recognized the need for a new economic model to support this kind of development. They proposed a cooperative ownership model for the newly built and retrofit housing units that would be supported by a local land trust. Residents would own shares, gaining access to tax breaks and an opportunity for appreciation that renters do not enjoy. If a unit is sold, appreciation will be distributed between the selling party and the land trust. The students also proposed a tiered maintenance and membership fee structure, where residents earning 100% or more of the AMI would pay a membership fee that would help to offset rents of low-income neighbors.

The proposal points to a potential alliance between district energy and affordable housing. New housing developments could help provide stable, affordable cooling sources for surrounding neighborhoods, creating value for individuals and the broader community in much the same way as when developers provide parks, playgrounds, or other public amenities. Furthermore, because the SunBlock system decouples heating and cooling from the electric grid, it would be technically possible to ensure the delivery of the minimum level of cooling necessary

to prevent dangerous overheating. This would reduce the threat of utility shutoffs to vulnerable populations and take a meaningful step towards treating access to cooling as a human right.

Enabling a scalable subscription model for district energy retrofit

A prime rationale behind Cooling as a Service is the potential carried by the shift from a business model predicated on the sale of mechanical equipment to a model that creates an ongoing stream of revenue through providing cooling. Rather than saddling the owner of the equipment with the responsibility to maintain and properly operate the equipment, the service provider takes on this role. The shift in business model has the potential to bring with it several benefits. The service model incentivizes the provider to reduce long-term costs by choosing highly efficient equipment and keeping it in good condition. Depending on how the financials are handled, it can also free up capital for other purposes by substituting regular and predictable monthly payments for the cost shock associated with installation, unexpected maintenance, and replacement. One problem with conventionally planned district energy systems is the very high cost of a central plant. While the aggregate cost is less than the cost of individually owned systems, an entity must be created with the funding and authority to make this investment. The DDES offers an alternative approach by leveraging existing sources of energy, such as underutilized mechanical systems in schools, and supplementing these with a scalable model that ensures that capacity and financial resilience of the system grows in line with the number of subscribers.

The district energy loop could be operated as a cooperative using a subscription approach. This idea was developed by several teams in the 2019 Solar Decathlon Design Challenge competition, with preliminary financial validation by student Tim Kilpatrick. The approach exemplifies the Cooling as a Service approach. The SunBlock Cooperative would own and operate the district loop, taking on the capital investment required to bury the loop lines. Owners of houses in the neighborhood would be offered the opportunity to join the cooperative. In exchange for a multi-year service contract, owners would be provided at no cost new equipment needed to use and contribute energy to the district loop. Equipment would be tailored to the load profile of the building, with all buildings receiving a new hydronic air handler and hot water storage tank, and others an air-to-water heat pump and thermal storage reservoir.

The monthly cost would be guaranteed for the first five years. To be an attractive offer, the average price of a SunBlock subscription would be less than or equal to the average monthly energy cost allocated to building conditioning and hot water. In contrast to conventional HVAC ownership, the subscription would include all regular and unscheduled maintenance, including a twice-yearly filter change and operations check. This would increase system efficiency and prolong the service life of system components by ensuring that mechanical systems are operating properly. The underpinning financial model, as well as adoption rates, could be further supported by electrification initiatives. For example, new subscribers could be incentivized to remove natural gas service with discounts or low-cost financing for new electric appliances, such as induction ranges. Whereas home utilities tend to be out of sight and out of mind, the kitchen range is at the center of daily life for many households. Wrapping it into a package of incentives could increase interest in a SunBlock subscription. New ranges would also inject a highly visible change into homes with the power to drive awareness via word-of-mouth.

Creating a market for local innovation in Advanced Building Construction components

DDES such as SunBlock could also help develop local markets for modular mechanical pods. The concept has been in circulation in the U.S. since at least the 1940s. Rather than installing the mechanical equipment needed for a building on-site— typically a furnace, boiler, or heat pump, sometimes coupled with a separate system for heating domestic hot water— these systems could be installed off-site in a volumetric building component that can then be placed by a crane or other machine. The intention is to reduce costs, reduce installation faults, and advance the standardization of high performance, efficient equipment.

Two finalist teams in the 2020 Design Challenge competition explored this potential. One created a mechanical pod with an air-to-water heat pump for space conditioning and contributing energy to the district loop; a heat pump water heater for generating domestic hot water; provisions for both thermal and chemical energy storage, and included space for a washer and dryer (see Figure 2). The other team refined the design so that it could be integrated into high-performance new construction or used to retrofit existing buildings. This approach was in part inspired by the Energiesprong initiative, which integrates a new mechanical system with an envelope retrofit and offers building owners the opportunity to roll the cost of small extensions into financing for the renovation.

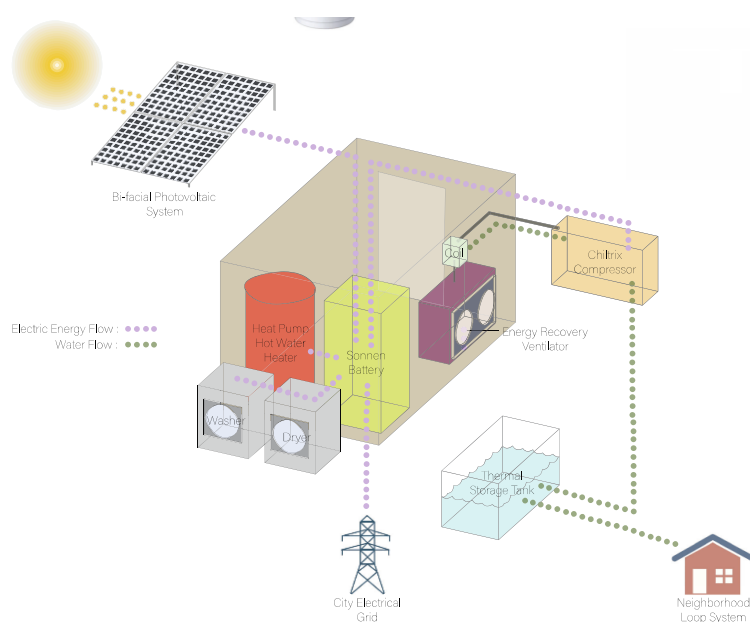


Figure 2: Schematic design of a mechanical pod to interface with the SunBlock DDES. *Source: 2021 Solar Decathlon Design Narrative.* Student work, The University of Arizona.

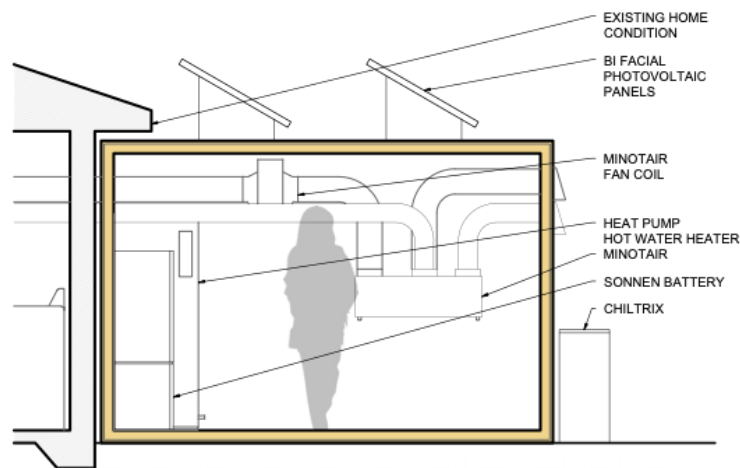


Figure 3: Schematic section showing the scale of the pod, which could allow for increased fire separation for chemical batteries if used to retrofit an existing building. *Source:* 2021 Solar Decathlon Design Narrative. Student work, The University of Arizona.



Figure 4: Floor plan diagrams showing integration of the prefab mechanical pod into the volume of a house (left) or as a separate element outside of the conditioned envelope providing conditioning services to a flexible modular building. *Source:* 2021 Solar Decathlon Design Narrative. Student work, The University of Arizona.

Rather than focusing on developing an approach intended to be universally applicable, the potential role of prefabricated mechanical pods in DDES shows the need for site- and climate-specific variation. The varying load and demand profiles of existing and new buildings in different climates will result in a mix of different mechanical equipment and energy storage needs. Remote locations may need larger batteries or a backup generator. Coordinating the development and implementation of the DDES with the design of mechanical pods would allow for flexible response to local market conditions that could further drive adoption of the DDES model. For example, space was included in the proposed SunBlock mechanical pod for a washer and dryer because many existing homes built in the 1950s with a washer and dryer in the kitchen have been renovated to keep up with changing tastes and demand for larger kitchen areas. As a result, many homes lack a dedicated place for laundry, with the water and dryer inconveniently located on a patio, in a carport, or in a shed. Providing space for them in a mechanical pod is an additional reason for adoption that creates a functional improvement with appeal independent of increased efficiency or carbon reduction.

Piloting alternative methods of cooling and construction

Alternatives to vapor-compression refrigeration are key to carbon reduction. To be useful, these alternatives should reduce the amount of energy required to drive compressors and the volume of high-GWP refrigerants. Existing technologies, such as evaporative cooling, can be combined with passive building strategies to reduce the need for vapor-compression cooling. Night sky cooling systems use radiative transfer to transmit waste heat into space. Recent technological developments in nanomaterials have also allowed for daytime radiant cooling. While the none of these alternatives require the development of a district energy system, all can be integrated into a DDES in ways that improve its performance.

Students Carina Eichorst, Wen Xie, Britt Wachter, and Alec Kelly-Jones were struck by the potential of combining night sky cooling and shading to increase the performance of an existing 1950s elementary school in Tucson. Their design, diagrammed in Figure 5, is an undulating mass-timber shade structure superimposed over the existing school. Tanks integrated with the support columns for the structure would hold up to 100,000 gallons of rainwater. The 39,732 cubic feet of timber in the structure would sequester carbon, reduce solar heat gain, and support enough PV panels to generate an additional 471,269 kWh per year of electricity (Figure 5). While the evaporative losses associated with an open night-sky cooling system should limit its use in drought-stricken areas, systems that control evaporation, such as the team's design, which was recognized with an honorable mention, shows the potential for the innovative combination of PV and night sky cooling. Students Courtney Klewer, Juli Bailey, Sasha Evans, and Bianca Bryant submitted to the Urban Single Family division using a variation of the same concept. Inspired by an influential building designed by Tucson architect Judith Chafee, they proposed a shading ramada with a denser configuration of PV panels over a newly constructed residential building. The solar panels would be used during the day to produce electric power and at night to cool water stored in an insulated underground tank

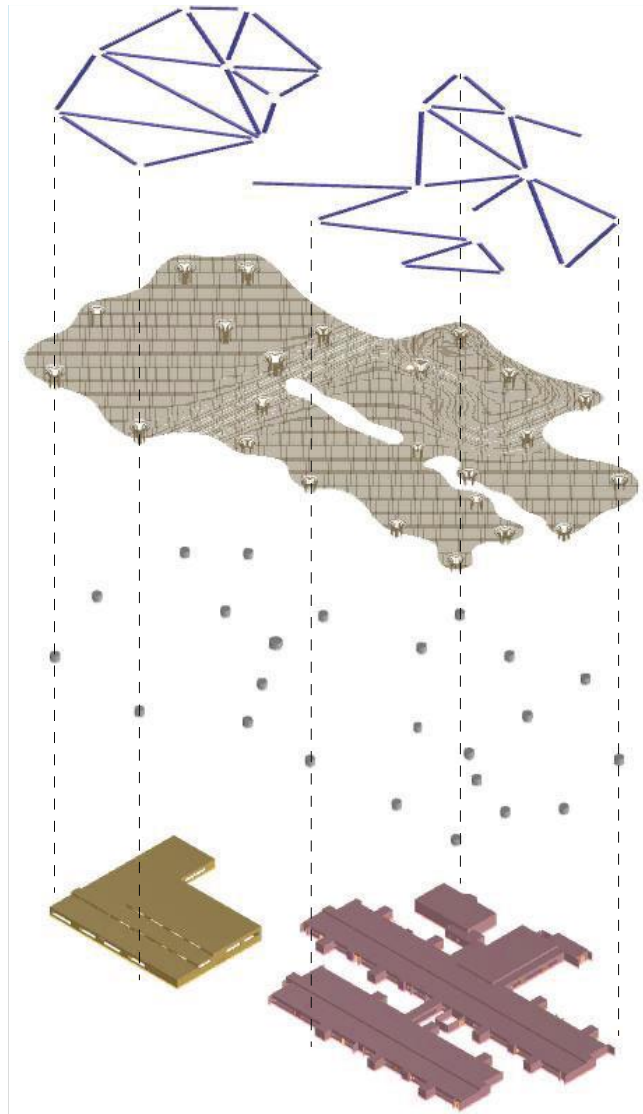


Figure 5: A wood superstructure shades the existing elementary school. It is supported by columns that come down outside of the existing building's footprint. Rainwater and thermal storage tanks are integrated with the structure's columns. PV panels are arranged in V-shaped channels and augment a large existing array shading play areas (not shown.) Student work, The University of Arizona.

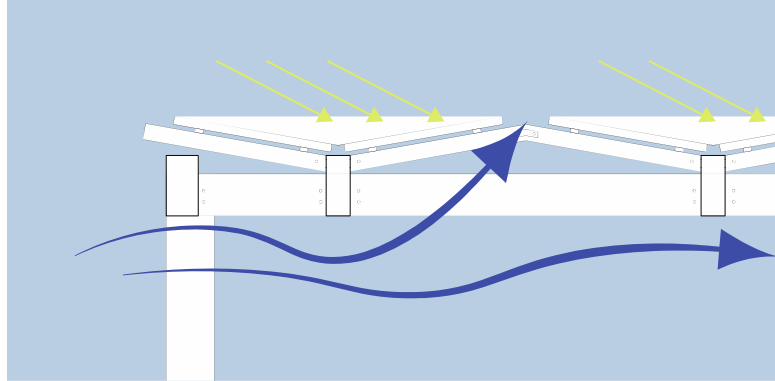


Figure 6: PV panels generate electrical energy during the day. In this configuration, they also reduce the amount of direct solar radiation on the roof surface and protect the roof surface from UV damage. Air circulation around the panels provides some cooling and increases efficiency. Student work, The University of Arizona.

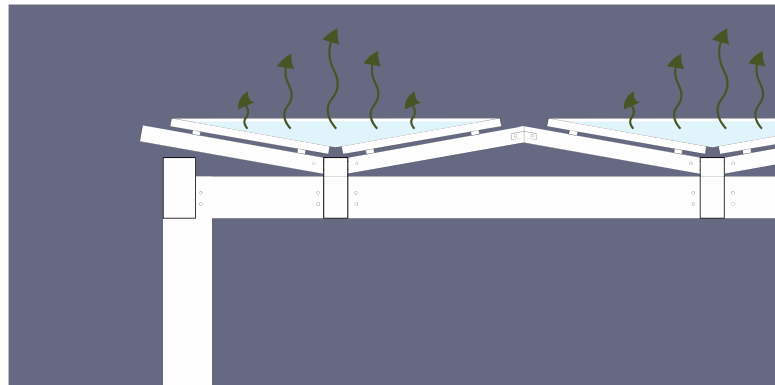


Figure 7: PV panels form channels where water is cooled via radiation to the night sky. Student work, The University of Arizona.

These designs show the potential of novel approaches to providing cooling without vapor-compression systems. Both would clearly require additional financial and material investments. At the scale of an individual project, these may not make sense, but a DDES operator could potentially incentive approaches that increase system capacity at peak times, increase system resilience, or benefit the ecosystem by capturing carbon. The inclusion of large volumes of water storage also points to the potential for distributed infrastructure with the primary function of generating, storing, and transmitting electric and thermal energy to help cities deal with larger and more frequent extreme rain events driven by climate change.

Conclusion: Moving Past Conservation

Focusing exclusively on conservation misses an important question especially relevant for existing buildings: if energy use can be significantly reduced, what can be done with the energy it is no longer using? What about publicly owned buildings, such as schools, with occupancy patterns that mean that systems sit unused for large portions of the year? In heating dominated climates, would it be a better investment to reduce the input power for industrial

processes, or capture and redistribute waste heat? Focusing only on reducing energy use through conservation misses the potential to use savings from retrofitting one building to offset another's consumption, to integrate and utilize existing publicly owned assets as part of a combined energy system, and to share energy between different building types.

Realizing these potentials will require at least two moves. First is delimiting the potential of existing metrics, such as EUI, which are applied at the building level. Such metrics have been effective in changing practice because they align the boundaries around energy use with the building enclosure. For the most part, though they may encourage closer cooperation between built environment professionals, these metrics do not challenge the existing claims of authority in architecture, engineering, or code enforcement. Second is the creation of intentional linkages between high-level goals, such as carbon neutrality, and existing metrics. Carbon neutrality targets, for example, are focused not on the performance of individual buildings, but instead on the collective transformation of sociotechnical systems at the city or regional level. To be effective, these two goals—one, the top-down intention to reduce or eliminate carbon emissions, and the other the bottom-up toolkit dealing with individual buildings—must be linked together.

The overarching goal must not be to simply use less, because at best, this can be asymptotic-- it will never get all the way to zero. Instead, the systems-level goal should be to generate a surplus of energy. Structuring rewards around this outcome could quickly shift the outcomes of the overall system. This could also open up new business models. For example, instead of focusing on reducing energy use, building owners could be incentivized to turn their buildings into grid-friendly producers of carbon-neutral energy. In this scenario, utilities could be relieved of some of the responsibility for generating energy, or, alternatively, their business could shift to a service model, taking on the operation and maintenance of these new distributed systems.

References

- Alajmi, A., & Zedan, M. (2020). Energy, cost, and environmental analysis of individuals and district cooling systems for a new residential city. *Sustainable Cities and Society*, 54, 101976. <https://doi.org/10.1016/j.scs.2019.101976>
- Buffa, S., Cozzini, M., D'Antoni, M., Baratieri, M., & Fedrizzi, R. (2019). 5th generation district heating and cooling systems: A review of existing cases in Europe. *Renewable and Sustainable Energy Reviews*, 104, 504–522. <https://doi.org/10.1016/j.rser.2018.12.059>
- Brasch, S., “‘Sewer Heat’ Could Be Hidden Ally Against Climate Change. Here’s How Denver Is Pulling It To The Surface,” CPR News. <https://www.cpr.org/2021/05/11/sewer-heat-could-be-hidden-ally-against-climate-change-heres-how-denver-is-pulling-it-to-the-surface/>
- Guy, S., & Shove, E. (2014). *The Sociology of Energy, Buildings and the Environment: Constructing Knowledge, Designing Practice* (1 edition). Routledge.
- Haggard, K. (2019). A clear sky story on the evolution of passive solar design: The source and multiple applications of Harold Hay’s roof pond system. In M. McDonald & C. Dayer (Eds.), *Activism in architecture: Bright dreams of passive energy design* (pp. 23–33). Routledge. <http://ezproxy.library.arizona.edu/login?url=http://search.ebscohost.com/login.aspx?direct=true&scope=site&db=nlebk&db=nlabk&AN=1925254>
- Hawken, P. (2017). *Drawdown: The most comprehensive plan ever proposed to reverse global warming*. Penguin Books. <https://openlibrary.org/books/OL26497978M>

- Henning, A. (2005). Equal Couples in Equal Houses: Cultural Perspectives on Swedish Solar and Bio-Pellet Heating Design. In S. Guy & S. Moore (Eds.), *Sustainable Architectures: Cultures and Natures in Europe and North America* (p. 89). Spon Press.
- Khosla, R., Miranda, N. D., Trotter, P. A., Mazzone, A., Renaldi, R., McElroy, C., Cohen, F., Jani, A., Perera-Salazar, R., & McCulloch, M. (2021). Cooling for sustainable development. *Nature Sustainability*, 4(3), 201–208.
- Kigali Cooling Efficiency Program. (2018). *Cooling as a Service (CaaS)*. Kigali Cooling Efficiency Program. https://www.k-cep.org/wp-content/uploads/2018/07/Cooling-as-a-service-Knowledge-brief-6.7.2018_Final_online_v1.pdf
- Lewis, P. (1979). Axioms for Reading the Landscape: Some Guides to the American Scene. In D. W. Meinig (Ed.), *The Interpretation of Ordinary Landscapes: Geographical Essays* (pp. 11–32). Oxford University Press.
- Lund, H., Østergaard, P. A., Nielsen, T. B., Werner, S., Thorsen, J. E., Gudmundsson, O., Arabkoohsar, A., & Mathiesen, B. V. (2021). Perspectives on fourth and fifth generation district heating. *Energy*, 227, 120520. <https://doi.org/10.1016/j.energy.2021.120520>
- McDonald, M., Dayer, C., & EBSCOhost. (2019). *Activism in architecture: Bright dreams of passive energy design*. Routledge. <http://ezproxy.library.arizona.edu/login?url=http://search.ebscohost.com/login.aspx?direct=true&scope=site&db=nlebk&db=nlabk&AN=1925254>
- Moe, Kiel. (2017). Energy and Form in the Aftermath of Sustainability. *Journal of Architectural Education*, 71(1), 88-93.
- Moore, S. A., & Wilson, B. B. (2013). *Questioning Architectural Judgment: The Problem of Codes in the United States*. Routledge.
- National Grid (2022), “National Grid Files Geothermal Program Implementation Plan.” <https://www.nationalgridus.com/News/2022/05/National-Grid-Files-Geothermal-Program-Implementation-Plan/>
- Nilsson, S. F., Reidhav, C., Lygnerud, K., & Werner, S. (2008). Sparse district-heating in Sweden. *Applied Energy*, 85(7), 555–564. <https://doi.org/10.1016/j.apenergy.2007.07.011>
- Reidhav, C., & Werner, S. (2008). Profitability of sparse district heating. *Applied Energy*, 85(9), 867–877. <https://doi.org/10.1016/j.apenergy.2008.01.006>
- Rezaie, B., & Rosen, M. A. (2012). District heating and cooling: Review of technology and potential enhancements. *Applied Energy*, 93, 2–10. <https://doi.org/10.1016/j.apenergy.2011.04.020>
- Sommer, T., Sulzer, M., Wetter, M., Sotnikov, A., Mennel, S., & Stettler, C. (2020). The reservoir network: A new network topology for district heating and cooling. *Energy*, 199, 117418. <https://doi.org/10.1016/j.energy.2020.117418>
- Sulzer, M., Werner, S., Mennel, S., & Wetter, M. (2021). Vocabulary for the fourth generation of district heating and cooling. *Smart Energy*, 1, 100003. <https://doi.org/10.1016/j.segy.2021.100003>
- Peterson, K., Torcellini, P., Grant, R., et al. (2015). A Common Definition for Zero Energy Buildings. DOE EERE & NIBS. <https://www.energy.gov/sites/prod/files/2015/09/f26/A%20Common%20Definition%20for%20Zero%20Energy%20Buildings.pdf>
- Tredinnick, S., Wade, D., & Phetteplace, G. (2015). District Energy Enters The 21st Century. *ASHRAE Journal*, 57(7), 48–55.

Wilkinson, K. (Ed.). (2020). *The Drawdown Review 2020: Climate Solutions for a New Decade*. Project Drawdown. <https://drawdown.org/drawdown-review>