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Climate Science Without Climate Action? An Impacts Approach to Decarbonizing University Systems

ABSTRACT:

The Earth is already at an unsafe level of carbon dioxide concentrations for much of the life that resides on it (Moseman and Selin 2021). Human society arose in the band between 280 and 350 ppm atmospheric CO2 concentration, and many other current species developed in this band as well: the current level of CO2 concentration, roughly 419 ppm (NOAA 2023), has most recently been seen roughly twenty-five million years ago; (Mulhern 2020) at which point Panama had not yet made contact with South America (O'Dea et. al 2016) and only a (relatively) short period of time after apes first evolved (Cantwell 2021). And yet, CO2 levels are rapidly increasing, with more CO2 added from fossil fuels in 2022 than any year in human history (Hausfather and Friedlingstein 2022).

Enter the University — as the dominant center of climate science, Universities contribute roughly 2% of the US' yearly greenhouse gas emissions. Their large district thermal systems provide an opportunity for innovative urban energy solutions — such systems have the potential to be very efficient (Ryan 2023), but typically rely on fossil fuel energy or biomass, (Wess et. al 2021). The imperative for moving off fossil fuels is obvious — the imperative for moving (mostly) off biomass is also strong when the impacts of biomass energy on water and land use are considered (Ai et. al 2021) (Fajardy and MacDowell 2017). Power models that move beyond fossil fuels are becoming more common (Wess et. al 2021) (UCB 2023) (UBC 2023), but most of these still rely on biomass.[1]

What Universities manage to design will serve as an example for broader society. The district systems Universities function on are efficient solutions to heating/cooling, and are often applied in residential contexts as well. Residential heating/cooling is a massive energy consumer in the US — as of 2015, it made up roughly 75% of the American single-family residential energy budget (Kuo 2021), and residential energy use is roughly 1/6th of total American energy

[1] Biomass is also known as RNG, or "renewable natural gas." It will be referred to here as biomass, as a simplification of what the fuel actually is.

consumption (EIA 2021). As of 2011, 47% of global energy consumption, and 37% of OECD energy consumption, was towards heat (EESI 2011).

This paper intends to act as a literature review of plans to decarbonize district thermal systems, primarily in the University context. What specific challenges are posed at the University/district level, technical and otherwise — both in decarbonizing and moving past biomass? What energy sources are currently being used or suggested, and what problems / impacts are associated with them? Are there energy sources currently underused or in need of technical development that could play a long-term hero? This paper will break the previous questions in to three sections - understanding the technical issues, energy or other technical solutions, and non-technical issues, such as administrative and political support.

Understanding the (Technical) Problem

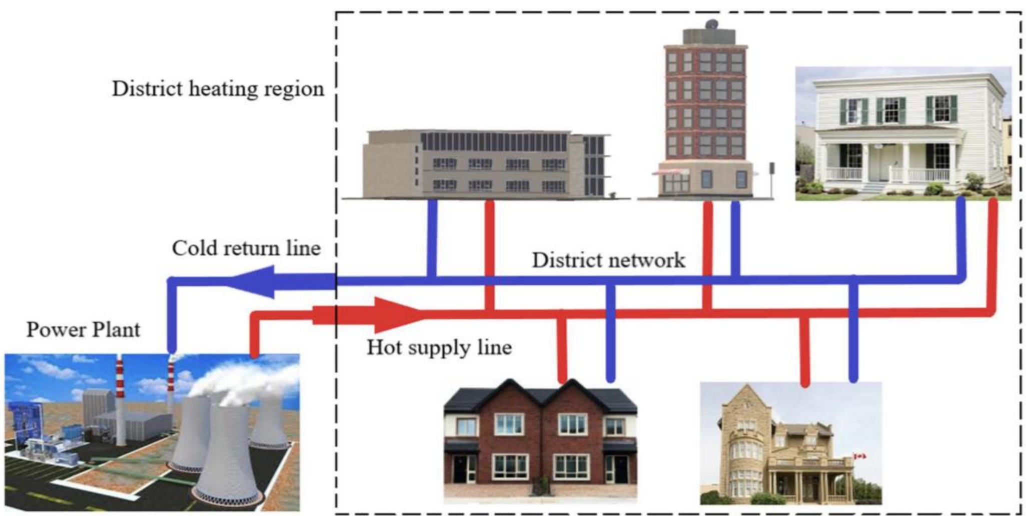

Figure 1: Principle of the district heating system

District thermal systems, in this context, refers to district heating (DH) and district cooling (DC). Both objectives are typically achieved in one system which relies on building proximity and connectivity — Rather than individual electric boilers or heat pumps on buildings, district thermal runs piping underneath urban centers, transferring energy from a central plant or from centralized heat pumps towards heating or cooling (Figure 1, Mahmoud et. al 2020). These systems can reduce energy use for heating by 60% (DOE 2020), and are often set up for localized power generation, providing protection in the case of an outage. Despite their efficiency, roughly 90% of power currently generated in district thermal systems[2] is generated by fossil fuels (Delmastro 2022), meaning adopting such a system requires transitioning away from its most conventional source of energy.

Relevant for transition, the end result of this energy takes two main types. In the urban context, almost all heat required is for low-intensity ambient heating or cooling — these systems need to heat or cool residencies and places of commerce from only a few degrees above or below room temperature to a comfortable room temperature.

However, high-intensity heating/cooling can play a role in industrial or medical settings. As example, in a University context, steam heat generation is currently necessary for lab experiments and hospital sanitation.[3] High-intensity heat generation poses different problems than ambient heating or cooling — while ambient heating or cooling can use ambient air heat pumps and renewable electricity, passive solar (Chan et. al 2010), or other low-intensity technologies, high-intensity generation requires either high-temperature heat pumps with high-energy waste heat sources (such as an industrial manufacturing process) (Harrison 2021), or some other direct generation of steam such as an electric boiler. Currently, fossil fuels or biomass (UBC 2023) (Vourdoubas 2022) provide essentially all high-intensity heating in district systems. Problematically, some district systems operate off steam thermal for both their low-intensity and high-intensity needs, meaning that the original energy source needs to be capable of generating high-intensity heat even if it is to be used for ambient heating or cooling (UW Sustainability 2023). This will be discussed more in Section 2.

Hospitals in district systems illustrate a third problem with decarbonizing and moving off biomass — backup fuels. Some conversion options exist for steam generation, such as electric boilers (Wallace and Spielvogel 1974), but most rely on the electrical grid. Backup fuels are a relatively minimal part of emissions portfolios, but can act as a barrier to 100% decarbonization. Localized steam solar (known as SHIP / Solar Heating for Industrial Processes) is one proposed option for high-intensity, off the grid clean energy, but may not be possible in all contexts (Yan et. al 2020) (Tyroller et. al 2006). SHIP is also usually limited by hours of daylight (Yan et. al 2020), making it potentially problematic for hospitals. Green hydrogen is another option (Clark 2020), and will be discussed in section 2.

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[2] Some district energy systems also provide "cogeneration;" — they create their own electricity for non-thermal needs through electric, biomass, or fossil fuel boilers and pour the waste heat from this production into their thermal piping (EESI 2011). However, many district energy systems are not microgrids, and purchase their electricity from elsewhere. For district energy consumers who purchase electricity from the grid, including major Universities, Scope 1 emissions can be 90-100% thermal-based (UW Sustainability 2023) (UBC 2023).

[3] Referred to as "moist heat," steam sanitation is one of the only sanitation methods for medical sterilization currently approved by the FDA, although other, less energy intensive options. seem promising (CDC 2023).

Why Not Biomass? (And why maybe to Biowaste?)

Biomass here includes all organic, renewable energy sources which can be directly consumed or thermochemically converted for energy production (EIA 2022). Biomass has many positives — it can be regenerated through farming, is naturally regenerated through processes that produce organic waste (such as composting and agriculture), does not require rare earth minerals, and has been used as an energy source for tens of thousands of years (Liska 2013). Biomass has another key benefit — it can directly plug in to current methane combustion systems and replace methane gas without intensive capital costs (UCLA 2022).

However, when biomass is not a waste product of other activities, it is extremely resource intensive. Processing, transporting, and farming biomass require enough energy that biomass projects are not always carbon-neutral / carbon-negative (Fajardy and MacDowell, 2017), the land use intensity is high given land constraints for necessary agriculture, and the water use intensity of growing biomass is also large (Ai et. al 2021).

Additionally, biomass is a health risk when burned in urban centers. Biomass air pollution kills at least 1.5M a year globally (Laumbach and Kipen 2012). Although the majority of these deaths occur in impoverished rural communities, where biomass is burned directly indoors with few safety procedures, biomass burned in combustion plants has been linked to asthma, strokes, and other conditions, killing between 8,000 and 15,000 in the US alone in 2017 (Buonocore et. al 2021). Polluting operations with high health risk have a history of being placed near BIPOC populations (Koester and Davis 2018)— although Universities and hospitals have little choice of where to place their generation plants, urban district energy systems could have more leeway in the future to repeat this pattern.

There may be some space for biomass in industries which are exceptionally hard to decarbonize through other means (Jodeiri et. al 2022), especially considering that a relatively unknown but potentially significant amount of biomass (biowaste) can be sustainably sourced (Paepatung et. al 2009) (Castro-Amoedo et. al 2021). Yet given constraints on sustainable sourcing and health risks — district thermal does not have the deep lack of other options which would allow for biomass to be primarily used. Biomass should be considered only a last-ditch option for district energy decarbonization, and systems which can move actively off of it to energy sources with lesser health and environmental impacts should.

Solutions in Use

Heat Pumps

For most district energy systems, the most straightforward change to make is the replacement of most plant thermal energy with heat pumps (UW Sustainability 2023) (UCB 2023). Heat pumps function off any type of electricity, and use ambient geothermal or outdoor air / water energy to heat or cool refrigerants. The return on energy input is high, at roughly 3-5 depending on the location of the pump and the local temperature — heat pumps work more efficiently when the outdoor temperature is closer to target temperature than vastly different (Simon 2023) (Carrier 2023) (Langer 2023).

Given the efficiency and high capacity, as heat pumps are not severely limited by scale in most district systems, heat pumps can easily be attached to district systems in a few ways. One involves decentralizing the system, where heat pumps are attached to every building on the district energy grid, and flow heat through the connected piping. Another proposal is to centralize heat pumps — if a thermal plant remains, a large heat pump there can recover waste heat, and large heat pumps can be placed in other key locations around the district system where the return on energy would be the highest, likely other buildings with high levels of waste heat. Both options are efficient, effective, and have been proposed in district system planning (UW Sustainability 2023). The IAE's 2050 net-zero scenario plans for 600 million heat pumps to be operating globally by 2030, an increase of more than 250%, current installation rates expect the globe to have 253 million operating heat pumps by that year, which would still be an increase from current numbers of roughly 50% (Rosenaw et. al 2022). As the world moves towards a heat pump thermal system, University and district systems have an opportunity to lead. As discussed earlier, current heat pump systems function best in low-intensity heat scenarios, and require a high-intensity heat source to be used for high-intensity heat generation. Technology could be rapidly changing this, and ambient air heat pumps may soon be an option for generating high-intensity thermal (Yan et. al 2020).

Energy Efficiency

Striking in decarbonization evaluations of major institutions is exactly how much decarbonization can be achieved through reducing use of energy, as opposed to switching mode. For many universities (UCLA 2016) (UW Sustainability 2023), energy efficiency is the pre-eminent path for reductions — energy efficiency offers not only emissions reductions but also reductions in material use and other health impacts from carbon or non-carbon fuels. At the University of Washington, energy efficiency reforms alone intend to cut the University's fossil fuel emissions 75% by 2035, leaving very little to the domain of heat pumps and other energy solutions (UW Sustainability 2023).

Much of this efficiency work happens building to building, and net metering is important in large institutions to identify the biggest "energy problems" in a system. Efficiency is normally not a technological issue but one of investment, and the technological debate has shifted to zero or very near-zero energy use buildings (Belussi et. al 2019) – hospital buildings outside of the US, for example, are already 2-10x less energy intensive than US ones (Vourdoubas 2022). Here, it is not the technical expertise Universities hold which make them potential efficiency leaders, but rather the status they often have as public entities and the ethical leadership they are often assigned in society.

Another key place for energy efficiency is upgrading the district's "generation," an opportunity provided only to district systems. The most efficient district energy systems use relatively low-temperature water, between 30-70C, which reduces heat escape throughout the system. The least efficient systems are steam-based; although steam efficiently transfers energy it also quickly "efficiently loses energy" (UW Sustainability 2023) in places of energy escape. Efficiency can increase by as

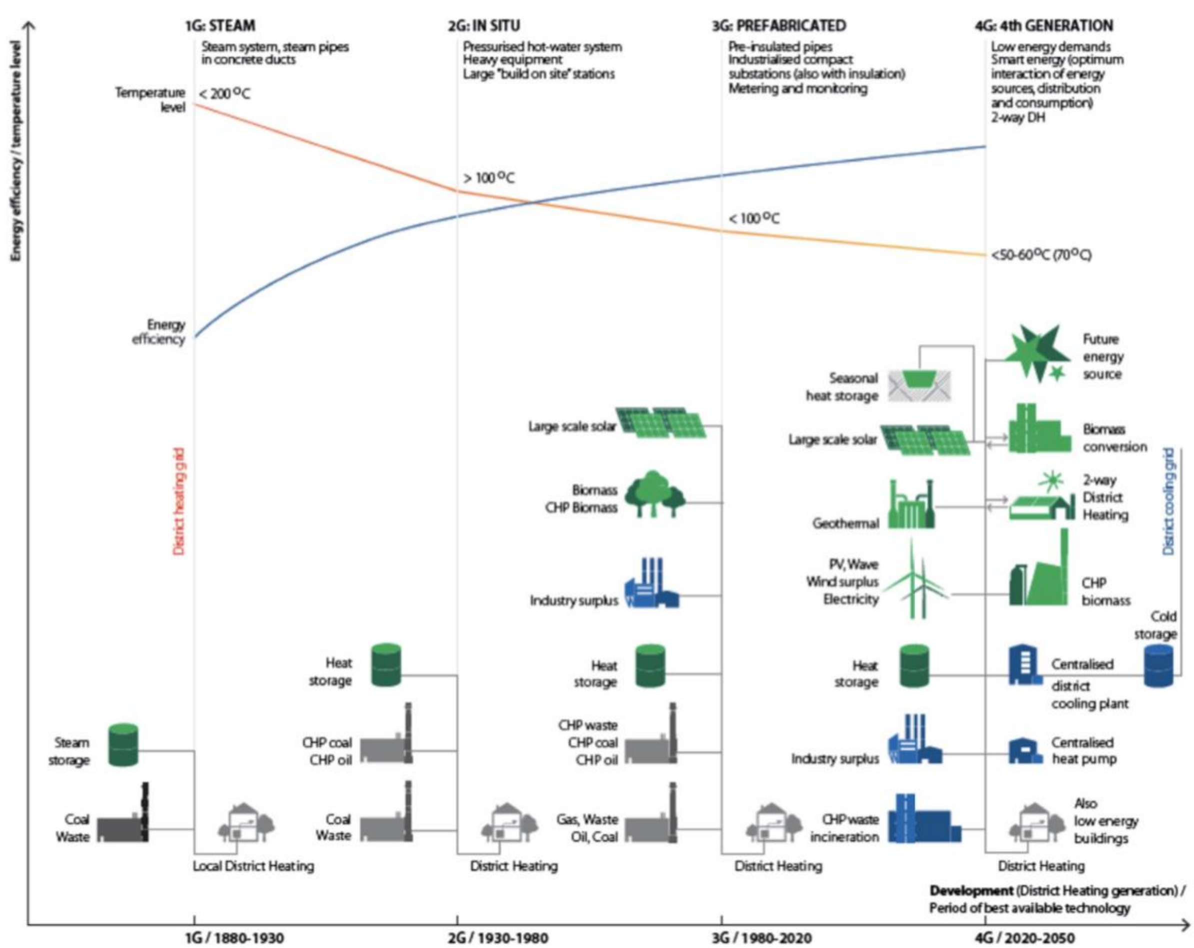


Fig. 2. Illustration of the concept of 4th Generation District Heating in comparison to the previous three generations.

much as 35% by moving from Gen 1 to Gen 4 (Delmastro 2022). The generations are mapped below in Figure 2 (Lund et. al 2014) — energy efficiency increases inversely with water temperature. Something else to note in Figure 2 is the available energy sources for each generation — this represents the transition between high-intensity and low-intensity energy. The transition to later generations is thus necessary for the implementation of many technologies, such as heat pumps and solar thermal, that can drive decarbonization of district systems beyond biomass.

Geothermal Energy

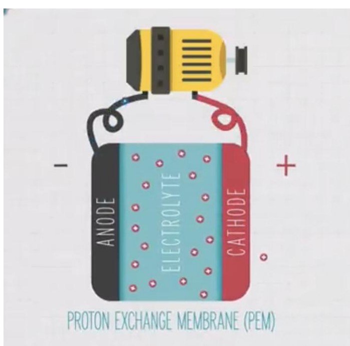
Given that low-intensity heat and cooling sources are compatible with leading-edge district thermal, a variety of geothermal energy sources are proposed in district thermal. More sources of geothermal are useful in what's called GDHS (geothermal district heating systems) than are conventionally used. The technology, however, is dependent on location.

Iceland, with lots of high-intensity geothermal, supplies roughly 90% of its space heating with GDHS. Boise, Idaho, with high-intensity (170F) geothermal springs has continuously operated GDHS since 1890 (Thorsteinsson and Tester 2010). Lakes are another potential reservoir – given their constant temperature, lake heat can provide heating in the winter and cooling in the summer to regions with strong seasonality. Transferring lake heat for energy can even be useful for protecting freshwater populations under a heating climate (UW Sustainability 2023). Sewer heat is another viable source; studied and used extensively in what is called British Columbia (Singh 2020) (Kaufman 2012). In many cases, the line between geothermal energy and heat pump energy is blurred, as waste heat is transferred to district thermal via heat pump (Audio Cities 2019). While there is no "single geothermal," district systems, especially in urban and freshwater areas, have lots of options and should consider their local "thermal inventory."

"Green" Hydrogen

As a replacement for methane, "green" hydrogen (or hydrogen fixed with renewable energy) is fairly straightforward. Hydrogen fuel cells are the mode for most thermal hydrogen (Dodds et. al 2015) — the typical fuel cell functions through the splitting of hydrogen protons and electrons with a catalyst and an exchange membrane, so that the electron needs to take an alternate pathway (through the generator) to recombine with the proton (Fig. 3). High intensity heat could use "solid oxide fuel cells," or SOFC — these function similarly enough to Fig. 3 to be conceptually identical, but require different materials. While conventional hydrogen fuel cells require precious minerals, such as platinum, high-intensity cells are actually lower in these materials and could have fewer health risks (Dodds et. al 2015). Hydrogen fuel cells, whether conventional or SOFC, are not technically difficult and have been used in a wide range of applications (Dodds et. al 2015). However, “green” hydrogen is still very problematic, and in the minds of many scientists, “overhyped” (Lakhani 2023).

Before entering the fuel cell, hydrogen needs to be “fixed,” or separated, as it is highly reactive and does not exist naturally on Earth as a separate element (Lakhani 2023). Hydrogen can be separated from a variety of sources, but most common are methane (Dainis 2021), and water (Jia et. al 2016). Separation requires high levels of energy — this energy input is the energy which hydrogen “stores” for future release (Boucher et. al 2022) (Lakhani 2023). For the final product to be “green,” the energy to fix the hydrogen initially needs to be entirely clean, and, given high occasionality of methane leakage (Sneath 2023) (Saul and Malik 2022), methane cannot be used as the source material. Other ethical concerns with methane extraction and use, from connections to the MMIWP crisis to environmental and health concerns around fracking, are serious (Joseph 2021) (Denchak 2022). Today, 96% of hydrogen fixing is achieved through burning of fossil fuels (Lakhani 2023), and as a source material, methane accounts for “nearly all commercially produced hydrogen in the United States” (EIA 2023).



(Fig. 3, Boucher et. al 2022. A conventional PEM (proton exchange membrane) hydrogen fuel cell. The electron, unable to move through the electrolyte-laden membrane, moves instead through the motor and generates energy. Though PEM’s/SOFC’s differ slightly technically, the concept is similar.)

Decarbonizing hydrogen is not simple, because the process of fixing hydrogen is so inefficient in energy storage. Hydrogen does not store all of the energy pumped in to its fixing process — as of 2016, the top performing STH (solar-to-hydrogen) process held roughly 30% of the energy being pumped in to the hydrogen (Jia et. al 2016). The energy efficiency rates are higher for methane-hydrogen (in 2016, 50-80%), but this requires continuing to mine a high-leaking fossil fuel at high amounts for hydrogen generation (Boretti and Banik 2021). Hydrogen is the least dense element on earth, meaning that the logistical issues / carbon emissions involved in moving hydrogen from fixing location to fuel cell could be significant (BNEF 2020) (EERE 2023). [4]

While legitimately “green” hydrogen can exist, the relatively low ratio of usable energy to energy input across the hydrogen production chain and the limited nature of renewable energy with which to create this hydrogen argues in favor of limiting “green” hydrogen to where it is absolutely necessary. This may change in the future — while “dirty” or methane hydrogen is an established industry practice, the extraction of “green” hydrogen from water with renewable energy is relatively new, and more scientific/engineering breakthroughs to improve efficiency and lower cost are likely. Such breakthroughs, alongside efficiency gains as producers simply gain expertise, previously led to a 40% drop in the cost of “green” hydrogen production in Europe from 2014-2019 (BNEF 2020). Although an eye should be open towards innovation in these fields, “green” hydrogen does not currently exist on scale, is for the foreseeable future inefficient, and provides a number of technical and logistical hurdles, even if produced in a just manner.

Electric Boilers / Modular Electricity

For high-intensity heat, electric boilers are an obvious option. They have decades of use history (Wallace and Spielvogel 1974) and function off any source of electricity input. They are more energy efficient than “green” hydrogen, without the density transportation issues, and are also roughly five percent more energy efficient than current methane boilers (Radulovic 2021) (Jia et. al 2016). Electric boilers often rely on the grid, and generally use more electricity per output than heat pumps, which is problematic as electric grid capacity development can, especially if energy use is inefficient, lag what is needed for a centralized grid to fully electrify (Traroja et. al 2018). This does not mean that electric boilers are infeasible but means that in many situations they would require localized electricity generation, through some form of localized renewable energy such as solar or wind.

Solutions in Use – Other Solutions, Agenda for Research, and Conclusion

SHIP, or Solar Heating for Industrial Processes, is a potential partial solution for high-intensity heat loads, as it could provide base energy which other solutions could fill when solar production is low (Yan et. al 2020). Direct solar-water heating is also effective for low-intensity water heat at a building level (Islam et. al 2013). Similarly, passive solar is not district system specific, and functions on a building-building level, but is crucial for reducing thermal energy needs (Stejanović 2013). Localized micronuclear, on scale of 10MW or less, is being adopted in many district systems, but is

[4] Hydrogen transportation would become more effective with on-scale transportation systems, but these would require massive pipelines and similarly massive investment. An obvious driver is a hydrogen-driven transportation system, which is not discussed in this paper and was not researched by the authors.

projected to be higher waste than conventional nuclear and a possible target for terrorism (McDermott 2023). High-intensity heat, while necessary for industrial processes, also may not be necessary for hospitals or labs — other sterilization methods, though not many, such as ozone gas or liquid sterilizers have been cleared by the FDA, and many more are approved outside the USA (CDC 2023).

Where high-intensity heat is necessary, local solutions which allow for energy generation on or near-site, while minimizing health/waste risks and energy consumption, localized pollution, health issues and labor issues along the supply chain (Dom et. al 2022) should be a continued area of research — given that many of the technologies already exist and simply have not been implemented, more institutions taking leadership and performing case studies of their implementation (what is known popularly as a “living lab”) is another potential place for research.

As technologies stand now, heat pumps and energy efficiency should dominate district thermal system decarbonization and energy needs in the vast majority of instances. Geothermal provides another promising avenue, dependent on the local heat sources such as nearby water bodies and the potential of local sewer heat. “Green” hydrogen is essentially non-existent at the moment, and although it could and likely will scale up, it is very energy inefficient and considered an inferior option. For high-intensity heat, which is a small but important component of decarbonization, several fossil-fuel-less options currently exist and more are being developed. Electric boilers and high-intensity heat pumps are exciting, as well as fairly efficient. Although biomass or fossil fuel currently dominates high-intensity thermal generation, this could and must change in the next 15-20 years.

Administrative/Funding Issues — Putting Solutions to Use

This section will combine the author’s personal experience in working with administration at the University of Washington with some research from other University transitions. It will focus on University systems, although some lessons are also applicable to general district thermal. Key limiters are administrative political will, upfront cost, and total financing.

Administrative Political Will

Fossil fuel companies have major presences, funding and otherwise, at dozens of the world’s most prominent Universities (Westervelt 2023). These presences and other marketing campaigns have significantly distorted the public’s views on the climate crisis and the feasibility of moving away from fossil fuels (Pierre and Neumann 2021). In the author’s opinion, many of the mainstream climate myths perpetrated by industry, including the myth that all climate decarbonization, including in upper-income countries, can be safely delayed to 2050 (UNSC 2023) (Peters 2021) (Hinman 2020) (Ganti and Schleussner 2023). Additionally, many Universities consider decarbonization "not a top issue" (University of Washington President Ana Mari Cauce, personal communication, 5/22/2023) and "rank" it below other high priorities (University of Washington President Ana Mari Cauce, personal communication, 5/22/202) The implementation of non-carbon technologies is necessary for reducing the impacts of the climate crisis, but local implementation will depend on local timelines, which will in turn depend on political will and the breaking of common myths,

Thus, avenues for speeding up transition and implementation will include local climate emergency declarations (CBC 2019), local or institutional climate goals (BNEF 2020), and local legal requirements or fines for not decarbonizing (UW Sustainability 2023) — direct mass mobilization has been successfully used in at least one major context (CBC 2019). Direct mass mobilization also plays in to the history of University politics (Brice and Yi 2019) (Richards 2023), but typically grows only in hotbeds, and moves in waves (Engler 2020) (van Dyke 1998) (author experience). One-off mobilizations outside of waves and hotbeds is usually not successful, although actors can look to stimulate small-scale waves and hotbeds which allow for multiple mobilizations.

Administrators at the University of Washington, one high-polluting center (UW Sustainability 2023), have pointed to the importance of student unions and student legislative lobbying bodies, up to the state level (University of Washington President Ana Mari Cauce, personal communication, 5/22/2023) (University of Washington Student Senate President Timothy Billing, personal communication, 5/22/2023). These were cited as they already have open channels of communication with decision-making administration — finding other bodies that discuss capital projects, funding, student, faculty. staff, or community opinion, the climate crisis, public health, or other "green" issues with decision-making administration is one way to make an "appeal to power," or for community pressure to feel more significant to admin than it actually is.

Financing

The large scale of district systems means that although reforms are often if not usually Net Positive Value (UW Sustainability 2023) (UCB 2021) before considering the cost of carbon, initial capital costs can be in the hundreds of millions. Zero-interest loan programs for emission reduction and energy efficiency, which regulate out "solutions," such as biomass and "green" hydrogen, that create other environmental ills, except for where they are necessary, can help to address the "capital gap." These programs would be needed on scale, since some already exist for homeowners which are unhelpful for municipalities, Universities, or other district energy systems (The RCS Network 2023). Subsidy programs and tax credits akin to the Inflation Reduction Act (CleanEnergy.gov 2023) have been significant already and will continue to be, especially if capital is provided upfront. The financing equation will change with local tax or fee programs on fossil fuels (UW Sustainability 2023), and solely removing subsidies from fossil fuel options could rapidly make these non-competitive, improving the budget picture for real, green, and healthy solutions (BNEF 2020).

High initial capital costs can also strain, at the university level, “debt capacity” to take on other projects (UW Sustainability 2023), so improving district systems should therefore be done with a particular eye on capital projects such as deferred maintenance (UCLA 2016) (UW Sustainability 2023) which can affect campus accessibility and safety. To the degree that universities are “debt-capped,” funding sources which avoid debt and allow for projects such as deferred maintenance to be continually addressed better address disability access and campus safety, therefore better exemplifying climate justice.

Public Universities have had their funding decline significantly since the 1990s and even since the early 2000s (Marcus 2019) (Newton 2019). Public Universities saw revenues, now in many cases their main sources of funding, drop and costs increase during the pandemic — some states also cut funding to Universities dramatically during the pandemic (Whitford 2020), and some schools closed entirely due to the increasing financial pressure (Fies and Hill 2020). All of this provides financial constraint, but also provides imperative for making changes that reduce long-term cost, which many district decarbonization programs are (UW Sustainability 2023) (UCB 2021) (Hanning et. al 2006) (Couture and Saporta 2023). More direct funding for these universities and their projects is a must for universities to lead, especially given that the researcher concentration at these institutions makes them well fit for “living labs” that can boost decarbonization implementation (UCLA 2016) (UCB 2023) (UW Sustainability 2023).

Administrative/Funding Conclusions

More localized action is needed for cities and Universities to consider district thermal decarbonization a top priority (University of Washington President Ana Mari Cauce, personal communication, 5/22/2023) (City of Seattle Office of Sustainability, personal communication, 4/25/2023). Once decarbonization is prioritized, increasing upfront funding access will not only increase the rate at which these systems are moved off fossil fuels, but will also provide protection for other crucial services that these cities and Universities provide. The “upfront” nature of this funding should be emphasized, since projects will often return in the long-run, and low or zero-interest loan programs can solve funding entirely.

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