Human-Infrastructure Interactions during the COVID-19 Pandemic: Understanding Water and Electricity Demand Profiles at the Building-Level

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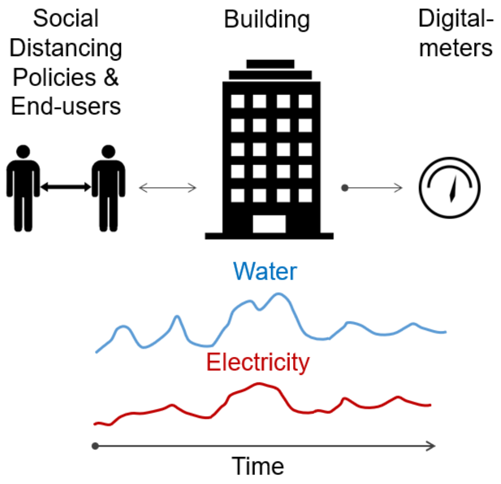
ABSTRACT

When engineers design and manage a building's water and electricity utilities, they must make assumptions about resource use. These assumptions are often challenged when unexpected changes in demand occur, such as the spatial and temporal changes observed during the coronavirus (COVID-19) pandemic. Social distancing policies (SDPs) enacted led many universities to close their campuses and implement remote learning, impacting utility consumption patterns. Yet, little is known about how consumption changed at the building-level. Here, we aim to understand how water and electricity consumption changed during the pandemic by identifying characteristic weekly demand profiles and understand how these changes were related to regulatory and social systems. We performed k-means clustering on utility demand data measured before and as the pandemic evolved from five buildings of different types at the University of Texas Austin. As expected, after SDPs were enacted both water and electricity use shifted, with most buildings seeing a sharp initial decline that remained low until the university partially re-opened. In contrast to electricity use, we found that water use was tightly coupled with SDPs. Our study provides actionable information for managers to mitigate negative impacts (e.g., water stagnation) and capitalize on opportunities to minimize resource use (e.g., HVAC settings).

KEYWORDS: water use profiles, human-infrastructure interactions, energy management, pandemic planning, clustering, systems thinking

SYNOPSIS: Using a systems lens, this study examined changes in water and electricity consumption during the COVID-19 pandemic at the building-level.

ABSTRACT ART



1. INTRODUCTION

Building infrastructure systems are designed to meet societal needs and serve a specific population. Engineers, for instance, base their designs for premise plumbing and heating, ventilation, and air conditioning (HVAC) systems on what purpose the building is to serve. They also take into account the building's expected occupancy and make assumptions about how people interact with the built environment—i.e., human-infrastructure interactions. Because building engineers and managers make assumptions about certain behavior patterns (e.g., peak demands[1]), the system they design may have to operate outside its design conditions (e.g., pumps schedules, thermostat settings) when human-infrastructure interactions change (e.g., occupancy changes). A prime example of such changes is the 2019 coronavirus pandemic (COVID-19). To help reduce the spread of COVID-19 and avoid overwhelming the healthcare system, governors enacted social distancing policies (SDPs).[2] SDPs began with recommendations to stay home except for critical trips (e.g., grocery shopping, essential work); they required many businesses, restaurants, schools, and offices to close, forcing many to work from home and attend classes online. Periodically throughout the pandemic, rules were relaxed in many places. For instance, businesses were allowed to re-open to limited capacity with social distancing measures in place. The pandemic gave rise to a sudden shift in human behavior, which inherently led to uncertain demand in the built environment. SDPs enacted during the COVID-19 pandemic changed how and when water and electricity were being used compared to pre-pandemic conditions. For example, while most businesses were expected to have decreased water and electricity consumption due to lower occupancy, residential water and electricity demands were expected to increase due to increased occupancy during the pandemic. Demand peaks and patterns also were expected to change in response to different work and school schedules.

Changes in water and electricity use have management implications. How the water distribution network is operated, for instance, may change due to spatial and temporal changes in water demand. Water-quality issues may also result due to conditions such as increased water age and low chlorine residuals,[3,4] creating public health issues. Further, decreased occupancy in some buildings might change the electricity demand needed to maintain the intended temperature for occupants. These changes might provide an opportunity to save energy by adapting building controls by, for instance, adjusting temperature setbacks—allowing temperatures to be a set amount lower or higher than the thermostat setting—based on occupancy.[5] Changes in building occupancy alter the expected human-infrastructure interactions at the building and household scale and potentially lead to infrastructure systems that are operating outside their intended design. Thus, there is a pressing need to research these demand changes to mitigate negative consequences and identify opportunities to improve operations. If managers understood how utility demands change in buildings during disruptive events such as the COVID-19 pandemic, they could develop appropriate tools (e.g., water-quality-monitoring protocols, implementing new thermostat schedules, increased workforce during uncertain times) to proactively plan for pandemics or other events that might cause changes in building-level demands.

COVID-19 related research in the water sector has focused mainly on changes at the municipal or neighborhood scale. Balacco et al.[6] studied water demand in five Italian towns, finding that changes in water demand varied by town. Some areas saw adjustments to water-demand patterns (e.g., morning peak delayed by two hours, absent lunchtime peak); cities that normally had substantial inbound commuter populations showed a decrease in water demand.[6] In Brazil, Kalbusch et al.[7] explored water demand changes in Joinville, using a linear regression to find a significant difference in water demand before and during SDPs. The authors found an increase in residential demand that was paired with a decrease in commercial, industrial, and public sector demands. Li and colleagues,[8] using the business-as-usual scenario as a baseline for demand modeling, found that in California the pandemic response (i.e., stay-at-home orders and changes in peoples' routines) had a statistically significant effect on water use.[8] Further, according to a study[9] of 28 utilities across the US, 86% of them observed changes in water use (e.g., altered profiles, overall demand changes, change in demand by customer class). Most previous work has examined water demand on a large scale, such as cities or utility service areas.[6,8,10]Although data about city-wide demand changes can provide insight into overall changes in water use, such aggregated data cannot be used to infer how water use in individual buildings changed. To understand human-infrastructure interactions on a granular scale, there is a need for a high resolution, temporal analysis of water use in buildings impacted by SDPs.

Compared to the water sector, more research on how the pandemic has impacted the energy sector has been done worldwide. This research has examined various contexts (e.g., national system consumption trends,[11] energy sector dynamics[12]) and spanned international (e.g., Europe[13,14]), national (e.g., Brazil,[11] Canada,[15] Australia,[16] US,[17] Spain,[18] Italy[19]), and regional/city-wide (e.g., New York City,[20] Ontario, Canada[12]) scales. Results from these studies varied, but most found notable changes to electricity-consumption patterns (e.g., weekday mornings in 2020 similar to 2019 weekend mornings,[13] reduced demand at hospitals due to restrictions on non-urgent surgeries[18]) and magnitude (e.g., overall electricity demand decrease of 14% in April in Ontario,[12] decrease of 20% on weekdays and 12% on weekends in New York City[21]). Despite abundant research on electricity demand during COVID-19, researchers have not, to our knowledge, focused on water and electricity in tandem; such a coupled analysis might reveal new insights.

Building utilities are naturally interconnected and should be studied together. Although implementation of electricity and water systems management is often done separately, managers of each system typically report to the same division that sets protocols for both systems. Further, system managers often have to coordinate during times of stress (e.g., outages, disasters). Some studies have recognized this connection, as they focused on coupled water and electricity demand patterns.[22] Such studies have given rise to recommendations for the creation of more resilient systems.[23] In uncertain operating contexts, it is important that division leaders adopt these multi-utility management techniques to ensure that water and electricity resources are being managed effectively at the building-level. Further, studying water and electricity systems in tandem allows us to understand differences between building systems, while also exploring building-level demand changes in electricity and water individually.

Here, we investigate water and electricity demand changes during the COVID-19 pandemic via empirical use data from five buildings on the University of Texas at Austin (UT Austin) campus. Results provide much needed insight into changes that can be made during the pandemic to alter building operations to continue the provision of services, while ensuring that water and energy resources are being used effectively. A college campus provides a unique opportunity to study demand changes as there are multiple building types (e.g., dorm, office, classroom) with various uses (e.g., lectures, lab work), that are akin to building types designated by the US Energy Information Administration (EIA), such as lodging, public assembly, and office.[24] Further, a college campus is a controlled environment, as campus operations are constrained by university policies. In turn, we can examine whether COVID-19-induced policies (and the associated occupancy changes) impact utility demand.

When studying demand changes, we frame each building as a system, which is interconnected because utility systems do not operate independently of one another. A building system can be driven, constricted, and triggered by outside forces.[25] Here the outside forces impacting building systems are the regulatory and social systems. As a framework to compare building (i.e., water, electricity), social, and regulatory systems, we use the work of Rinaldi et al.[26] on systems approaches. The regulatory system encompasses SDPs enacted by the university and the local government (e.g., building closures, research lab occupancy limitations). The social system—a group of individuals that interacts in a physical space—is made up of the building occupants.

Figure 1 shows our systems framework and research design. First, we trace the COVID-19 pandemic to the regulatory system (i.e., policies enacted by the government and institutions, such as UT Austin, to curb the spread; see Arrow 1 in Figure 1). Then we connect the regulatory system to the social system (i.e., occupancy changes and human behavior). We note that changes in occupancy might be directly due to policies (see Arrow 2 in Figure 1) or to people's personal choices or circumstances in response to the pandemic (Arrow 3 in Figure 1). For instance, people might have varying levels of comfort being around other people indoors. For instance, a more risk-averse person might choose to never go back to campus during our study time frame, while a less risk-averse person might choose to return to campus to work. In another instance, people may need to return to campus due to inadequate access to infrastructure needed for work such as reliable internet connectivity or access to technology. Finally, we connect occupancy (i.e., the social system) to the water and electricity systems (see Arrows 4 and 5 in Figure 1).

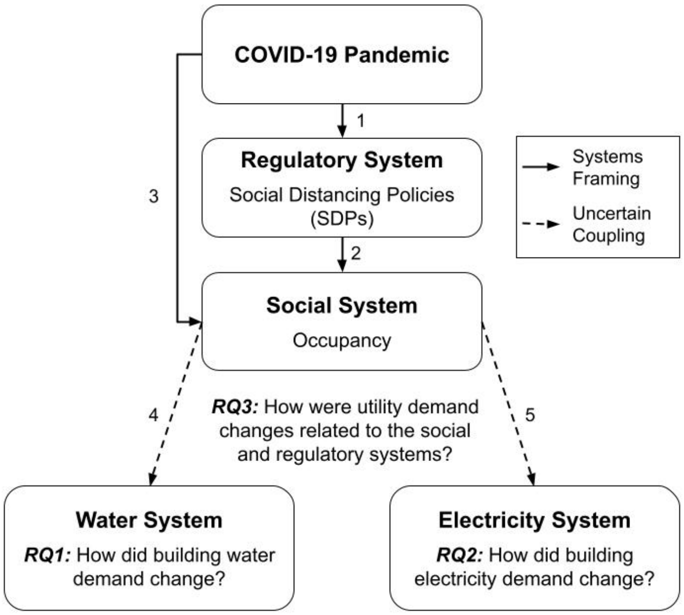


Figure 1. Systems conceptualization and coupling. Arrow labeled as systems framing show how we conceptualized building systems while arrows labeled as uncertain coupling represent relationships we explore in the current study.

Through the systems framework shown in Figure 1, we aim to answer three research questions: During the COVID-19 pandemic, how did consumption, both in patterns and magnitude, change for the (1) water system and (2) electricity system, and (3) how were these demand changes related to the regulatory and social systems as revealed through occupancy? To answer Research Question 3, we explore the uncertain "coupling" between each system. As defined by Rinaldi et al.,[26] systems can be loosely or tightly coupled to one another. Notably, we did not study the relationship between water and electricity systems (i.e., the water-energy nexus; e.g., electricity needed for water distribution, water needed for cooling). Instead, we studied water and electricity at the human-infrastructure interaction level in parallel to understand if both systems changed similarly. This allowed us to explore whether policies and human behavior are tightly coupled with both systems and to understand differences between building utility systems.

Revealing water and electricity consumption trends helps reduce the epistemic uncertainty around demand changes during pandemics and other disruptive events. By comparing between systems, we can identify which utility system is more tightly coupled with policies and occupancy. With such knowledge, managers can grasp how policies might drive, constrict, or trigger utility demand. Finally, we make recommendations for division/building managers to reference as they continue to respond to the COVID-19 pandemic, future pandemics, and other extreme events.

2. DATA AND METHODS

The research approach relies on (1) collecting data on water and electricity use from five buildings that are designed and operated for different uses (dorm, lab, assembly, classroom, and office; see Supplemental Table 1) at UT Austin, (2) extracting characteristic weekly demand profiles, and (3) synthesizing resulting profiles using a systems framework.

2.1 CONTEXT

UT Austin is a large, urban university located in Austin, Texas, that, during the Fall 2018 semester, served more than 70,000 people.[27] It is important to discuss the unique characteristics of UT Austin's water and energy systems because the water system is largely driven by occupants, while the electricity system is partially driven by HVAC systems. UT Austin's water and electricity systems are managed by the Utilities and Energy Management Group. UT Austin's water system can, according to the EPA's classification system, be considered a large water system.[28] The majority of UT Austin's buildings are served by a water distribution system supplied by Austin Water and managed independently by UT Austin utilities. In turn, we can compare the management framework at UT Austin utilities to a traditional water utility, while acknowledging that UT Austin manages only the distribution system on campus, not water treatment. UT Austin manages its own combined heat and power plant, which is one of the largest microgrids in the US.[29] Since chilled water and steam required for heating and cooling are produced outside of the buildings, the electricity use data represents the mechanical subsystems required for distributing the conditioned air in the buildings (e.g., pumps and fans), along with other electricity uses (e.g., lighting, plug loads).[30]

To understand demand change in the context of changing policies, it is important to understand key policies that impacted the buildings studied (see timeline; Figure 2). Policies A-C are applicable to all buildings while Policies D-E apply to labs only. Shortly after a state of disaster was declared in Austin (on March 12th),[31] UT Austin closed their campus (March 13; Policy A). After spring break, residence halls and assembly buildings (including most dining services) were closed and UT Austin transitioned to remote learning through summer 2020. Notably, emergency housing and dining were available to students through the spring 2020 semester when needed.

When the UT Austin campus closed in March, research operations were paused aside from "access to maintain essential research capability or to prevent catastrophic disruption";[32] COVID-19 research was allowed (at full capacity) during this time. When re-opening campus to research activities, UT Austin took a phased approach, called Research Restart.[32] On June 1st the campus opened to time-sensitive research (shown as D in figures). This phase, known as Level 3B, was associated with 30-40% lab capacity and lasted for the remainder of 2020. Notably, capacities at labs may have exceeded 40% if COVID-19 research was prominent in the building. To allow more researchers access to on-campus laboratories, UT Austin implemented a cohort system[33] (i.e., researchers assigned to morning or afternoon shifts) on July 27th (shown as E in figures) and remained in this system until the end of data collection (November 16th, 2020). In most cases, the cohort system allowed 100% of laboratory-based researchers to be on campus.

For the fall 2020 semester, UT Austin operated with hybrid learning (i.e., part in-person and part online instruction).[34] Dorms opened for the fall semester on August 20th (indicated as C in figures) and classes began on August 26th. During the fall, buildings and dorms were opened at a reduced capacity (e.g., 40% capacity in classrooms;[34] under 50% in dorms). Dining services in the assembly building were restricted; all food was served in disposable containers and students who decided to eat at the dining hall had to adhere to SDPs.

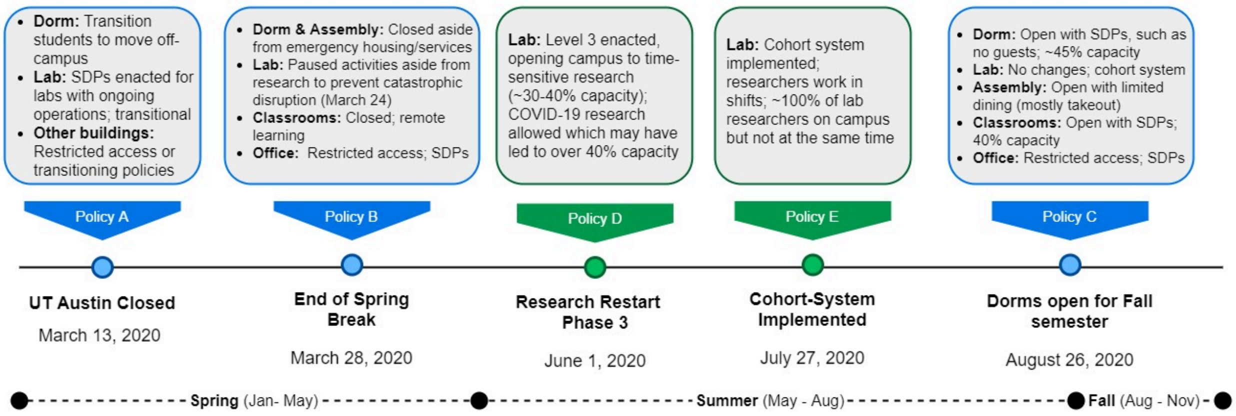


Figure 2. Key policies[31–34] implemented at UT Austin from January to November 2020. Boxes describe what building operations looked like in practice during that policy. Policies marked in green are applicable only to research labs, while those in blue are for all buildings.

2.2 DATA SOURCES AND COLLECTION

Water and electricity use data has been collected by UT utilities since 2009 (see UT Energy Portal[35]) using digital meters placed in buildings. We collected data from five buildings that were representative of the different uses, as designated by UT Austin (shown in Supplemental Table 1). These buildings range in size, age, functionality, and water and electricity use. As mentioned, building classifications by UT Austin are similar to the building types surveyed by the EIA,[24] shown in Supplemental Table 1, and as such, the results of this work can be generalized beyond university buildings. For instance, housing and office & administration buildings are comparable to EIA lodging and office buildings, respectively.[24]

The dataset used here includes data from January 1 to November 16, 2020, to capture demand changes before (January-March) and during the pandemic (March-November). To establish the typical water and electricity consumption trends at UT Austin's campus, we compared 2019 and 2020 demand data (see Supplemental Figure 1). All buildings had lower average daily water and electricity demands in 2020 compared to 2019, ranging from 42% to 72% water use reduction and 14% to 30% electricity use reduction. On the other hand, water and electricity use from January to March of 2020 (before SDPs) was similar to that same time period in 2019 (see Supplemental Figure 1). We observe that water and electricity consumption during January to March 2020 is comparable with the normal consumption during 2019, and in turn, we use January to March 2020 as a reference for normal operating contexts when we discuss our results.

2.3 DATA PROCESSING AND CHARACTERISTIC DEMAND PROFILE IDENTIFICATION

To determine if demand patterns changed, we used time-series data to extract representative weekly patterns throughout the analysis period. Then to detect changes in the patterns, we performed clustering analysis to group similar patterns into individual clusters. We expect similar demand patterns (e.g., during fall/spring semester) to exhibit similar behavior and be classified into the same cluster, and significantly different patterns to be grouped into different clusters.

First, the raw water and electricity data were aggregated into daily use from 5-min, summative data. Any data points with obvious errors (e.g., negative values) were removed from the data set and linearly interpolated. At most, three days (0.1% of the data) were replaced in this manner. Next, outliers were removed using a 30-day rolling filter to remove data points above or below two standard deviations from the median. We also reviewed each demand profile for qualitative outliers. The number of outliers removed ranged from 1.6 to 6.3%, aside from the electricity data for the research laboratory, which had a meter outage from August 6th to September 12th. A table with descriptive statistics and more information about the data-cleaning process are shown in the supplemental information (Supplemental Table 2).

We then identified characteristic weekly demand profiles during 2020, before and during the pandemic. There are many clustering algorithms that can be used to analyze time-series data (e.g., hierarchical, spectral clustering); previous research has shown that no "best" algorithm exists because ground-truth labels are unknown.[36] However, previous studies have shown k-means to produce robust results,[37–40] and as such, we use k-means clustering algorithm here. To perform the clustering, we first normalized daily-use data to create a signal between 0 and 1, and then the normalized weekly demand patterns were clustered using *k*-means[41] (using scikit-learn[42]). To select the number of clusters for each building's water and electricity demand, we used the elbow and silhouette methods[42] (see Supplemental Figures 2 and 3 for corresponding elbow and silhouette figures). To evaluate the quality of the clustering, we further examined the clustering results based on our knowledge of the buildings system and the contextual information about campus operations.

2.4 LIMITATIONS

Like any study, there are limitations present. We only use data from five buildings on a university campus, which limits conclusions that can be drawn at larger scales. Despite this, we can still make conclusions about uncertain demand at the building-level. Further, by comparing between the water, electricity, regulatory and social systems at the building-level we can gain insights on a more granular scale. Building-level insights (e.g., how building-specific policies impact utility use) could not be captured if studying larger geographies (e.g., utility service areas) as human-infrastructure interactions may not be captured when studying aggregate use. Additionally, specific findings about each building can be transferred to other contexts based on building use using the US Energy Information Administration's building types[24] (see Table 1 in Supplemental Materials). Lastly, it is important to note that the time frame analyzed here (January to November 2020) is only a portion of the COVID-19 pandemic, limiting our findings about the pandemic as a whole (e.g., how vaccine availability impacts utility use). On the other hand, by analyzing and disseminating findings during the pandemic, practical recommendations put forth here can be used in responses (e.g., universities managing the delta variant during the 2021-2022 school year).

3. RESULTS AND DISCUSSION

Water and electricity profiles were extracted and analyzed, and the main results are displayed for a laboratory, dormitory, assembly, classroom, and office building. Policies discussed in Section 2.1 are displayed in tandem with water and electricity use data (i.e., as reference lines). Figure 3 shows the daily water (blue) and electricity (orange) demand during 2020. Figure 4 shows the characteristic weekly demand profiles (the line plots) for each building for water (left) and electricity (right), visualizing each cluster as different colors, where blue and green represent the lowest and highest demand magnitude, respectively, and red and purple represent medium demand magnitudes. For example, four unique weekly water-demand patterns were identified for the laboratory building for the period between January and November 2020 while for electricity during the same time period only two unique demand patterns were identified (see Figure 4). To demonstrate how the demand patterns changed over time for each building, the dot plots in Figure

4 show cluster occurrence over time. For example, in the assembly building, water and electricity demands were high during the spring semester between January and mid-March, low between mid-March and the end of August, and medium in the fall semester between September and November 2020. Figures 3 and 4 jointly demonstrate the dynamic change in shape and magnitude of water and electricity demand.

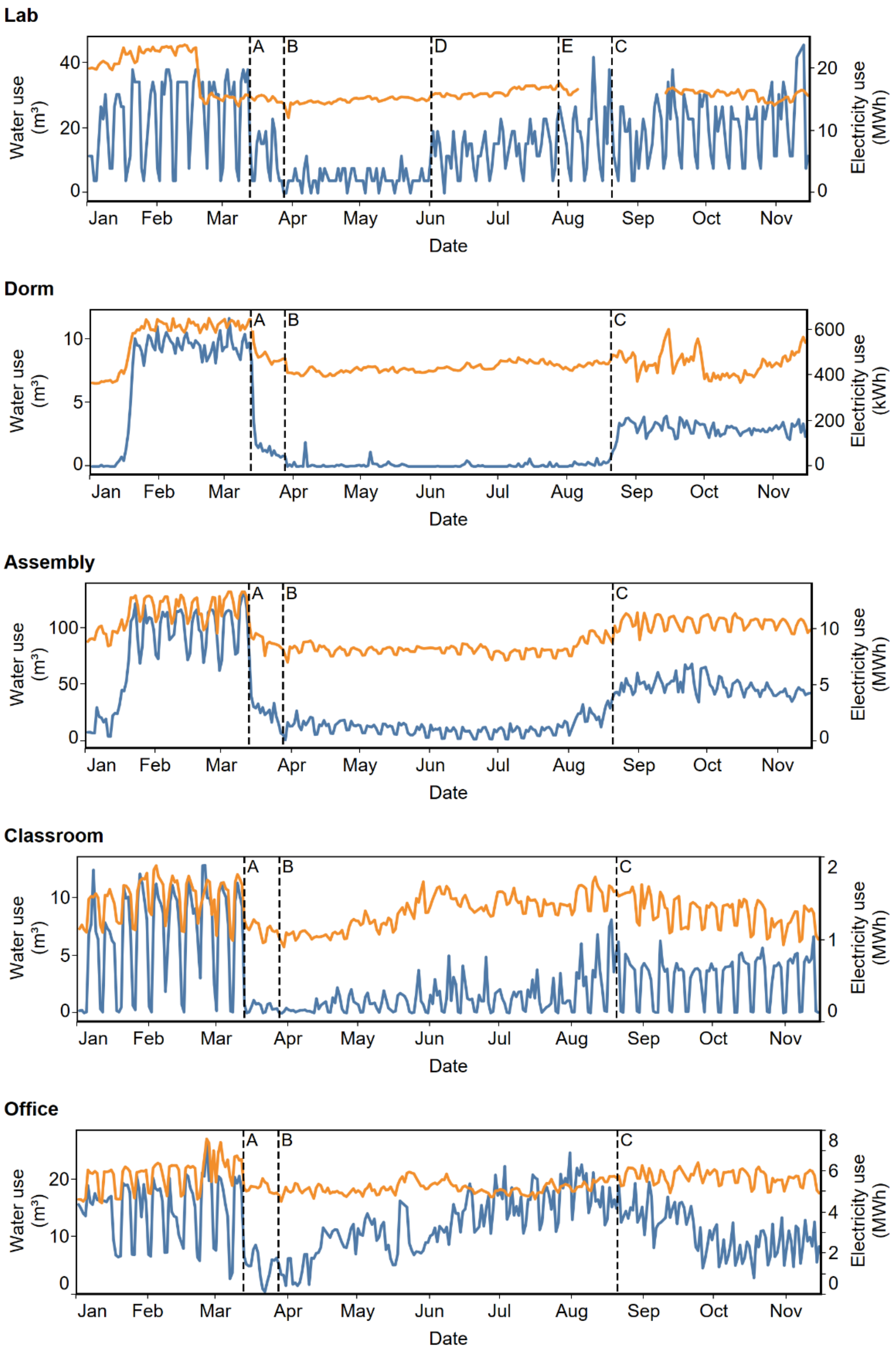
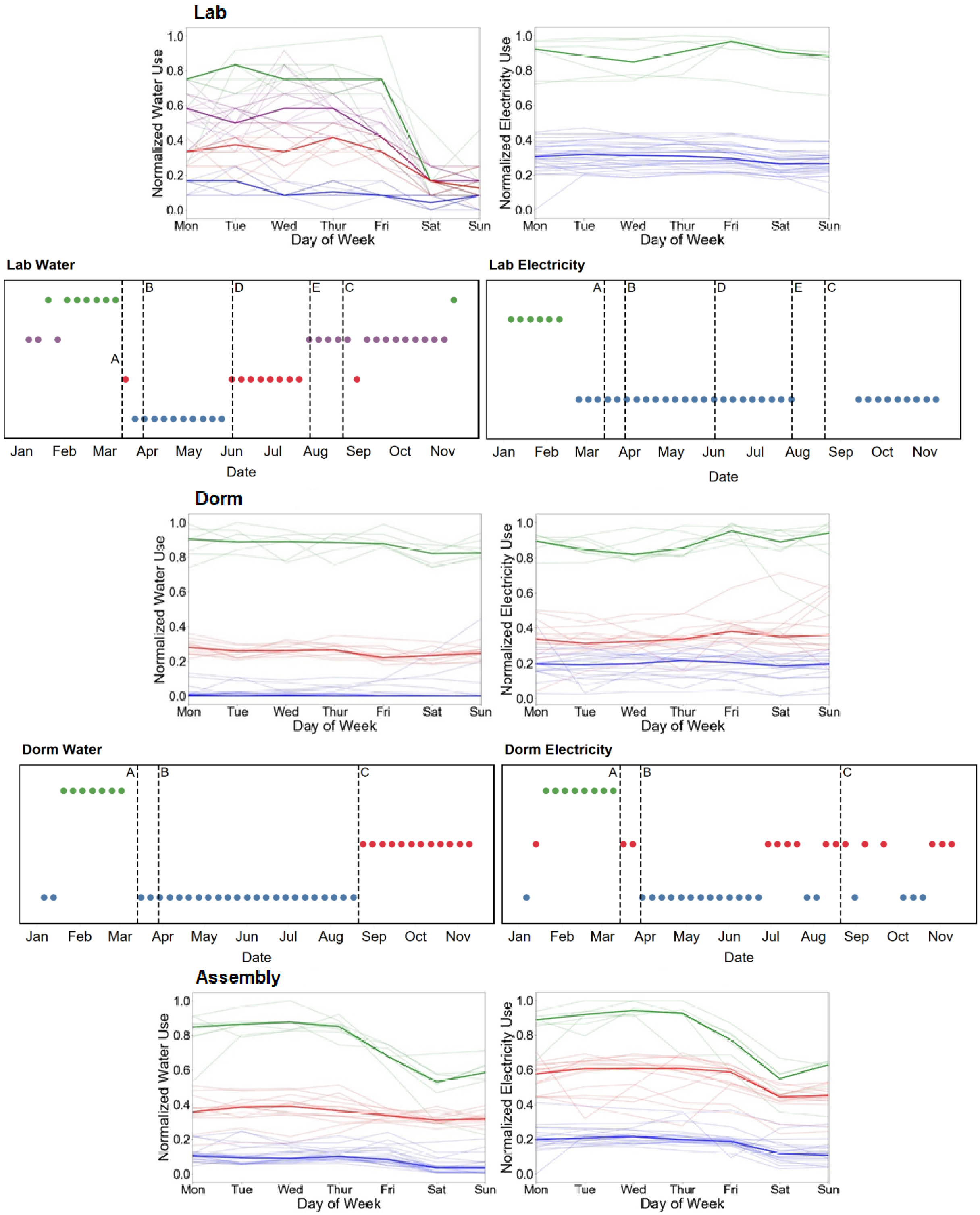


Figure 3. Water and electricity demand during 2020; orange represents electricity demand; blue represents water demand. Gaps in data represent days with meter errors. Vertical lines A-E represent the different policies outlined in Figure 2. Policies D and E are only present in the lab panel because they are research policies.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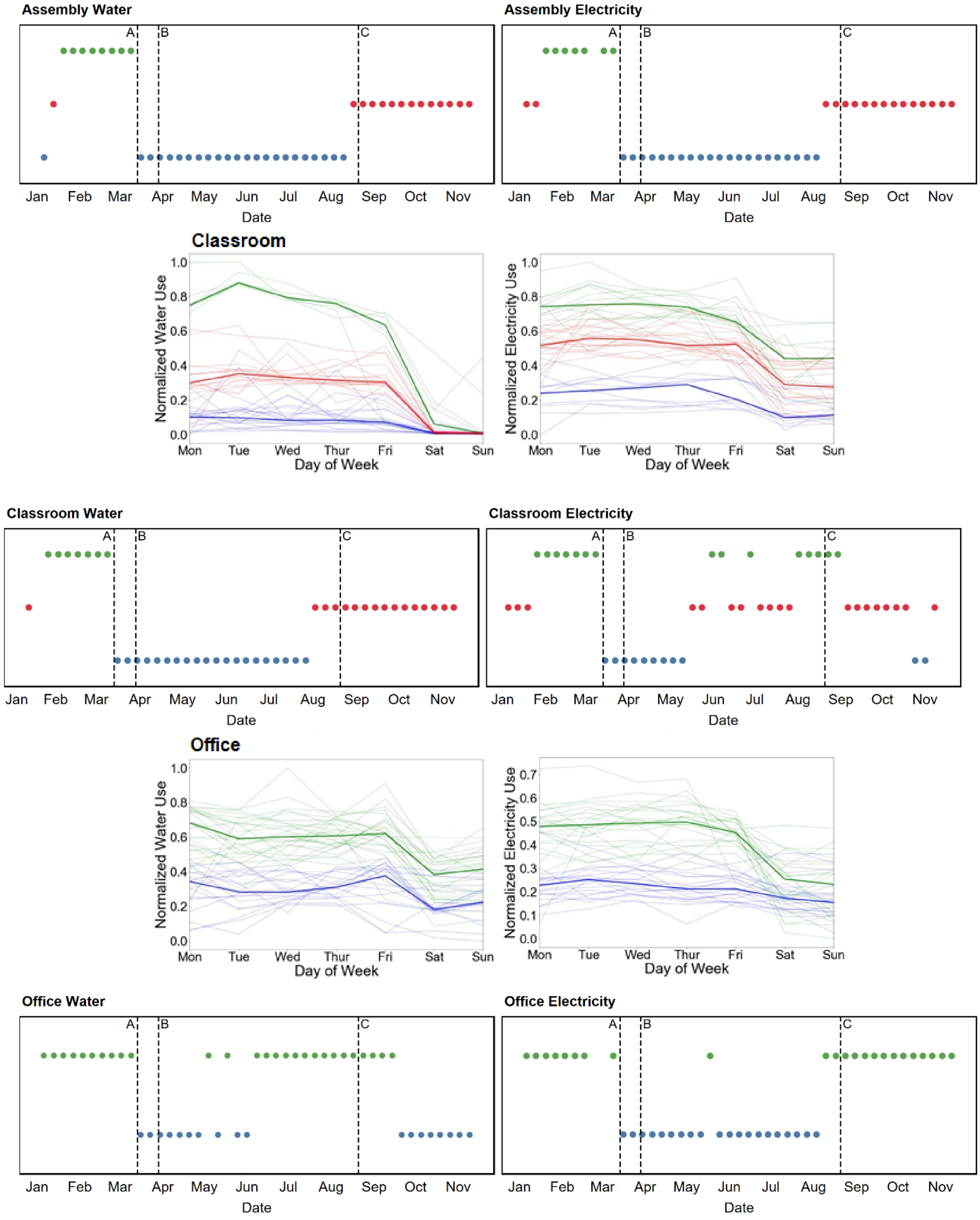

Figure 4. Characteristic weekly demand profiles shown in clusters and dot-plots showing clusters associated with each week from January to November 2020; colors are consistent between dot and line plots. Light lines show a weekly demand profile and bold lines show the characteristic demand profiles; each color represents a different characteristic demand profile. Dots shown higher on the plot are associated with higher magnitude use but are not to scale.

3.1 CHANGES TO WATER SYSTEM DEMAND (RESEARCH QUESTION 1)

As expected, water demand changed during the pandemic. All buildings showed an initial, sharp drop in water demand corresponding to the March campus closure, when the governor declared a disaster in Austin.[31] Notably, the water demand patterns during COVID-19 departed from typical weekly demand trends on UT Austin's campus.[22] After policies were enacted (Policy A), the dorm, assembly, and classroom buildings showed a sharp drop in weekly demand. From spring break to the fall semester (Policy B), demand remained low but when UT reopened (Policy C), demand increased to an intermediate magnitude level. Water demand at the lab building closely matched the various policies enacted, while the office building showed a mixed trend of low and high demands during the different policy periods. During the spring semester, many buildings (dorms, assembly halls, and classrooms) exhibited a water demand similar to that observed in the summer (see Figure 4). For the dorm and assembly buildings, the water-demand pattern during summer 2020 was similar to that of January 2020 (i.e., winter break when there were fewer residents, classes, and research activities). From this, we infer that water demand during the COVID-19 pandemic is similar to that during university breaks. This implies that building and division managers can leverage existing building-management protocols for university breaks to respond to disruptions such as pandemics or to other times of low occupancy (e.g., closures due to weather). For instance, managers could use the same flushing protocol, something routinely done in premise plumbing during times of low occupancy, to minimize stagnant water and the associated water-quality challenges.

The weekly water-demand patterns at many buildings changed during the pandemic. For instance, the assembly building changed from a pattern where weekend use was lower than weekday use (before SDPs) to a relatively flat demand pattern during the pandemic (see Figure 4).

There was a greater reduction in demand during weekdays compared to weekends. This implies that the way in which people used services in the assembly building changed (e.g., absence of gatherings, the timing throughout the week). In fact, during the pandemic, weekly demand patterns at the assembly building were similar to that of dorms (i.e., flat across the week). This trend might have emerged because of occupancy restrictions at the assembly building (i.e., most food served as take-out). As a result, fewer students entered the building but those who did were doing so on a more consistent basis throughout the week (similar to the dorm). For instance, students might go to the dining hall more regularly to get takeout (leading to a "flat" demand curve) than they did in pre-pandemic times when students assembled to eat together at the buffet. Alternatively, the peaks in water demand before the pandemic may have been due to dish washing after meals which was reduced during the pandemic due to take-out policies. Similar trends might be present in buildings outside of college campuses that are used for service and public assembly as they adhered to SDPs, such as limited capacity at stores and restaurants transitioning to take-out. On the other hand, the classroom consistently reflected this weekend water-demand dip throughout 2020, while the magnitude change was isolated to weekdays. This was expected, as classes are typically held Monday through Friday. Interestingly, the weekly water-demand profile at the office building showed little change besides a magnitude decrease (Figure 4). This is not surprising because the days of the week university employees worked (Monday through Friday) did not change during the pandemic, so we would not expect to see a different pattern emerge (aside from a decreased magnitude due to remote work).

The change in water-demand patterns and magnitude could have operational, technical, and managerial impacts on water systems. For instance, the decreased water use might lead to stagnant water in premise plumbing, and as a result, water-quality declines. In turn, water quality should be monitored closely to determine appropriate management actions, such as flushing (actions UT Austin facilities did take). In addition to impacting water services in the building, changing demand patterns might alter operations in the water-distribution system, creating a need to adapt system operations (e.g., pumps, valves). Notably, many utilities lack the human and financial resources needed to do increased testing and flushing or make other system adjustments, particularly during a protracted crisis like the COVID-19 pandemic.[9,43] Some utilities with well-developed hydraulic models might be able to simulate changing demand conditions to better target their operational response. Nonetheless, many utilities lack the modeling capabilities to do so quickly and effectively.

3.2. CHANGES TO ELECTRICITY SYSTEM DEMAND (RESEARCH QUESTION 2)

At the start of the pandemic, electricity demand at all buildings, as with water demand, dropped. The assembly building showed low electricity use from March through August (Policies A-B), followed by an increase for the fall semester (Policy C). The office building also saw decreased electricity demand from March through August (Policies A-B) where we might expect to see increased electricity from air conditioning during summer months, but this was followed by an increase in demand during the fall semester, attaining pre-pandemic levels (see the green cluster in Figure 4). The electricity use in the office building showed that although the university was doing hybrid learning in the fall (Policy C), the demand in the building was similar to before the pandemic from January to March 2020. Other buildings, such as the lab and dorm, showed different trends. The lab saw a relatively constant electricity demand during the pandemic (March to November), aside from August 6th to September 12th when there were meter errors. As expected, there was low electricity use in the dorm during the summer (Policy B) due to it being closed. Electricity demand in the dorm increased for some weeks during the end of the summer and fall semester but compared to pre-pandemic levels, were relatively low. This is likely due to limited occupancy of dorms (about 45%) and the implemented SDPs (e.g., no guests allowed). Similarly, the classroom saw an initial drop in electricity demand after SDPs were enacted in March (Policy A), but during the summer and fall saw fluctuations that ranged from low-use to pre-pandemic levels.

It is important to note that electricity demand unlike water demand, never approached zero. This is due to the base load needed to operate buildings. The pandemic could in fact provide a unique opportunity for electricity managers to gain a better understanding of base load. They could infer that pandemic-related low-occupancy is similar to minimum electricity use. Further, due to the length of the pandemic, managers could look at low use during various weather conditions to better understand how weather impacts base load. This is especially applicable to commercial buildings that were closed for part of the pandemic. Managers could assess electricity-use data during the pandemic to understand if the building system is operating as designed and make changes to building-energy management (e.g., optimizing air handling units, adjusting thermostat schedules).

In summary, weekly electricity-demand patterns remained largely unchanged throughout the study period. For instance, the lab, dorm, and classroom-demand profiles saw a magnitude shift with minimal changes to profiles. On the other hand, the demand profiles for some buildings flattened during times of low use. During the summer, for instance (see the blue cluster in Figure 4), the assembly building’s profile was flatter than those of the fall and spring (see the red and green clusters in Figure 4). This may be expected, as the blue cluster represents low-occupancy operations (similar to the base load), which mainly consist of HVAC system operations.

3.3 RELATIONSHIP BETWEEN UTILITY, REGULATORY, AND SOCIAL SYSTEMS (RESEARCH QUESTION 3)

The pandemic provided a unique opportunity to understand how policies impact building utilities. SDPs were enacted to curb the spread of COVID-19, but these changes also impacted technical systems because infrastructure systems and the regulatory environment in which they operate are intrinsically tied. In our study, a building's occupancy, affected by policies, was revealed through altered demand profiles (see Arrows 4 and 5 in Figure 1). Although we cannot understand the micro-behaviors causing shifts in water and electricity use practices (e.g., increased hand washing, decreased lighting use), assessing the overall demand shifts in a building allows us to understand human-infrastructure interactions (i.e., how people were using utility systems). This is especially evident when looking at the water profiles at the lab building. Instead of the typical, three-cluster demand seen in most other buildings, the lab data revealed four distinct clusters. These clusters are directly connected to university-level research policies (see Figures 2 and 4). Instead of low water use throughout the summer, the lab saw a demand increase during June and July, followed by another increase in the fall. Notably, at the start of June, the university increased the number of researchers allowed on campus (Policy D) and the next increase was due to the cohort-system implementation (Policy E), which, in most cases, allowed lab-based researchers to come to campus through shift work. Water demand at the dorm also showed a tight coupling with policies, as water demand was directly connected with the dorm opening and closing, as expected. Similar trends are evident in the classroom and assembly buildings. Additionally, the water demand at the buildings studied were impacted by the first SDPs (Policy A), as shown in the initial, swift change in occupancy at the university at the start of the pandemic.

In summary, our findings show that, by changing building occupancy, policies are directly related to building water demand—meaning water demand is tightly coupled with the regulatory system. In turn, during uncertain operating contexts, such as pandemics, water system managers should reference policies enacted and make proactive management decisions to respond to demand changes. These operational changes should vary based on building-specific uses and policies. For instance, when the cohort system was implemented on July 27th all lab-based researchers were allowed to work in the lab building in shifts (see Policy E in Figure 2). Prior to this policy, lab buildings were only at 30-40% capacity, which may have led to stagnant water. In turn, the division manager could use this information to adjust their flushing and water quality testing schedule (e.g., flush on July 26th, increase testing when researchers return). On the other hand, the dorm and classroom buildings were still closed during July, so the low-occupancy flushing schedule (about bi-weekly) used after campus closed (Policy B in Figure 2) could be maintained.

Using SDPs as a guide for adapting building management is transferrable to contexts outside university campuses. For example, a manager of a commercial building could adapt management protocols, such as flushing or water quality sampling, based on the percent capacity allowed at businesses, offices, or restaurants. Additionally, managers in charge of system-level operations could use this information to better understand hydraulic operations. For instance, in a non-metered building, system managers might use policies to estimate building-level demand changes and input this into models (e.g., classrooms with 40% occupancy during the Fall 2020 semester can be assumed to have about 40% of the normal demand).

Not all water-demand profiles were directly connected to policies but instead displayed nuanced human behavior during the pandemic (Arrow 3 in Figure 1). Although SDPs constrained building occupancy and therefore influenced how people interacted with their infrastructure systems, our results highlight the role that personal choice likely played. For instance, in the office building, water use peaked during July and August (see Figure 3) before declining after the start of the fall semester. This unexpected spike in water use could be attributed to employees' individual choices or circumstances that necessitate the need to work on campus. Anecdotally, administrators at UT Austin discussed "work-from-home fatigue" after working remotely in the spring; other individuals discussed unreliable or inadequate infrastructure (e.g., poor Internet connectivity) when working-from-home. Of note, at the start of the fall semester, many employees anecdotally shared that they abruptly stopped working from campus due to concerns about students returning and an increased campus occupancy. Here water-use trends are not aligned with policies, reflecting (likely) human behavior instead.

The electricity system was loosely coupled with policies (Arrows 2 and 5 in Figure 1), as evidenced by the lab, classroom, and dorm buildings. The electricity profiles at the lab do not have four clusters like water, indicating a consistent lower magnitude demand (when compared to that of pre-pandemic demand) throughout the summer and fall. In the classroom and dorm, the summer and fall variations show that weekly electricity-demand profiles were inconsistent from week to week and fluctuated between clusters. This variation is not surprising as the base electricity load is dependent on weather. In turn, occupancy is not the only driving factor in electricity demand. For instance, if building managers did not adapt the HVAC and lighting systems based on low-occupancy, we would not expect policies to have a significant impact. Practically, our findings confirm that demand-driven control strategies (i.e., automatically update set-back times and set-points instead of following a fixed operation schedule) might provide a solution to managing building-energy systems during pandemics or other population shifts.[44,45]

Compared to the water system, the electricity system was not as tightly coupled with building occupancy and policies, aligning with previous work[46] that found building electricity demand profiles at a university building in the United Kingdom were not strongly connected with occupancy patterns. In our data, when building occupancy (i.e., the social system) changed—whether due to SDPs or individual choices—water use reflected this change (i.e., revealed human-infrastructure interactions), while the electricity system did not change to the same magnitude. This trend is evident in all the buildings studied (see Figure 3) and is likely due to the base electricity demand necessary to keep the buildings operating (e.g., HVAC systems with pumps and fans) and the inherent fluctuations in electricity use during weather changes. These factors make building-energy management challenging during uncertain operating conditions. In turn, we propose that water-use data can be used to inform energy management. We recommend protocol changes at the division level that allow for increased information sharing between utility systems (e.g., within the Utilities and Energy Management Group). With this data, a division/building manager could alter temperature setback hours based on water-demand changes, increasing building energy efficiency during times of low-occupancy (e.g., holidays, pandemics). High-resolution water-demand data (i.e., hourly or a more granular scale) can provide unique insight into building occupancy, which can be used to get information about human-infrastructure interactions and to alter building-energy management.

4. CONCLUSIONS

We assessed building-level water and electricity demand changes during the COVID-19 pandemic. To do so, we performed clustering analysis on utility demand data for five buildings of different uses at UT Austin. We used a systems approach to understand how changes in utility demand were related to social and regulatory systems. First, we found that water and electricity demand changed, in both patterns and magnitude, reducing epistemic uncertainty around how SDPs have impacted utility demand. Additionally, we found that the water system is more tightly coupled with policies and occupancy than is the electricity system. This implies that managers can use water-demand data to inform how they manage their building's energy use, for instance, by adjusting temperature setbacks based on water demand trends.

This study demonstrates that smart meters can reveal demand changes that would otherwise not be possible without high-resolution, timely data, revealing the benefits of smart metering. Although many utilities are installing smart meters that collect large amounts of data, much of this data remains unused, or is primarily used for billing. This research contributes to other studies that advocate for promoting smart metering to support infrastructure management by showcasing how demand data can inform utility management during pandemics. Practically, results from this study will help system managers prepare for future pandemics and adapt their current management protocols during the COVID-19 pandemic, when the operating context is uncertain. More broadly, practitioners could adapt building practices based on our findings. For instance, utilities might increase water-system flushing in premise plumbing of buildings that are at risk of stagnant water due to SDPs. Notably, results can be transferable to contexts aside from universities based on building use (e.g., offices on-campus are similar to offices off-campus).

ASSOCIATED CONTENT

The following files are available free of charge.

Table S1: UT Austin building characteristics

Table S2: Water and electricity data cleaning process and descriptive statistics

Figure S1: Comparison between 2019 and 2020 water and electricity use

Figure S2: Elbow figures for water and electricity weekly clustering

Figure S3: Silhouette score figures for water and electricity weekly clustering

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Notes

The authors declare no competing financial interests.

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