Water Power: Measuring Household Water and Energy Intensity

Final Report: *August 30, 2016*

Summary

Energy and water are linked through their reliance upon one another from creation to end-use. Energy requires water for fuel production. Water must be pumped from the ground, treated, and distributed for use while wastewater must be collected, treated, and discharged - all activities requiring energy. This interdependence is referred to as the energy-water nexus. It is increasingly understood that conservation of one conserves the other. This report evaluates and quantifies the energy and water cost of residential activities like running a sprinkler, charging your electric car, running your air conditioner, taking a shower, washing and drying your clothes, in Central Texas.

Pecan Street has been tasked by the Environmental Defense Fund to analyze and report on the total energy and water costs of whole home and various appliance-level end-uses. Pecan Street is in a unique position to study this relationship at the residential level using high frequency ground truth disaggregated energy data and the most granular whole home water use data available today.

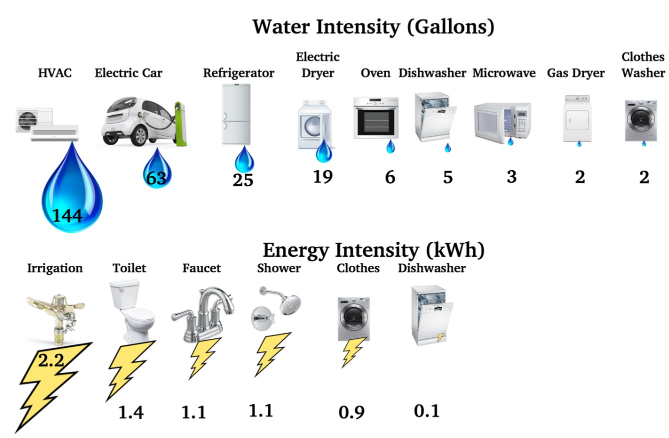
A total of 38 homes in Texas were selected for inclusion this study, 30 in Austin and 8 in Houston. During the first six weeks of 2016, BluCubes, gateways developed by Pecan Street to collect water use data, were deployed in 8 homes in Houston that already had Pecan Street's high-resolution electricity data equipment installed. Initial review of the Houston water data found the frequency of water read intervals to be sporadic ranging from 1-minute to over 20-minute intervals and resolution of 10 gallons to be inadequate for disaggregation to the appliance level.

In addition to issues with the frequency and resolution of the data available from Houston's smart meter system, severe flooding events submerged meter pits resulting in data reporting outages of multiple weeks, the worst temporary outage being 53 days. Therefore, Pecan Street was only able to use data from the Austin homes for creation of the water disaggregation algorithms. Water data from the homes in Houston was salvaged for monthly analysis, but no water disaggregation work could be performed.

In order to understand opportunities to leverage the energy-water nexus for optimized conservation of both resources, the project team first needed to disaggregate the whole-home water use to the major appliance level. Following disaggregtion of uses, calculations on embedded energy in water use and embedded water in energy use were applied to identify the total (actual+embedded) resource use associated with common household activities. Understanding the total use enables identification of the opportunities to more effectively target water and energy conservation resources.

Using the high-resolution energy and water data collected for this study, Pecan Street was able to disaggregate the large water uses in the home. The five appliances with the highest per use electrical requirement and therefore the highest water intensity are central HVAC, electric car charger, refrigerator, and electric dryer. The average monthly water intensity and energy intensity values for common household activities are depicted in Figure 1.

Figure 1. Average Monthly Intensity

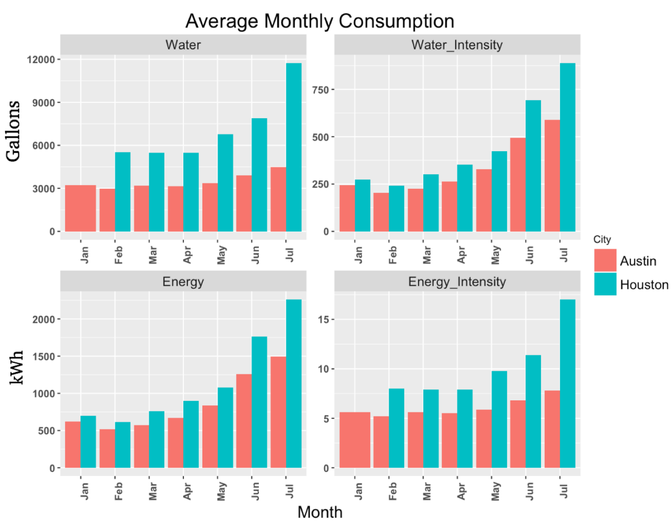


In addition to creating reliable water disaggregation algorithms, the analysis results reveal that irrigation and air conditioning present the greatest opportunity for combined energy and water savings. Homes with solar panels were able to reduce their water footprint by offsetting the water intensity required to deliver electricity to their house. The cumulative reduction in water intensity observed for the 21 homes in the study with rooftop solar panels was approximately 79%.

Results

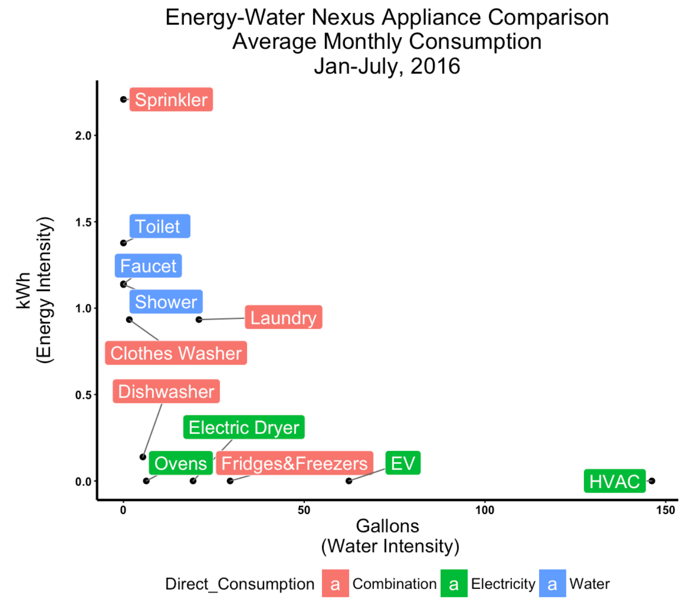
The overall water and energy consumption patterns of both cities is similar in that we see non-linear increases as the study progresses from winter to summer. Energy use slightly dips from January to February due to furnace use, but then climbs each month thereafter. The Austin homes consumed less than the Houston homes which could be due to Houston's small sample size and the Austin homes' being located in the Mueller neighborhood.

Figure 2. Average Monthly Consumption and Intensity



Irrigation and HVAC had the biggest impact on energy and water intensity, exceeding the 2nd ranked appliances by factors of 1.6 and 2.4 respectively (see figure 3).

Figure 3. Average Monthly Energy & Water Intensity by Appliance



Climate and Weather have significant impact on both water intensity and energy intensity. The clear sunny days and extreme high temperatures of a Texas summer increased HVAC water intensity from a low of just under 20 gallons in February to 400 gallons in July. Minimal rainfall and high temperatures drove the average energy intensity of homes with irrigation systems from 1.95 kWh in February to 5.15 kWh in July (see Figures 4 & 5).

When HVAC is held in check by cool to moderate temperatures the water intensity of an electric vehicle charger at 58.3 gallons, was almost 3 times higher than HVAC, which was on par with electric dryers at 20 gallons in February (see figure 4). Homes with two or more refrigerators and freezers surpassed HVAC and electric dryers in February by about 25%, reporting 25 gallons.

Most appliances are much less sensitive to the climate and weather and reported fairly constant water intensity throughout this study. The exception was the one monitored freezer in the study with consumption increasing by over 50% between Jan and July, suggesting it is location in the garage.

Doing laundry, a combination of clothes washer and electric dryer, has a fairly significant impact on both water and energy demand, ranking 4th with respect to both water and energy when electric vehicle charging and irrigation are present in the home. In the absence of electric vehicle charging and irrigation, laundry ranks as the 3rd highest consumer of both energy and water intensity.

Figure 4. February Energy & Water Intensity by Appliance

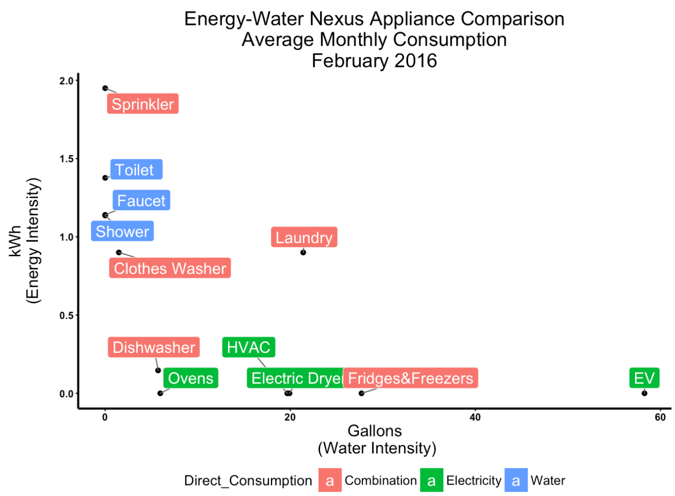
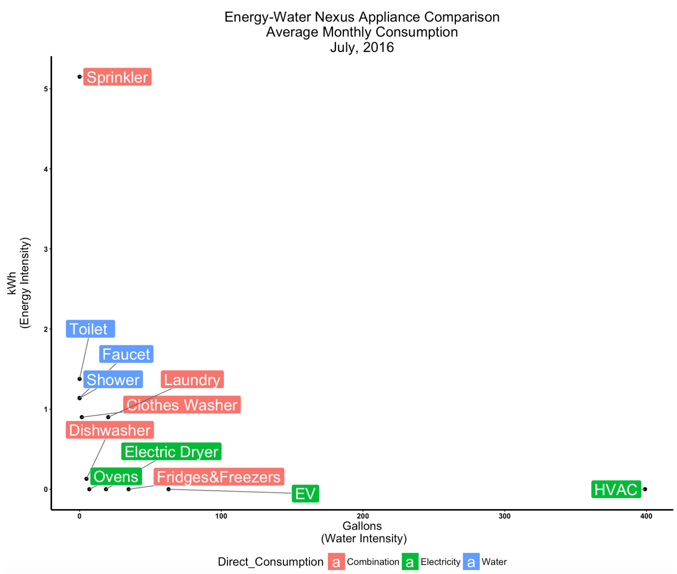


Figure 5. July Energy & Water Intensity by Appliance



Electric Vehicles

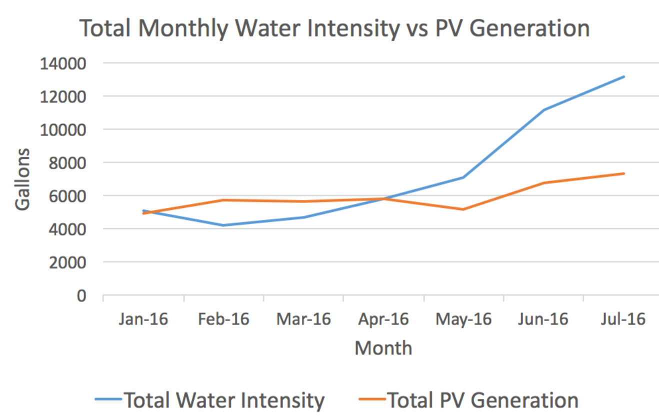
As more electric vehicles are introduced the demand for power at the residential level will increase, but will the overall demand increase? It's beyond the scope of this study, but it is worth noting that estimates of kWh required to produce 1 gallon of gasoline range from 4kWh to 6 kWh(8). Per the U.S. Department of Energy(7), the average annual gasoline consumption per car is 480 gallons, or 40 gallons per month. At 4kWh to 6kWh per gallon, that is 160kWh to 240kWh per month, water intensity of 62.9 gallons to 94.3 gallons per month per car. A complete study of water intensity with respect to residents should in some way incorporate the water intensity of the gasoline consumed by consumer vehicles.

Reduced Water Intensity Footprint with Solar

Twenty-one homes in the study with PV systems averaging 5.25 kW in size, generated 41,462 kWh of energy between January and July. The energy used by the PV systems' electronics to produce this was approximately 672.8 kWh, yielding a net of 40,789.2 kWh, equivalent to 16,029 gallons of water. The net energy produced can be thought of as an offset to energy generated by natural gas, coal, and nuclear.

The total energy consumed by these 21 homes between January and July 2016 was 51,418 kWh, equivalent to 20,205 gallons of water. Between January and May, the cumulative water intensity offset by these PV systems was more than enough to cover these homes collectively (see figure 6).

Figure 6. Water Intensity Offset by PV Generation



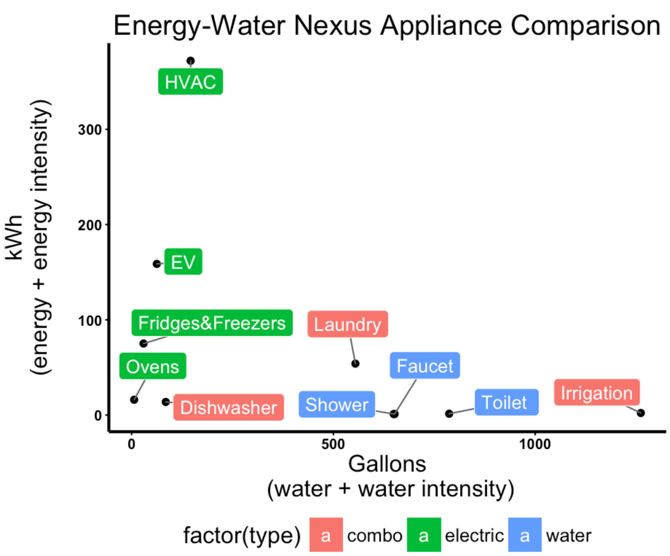
Total Water & Energy Cost

The total water cost and total energy cost have been calculated for various appliances and common household activities. All available data for each home was used to calculate the average monthly energy (kWh), water intensity (gallons), average monthly water use (gallons), and energy intensity (kWh) for each appliance.

Homes with multiple monitored appliances such as refrigerators and ovens were calculated using the total energy consumed by all monitored appliances. For example, one home has 2 refrigerators, 1 wine fridge , and 1 freezer monitored, so all four were included in that home's monthly calculation. Laundry combines the clothes washer average monthly data and the electric dryer average monthly data.

Figure 7 shows the total demand each appliance or event places on our energy and water infrastructures. Averaged over the full seven months of the study, HVAC and Irrigation are the primary consumers of energy and water respectively. Doing laundry with an electric dryer has a fairly significant impact on both water and energy demand, ranking 4th with respect to both water and energy when electric vehicle charging and irrigation are present. In the absence of electric vehicle charging and irrigation, laundry ranks as the 3rd highest consumer of both energy and water.

Figure 7. Average Monthly Total Consumption and Withdrawals by Appliance



Project Overview

Nexus – The Rest of the Equation

Energy embedded in water, or energy intensity, and water embedded in energy, or water intensity, are hidden costs which need to be quantified in order to fully understand the total cost of energy and water at the residential end-use level.

The total embedded energy consumed through direct water use, also known as the energy intensity, is the amount of energy required to distribute water to its end use. In general, the energy embedded in water arises from the sourcing of water through surface and/or groundwater pumping, the treatment of water and wastewater, the distribution to the point of use, and finally the ultimate use of the water. The energy embedded in water due to the distribution of water depends on factors including climate, temperature, rainfall, and topography.

The embedded water consumed when using electricity, also known as water intensity, is the amount of water used to generate electricity.

Methodology

Energy intensity data was provided by Austin Water and was used to calculate the embedded energy in this study to be 0.00175 kWh/gallon in Austin and 0.00145 kWh/gallon in Houston.

Water intensity data was estimated based on two reports "Value intensity of water used for electrical energy generation in the Western U.S", which uses data obtained from Sandia National Laboratory, the U.S. Environmental Protection Agency and U.S. Energy Information Administration online databases and "The Energy-Water Nexus in Texas" by M.E. Webber, et al. A working estimate has been adopted based on the findings of these studies of 0.393 gallons/kWh.

Irrigation, clothes washer, and dishwasher water use were disaggregated from the whole home water use while toilets, showers, and faucets were extrapolated based on the national average of the daily consumption of these events. The top five with respect to energy intensity are irrigation, toilet, faucet, shower, and clothes washer.

Nexus – The Rest of the Equation

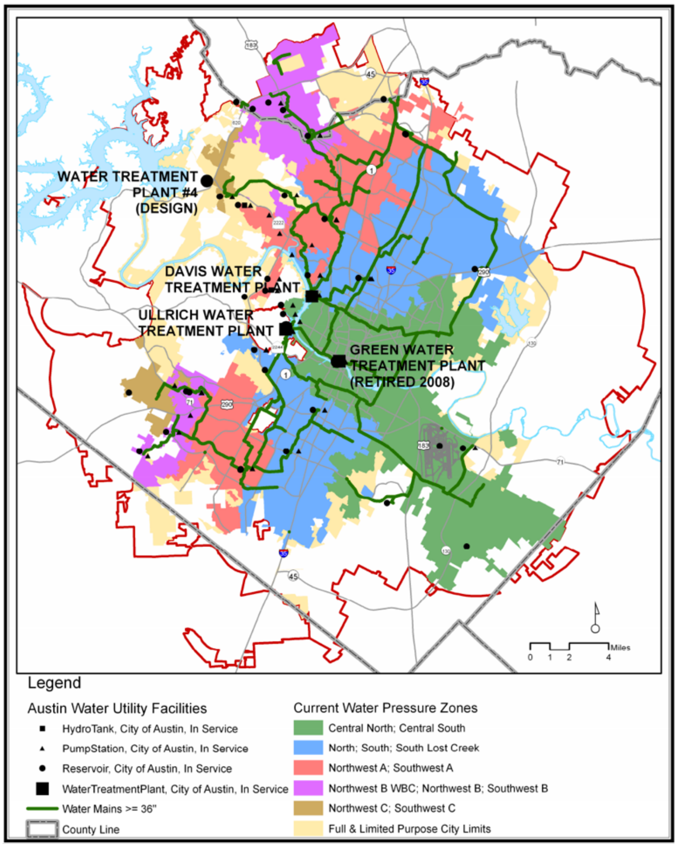
Direct water and energy end-use data is being collected by Pecan Street, but this is only half of the story. System-level data is required to the energy required to deliver clean water to end users and to understand the water required to produce electricity.

Energy Requirements for Water Supply

In general, the energy embedded in water arises from the sourcing of water through surface and/or groundwater pumping, the treatment of water and wastewater, the distribution to the point of use, and finally the ultimate use of the water. The energy embedded in water due to the distribution of water depends on factors including climate, temperature, rainfall, and topography.

Based on seven years of monthly energy intensity data provided by Austin Water for the period covering 2008 to 2014 (prior to Water Treatment Plant 4 coming online in November of 2014), average values were calculated for each pressure zone. The values provided by Austin Water include all raw and treated water pumping as well as approximately 220 kWh/MG for treatment at the Davis and Ullrich Water Treatment Plants. There is no ground pumping in Austin Water's system. Austin's energy intensity values range from 1.5 to 4.1 watt hours per gallon of water, depending on region as shown in figure 9. The Austin homes selected for this study fall into the Central/North Pressure Zone shown in figure 8. For the initial purposes of this study an average of the Central and North Zones, or 1.75 watt hours per gallon, will be assumed for all Austin homes. A 1.45 watt hours per gallon energy intensity value will be applied for all Houston homes based on the topological similarities between Austin's Central Pressure Zone and Houston.

Figure 8. City of Austin Utility Facilities & Pressure Zones



11 Dec 2009 DRAFT City of Austin Community Inventory Report (3)

Figure 9. Energy Intensity of Austin, TX Regions

Energy Intensity of Austin, TX Water

Pressure Zone (Austin)	Avg Energy Intensity (Wh/Gallon)
Central	1.45
North	2.08
South	2.16
Northwest A	2.85
Southwest A	2.89
NWB- Four Points	3.48
Southwest B	3.56
Northwest B	3.59
Northwest C	3.99
Southwest C	4.09

*calculated based on monthly values provided by the City of Austin from Jan 2008 to Aug 2014

Water Requirements for Electricity Generation

Two studies on the water embedded in energy in the Western United States and Texas have been produced and were used to calculate the water intensity figures for this report. The first report, "The energy-water nexus in Texas" by M.E. Webber, et al(1) provides water requirements for typical electricity generating facilities nationally and within Texas. The available data for Texas revealed approximately 595,000 megaliters of water annually are used to cool the state's thermoelectric power plants that generate approximately 400 terawatt-hours of electricity, or 392.96 gallons per MWh, as shown in figure 10.

The second study, "Value intensity of water used for electrical energy generation in the Western U.S", uses data obtained from Sandia National Laboratory, the U.S. Environmental Protection Agency and U.S. Energy Information Administration online databases. An explanation of the data used along with accompanied citations can be found in the referenced paper. The important takeaway from this analysis is figure 10 from that report, which shows the calculated water intensity for each of the 11 Western States in the study. This brief explanation of how the values in this table were computed along with a reference to limited data availability echoes the concerns pointed out in the first study.

> "The numbers used in this study were obtained by computing averages for each state based on water consumption of energy generation at each plant and average retail price charged by each utility within each state weighted by total energy produced by each plant and electricity sold by each utility. Note that we aggregate electrical production and distribution together as a single process; this assumption is necessitated by limited data availability."

Figure 10. Water Intensity of Power Generation by State

TABLE 1

WATER INTENSITY OF POWER GENERATION BY STATE, LISTED HIGHEST TO LOWEST, AND PRICE OF ELECTRICITY BY STATE

	Water Intensity (gal/MWh) $\Phi[s]$	Price ($/MWh) $f[s]$
New Mexico	437.25	$103.56
Utah	411.77	$81.35
Wyoming	384.17	$85.57
Colorado	352.66	$100.26
Nevada	349.23	$80.10
Montana	297.32	$81.57
Arizona	183.81	$86.23
California	129.69	$125.26
Idaho	83.31	$62.91
Oregon	82.04	$67.65
Washington	52.52	$61.65

E.A. Martin, B.L. Ruddell, Value intensity of water used for electrical energy generation in the Western U.S.; an application of embedded resource accounting (2)

The water intensity numbers for the 11 Western states range from 52.52 gallons per MWh to 437.25 gallons per MWh. The calculation from Dr. Webber's study for Texas estimated 392.96 gallons per MWh, falling in between Texas' nearest neighbors; Colorado at 352.66 gallons per MWh and New Mexico at 437.25 gallons per MWh. The project team used these values to stimate the water embedded in energy to be 0.393 gallons per kWh in Texas.

Household-Level Energy Data

Pecan Street's residential energy database, which is the nation's largest database on residential energy use available to researchers, provided 1-minute interval, circuit-level electric use data for this study for each of the 34 homes. Participating homes were instrumented with an eGauge energy monitor device by Pecan Street's Master Electrician. The eGauge device is installed inside the main electrical service and can log up to 12 current transducers (CTs) that record current flow on individual circuits. In some cases, the sub-panel is also monitored allowing data to be collected on up to 24 individual circuits. The data is stored locally on the eGauge device for up to one year to prevent loss of data in the event that communication is lost with the central server. Data is pushed to an external server every 24 hours where it is maintained, managed, and owned by Pecan Street Inc. in accordance with the organization's cybersecurity policy.

The total home energy use for 34 homes in the Austin and Houston area was monitored for 7 months, between January 1st, 2016 and July 31st, 2016.

The hardware used for energy monitoring, the eGauge, is generally more reliable than the water monitoring hardware due to proximity to the source of the data. The eGauge is mounted directly inside the electric panel where current transformers (CTs) are clamped around individual circuits. The electric data is recorded in real-time and cached locally for up to 1 year. Energy data is recoverable for all of the failure modes listed below except power outage at the residence. One home in the Houston area lost one of two eGauge systems due to flooding in the home in March. Unfortunately, the device lost was monitoring whole home electricity use causing this home to be dropped from the analysis.

Since in most cases each home was originally wired based on the preferences of the electrician doing the work, Pecan Street is limited in the set of circuits that can monitored by the eGauge. In some cases, it is not possible to know the specific appliance or device consuming electricity. For example, circuits such as 'bedroom', 'living room', 'dining room', 'garage, light & plugs', etc., are a mixture of consumer electronics, room lighting, and temporary use devices like vacuum cleaners and floor heaters.

The following is a summary of the energy circuits monitored in the homes selected for this study.

Figure 11. Monitored Circuit Sample Size

Sample Size	
Appliance	Sample Size (n)
Total_HVAC	34
Refrigerator	23
Microwave	22
ClothesWasher	22
Dishwasher	20
Dryer_Electric	18
Oven1	15
Electric_Car	10
Range	7
Dryer_Gas	7

Figure 12. Pecan Street's BluCube

Household-Level Water Data

An innovative product, developed through rigorous lab and real-world testing by Pecan Street, was used to monitor and record total residential water usage data from the participant's water meter.

The BluCube plugs into a standard outlet and records data over a secure wireless connection to the customer's existing smart and gas meters with zero impact to the meter's operation. The interval of the data read collected by the BluCube can significantly vary from home to home, from 4-second intervals to more than 15-minute intervals, because the BluCube is reading the data as it is broadcast by the meter. Meters are programmed to different reporting intervals seemingly at random.

The BluCube can be paired with most common smart water and meters, including Badger meters with Orion CE endpoints, the meters commonly found in Austin and with Itron model 60w endpoints commonly found in Houston. The data is streamed in real-time over a secure pathway and batch uploaded to Pecan Street's data center every 24 hours using cellular network or the resident's internet with no burden or risk to utility operations.

In Houston, the reporting interval of the water meters installed at participating homes was not frequent enough to enable disaggregation of the home's water use. Pecan Street has developed an additional data logging device, the BluBand, that sits on top of the meter and reads the magnetic clicks as the meter rotates when water is used, ensuring sufficient granularity of data for disaggregation. Collecting meaningful water data from Houston residences in the future will require permission from the City to install the BluBand or similar monitoring devices on top of the meter. The project team was not able to obtain permission from the City of Houston to install the devices for this project.

As with any real-world implementation, there are risks to the continuous collection of water data. The recent floods in Houston highlight one of the most common causes of data collection interruptions. When the water meter pit floods and the endpoint is submerged in water, the broadcasted meter read is muted until the pit clears. It's worth noting that many of the monthly water consumption totals for the Houston homes had to be extrapolated when gaps in meter reads spanned two months. Events leading to the interruption of water data include:

- Meter pit flooding
- Internet connectivity issues
- Device unplugged

- Power outage

The impact to the data depends on the root cause of the failure. In all cases, the whole home use is not impacted, however the granularity of the water use data may decrease proportionally to the duration of the issue. This is the case with the flooding in Houston. Around April 17th water meter pits began to fill with water and once submerged the signal was no longer detectable by the BluCube. On April 24th the first BluCubes started to collect and push data back the database. In this case it is known how many gallons were used between April 17th and April 24th, but no insight was gained into when the gallons were used during that time interval. However, it is possible to interpolate the water use based on the energy data available during the period coupled with the disaggregation model built using the available complete data for each home.

In some cases, the BluCube was unable to connect to the internet and report back to Pecan Street's database, but was still collecting meter data. All data collected is cached within the BluCube, so when connectivity is restored the data is pushed to the database with no loss of granularity.

Analysis Dataset

A total of 38 homes were originally selected for this study, 30 in Austin, TX and 8 in Houston, TX. During the first six weeks of 2016, BluCubes, gateways developed by Pecan Street to collect water use data, were installed in eight homes in Houston. In mid February three BluCubes went offline and were unrecoverable, one in Austin and two in Houston. In addition to this, one eGauge system was lost due to flooding in a Houston home, reducing the number of homes analyzed.

A total of 34 homes were therefore analyzed for this study, 29 homes in Austin and 5 homes in Houston. The energy data for homes in both cities is recorded at a 1-minute interval and measured in kW. The whole home use is available as well as some appliance-level data.

The water data collected was for the whole home in gallons at varying intervals based on the capabilities of the water meter installed at each home. In Austin, raw water meter reads are generally sub-minute and rolled up to gallons per minute in Pecan Street's curated database. In Houston, raw water meter read intervals are typically greater than 1-minute, sometimes greater than 15-minutes under normal conditions. As water meter read intervals expand beyond 1-minute the difficulty of disaggregation of the whole home water use data increases. Endpoints in Houston only broadcast meter clicks in 10 gallon increments, which is sufficient for billing but not for use disaggregation.

Severe flooding in the Houston over the course of the study resulted in multiple week gaps in water meter reads, the longest temporary outage being 53 days.

A mitigation to both issues above was planned early in the study. A special submergible data-logging Bluband was developed which could read directly from the water meter and cache data until the data-logger was retrieved. This would eliminate gaps and improve the resolution of the meter reads both in volume and time. Permission was sought repeatedly from the City of Houston to install these devices but was ultimately declined.

Water Disaggregation Methodology

To understand the amount of energy embedded in water used by various household activities, such as washing clothes, washing dishes, watering landscaping, and bathing, requires first disaggregating the whole home water use data collected by Pecan Street into individual uses.

Data disaggregation involves applying a validated algorithm to the whole home data to convert that data into appliance-level uses. No validated whole water disaggregation algorithm exists to Pecan Street's knowledge. The project team therefore developed its own algorithms and validated them through collection of use-level water data at its lab using unique water flow monitors developed by Pecan Street Inc. By characterizing common residential water use events, the team was able to construct a library of water events that can be used to develop the disaggregation algorithms.

Circuit-level electric data is required to disaggregate whole home water use into appliance-level uses. The analysis requires energy data for appliances that directly use water, such as clothes washers, dishwashers, and irrigations systems, as well as energy requirements for appliances indirectly related to water use, such as bathroom lights, clothes dryer, and kitchen appliances. The direct and indirect electric uses narrow down the possibilities for a given water usage event. For example, in a home where the energy use of the clothes washer is not directly monitored, the energy use data for the clothes dryer can help identify clothes washer events. Water flow to the clothes washer should be detected prior to the start of the clothes dryer. The volume of the water flow should help determine whether the clothes washer is a high-efficiency or older model.

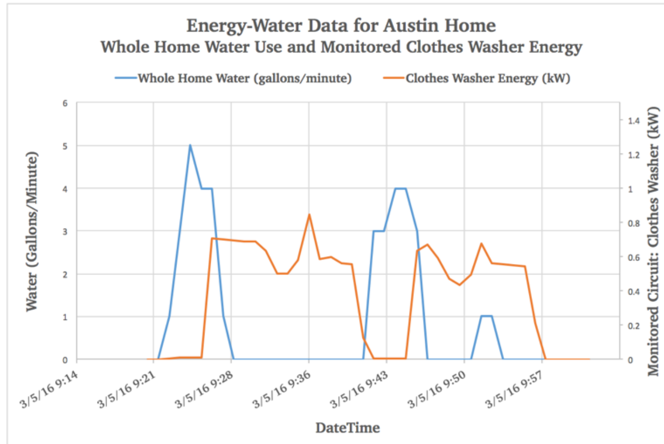
Characteristics of Water Use Events & Measurements

Pecan Street's data analyst identified six key characteristics of water use that must be understood in order to properly develop a disaggregation algorithm:

1. Resolution: the increment of water use measurements.
2. Frequency: the occurrence of water use measurements, this is the rate at which the endpoint can be read. BluBand allows us to pull sub-minute reads.
3. Duration: the length of a water use event.
4. Volume: the total amount of water flowed over a given time period.
5. Max Flow Rate: the maximum rate of water consumption over a given time period.
6. Mean Flow Rate: the volume of a water event divided by the duration of the water event.

Appliance-level end-uses, like the clothes washer water use in figure 13, can be thought of in terms of consumption rate over time.

Figure 13. Energy-Water Data for Austin Home Clothes Washer Event



Residential end-uses of water can be characterized by three types of water events:

- Type 1: Water use events from appliances that do not have a set duration or consumption pattern. Rather, the duration of the water use event is determined by the user. For example, a water use event from a shower, bath, or faucet may last a few seconds or 10 or more minutes. Generally, type 1 events have a near constant flow rate, although flow rates can be tuned up or down by the customer.
- Type 2: Water use events from appliances that have a programmed or pre-determined consumption pattern over a single time interval. For example, a toilet bowl that fills after a flush. Type 2 events will typically have a constant flow rate for a fixed amount of time.
- Type 3: Water use events from appliances that have a programmed or pre-determined consumption pattern over multiple time intervals.

  For example, a washing machine, dishwasher, or automatic irrigation system are programmed to operate according to a fixed schedule. A single type 3 event, such of a load of laundry, is actually composed of several smaller water events that are separated in time. Distinguishing type 3 water use events from whole-home data may be difficult because they may be easily mistaken for type 1 or type 2 water use events. Please note that a programmed pattern does not necessarily mean the flow pattern or flow volume are the same every time. Modern clothes washers, for example, will sense load balance and weight and can adjust flow or repeat actions until a desired outcome is achieved.

- Type 4: All other events that are not identifiable by flow rate, duration, pattern, or time. General leaks are type 4 events.

The chart above (see figure 13) shows an example of a Type 3 residential end-use event using data collected from one of the Austin homes in this study.

Figure 14. Energy-Water Data Minutely Values for Austin Home Clothes Washer Event

Water Energy Detailed Data		
DateTime	Whole Home Water (gallons)	Clothes Washer Energy (kW)
3/5/16 9:21	0	0
3/5/16 9:22	0	0
3/5/16 9:23	1	0.007
3/5/16 9:24	3	0.008
3/5/16 9:25	5	0.008
3/5/16 9:26	4	0.008
3/5/16 9:27	4	0.707
3/5/16 9:28	1	0.703
3/5/16 9:29	0	0.694
3/5/16 9:30	0	0.691
3/5/16 9:31	0	0.687

Figure 14 contains the first 11 minutes of actual data pulled from the Pecan Street database. This is an example of how circuit-level electric data can assist in the disaggregation of whole home water data. The blue line plots the flow of whole home water data measured in gallons at a 1-minute interval. The red line plots the energy consumption in kW of the clothes washer at a 1-minute interval.

The 8 watts of power used by the clothes washer in the first 4 minutes is the homeowner turning on the washer and selecting the program to run. Before the first minute is up the washer begins to fill with water. Over the next 4-5 minutes the washer fills with 18 gallons of water and then begins its cycle using more power, around 700 watts, to agitate the water and clothes. Around 9:40am, the power quickly reduces and more water is added, representing the rinse mode. Once the water use rate reduces, the power increases again to begin the spin cycle. It's interesting to note that around 9:52am 2 gallons of water flows and then shuts off, this is either a second rinse and spin cycle or someone flushing a toilet. Given the drop and rise in power at the same time as the water flows suggests it is a second rinse cycle.

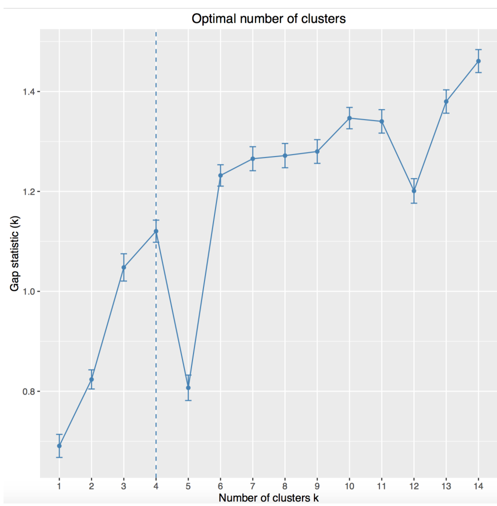
Water Disaggregation at the Appliance Level

Clothes washer and dishwasher appliances were disaggregated using the electricity data collected. First, all 1-minute time intervals with more than 7 watts of power were pulled for each home between January 1st and July 31st, 2016. The threshold of 7 watts was selected in order to exclude all intervals where a smart device is in stand-by mode. Next, "washer events" are identified by stepping through the ordered list of 1-minute intervals with power greater than 0.007 kW. Each event is numbered and key information and statistics are calculated; start time, end time, duration in minutes, peak power (kW), average power (kW), and total kWh.

Now a collection of events describing when and how a given homes' washer has run exists. Please note, a "washer event" does not necessarily represent a full cycle of a given appliance. In some cases, the power draw from an appliance may fall below the 7-watt threshold as it switches operation, say from a soak to a spin. Events are grouped by similar behavior and the whole home water consumption is analyzed for the duration of each event.

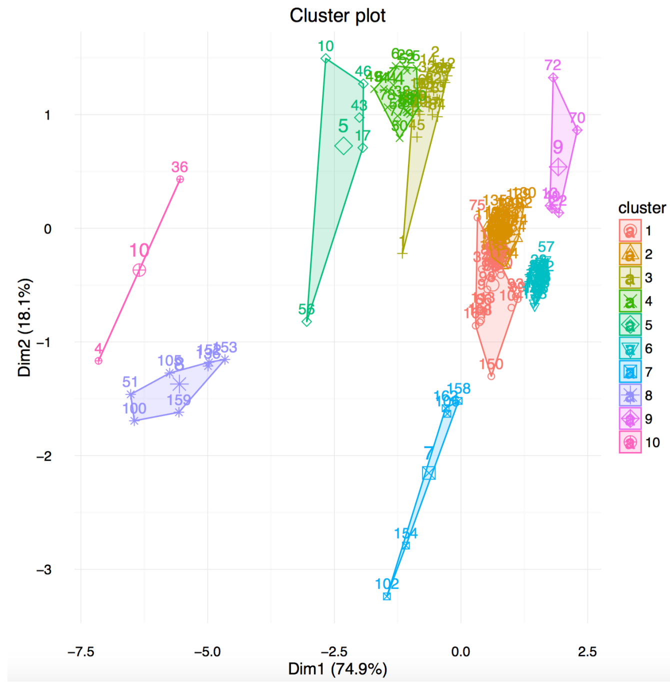
To group the events defined above an unsupervised learning technique called K-means clustering was employed using the gap statistics for identifying optimal numbers of clusters. Each of the homes being analyzed presumably has a different make and model of washer and uses different cycles and programs based on the needs of the family. It is not yet determined how many groups, or clusters to look for, so the gap statistic is used to identify the best choices. An example (see figure 15) from one of the homes in our study, k=4 and k=10 are candidates.

Figure 15. Gap Static Number of Clusters Analysis



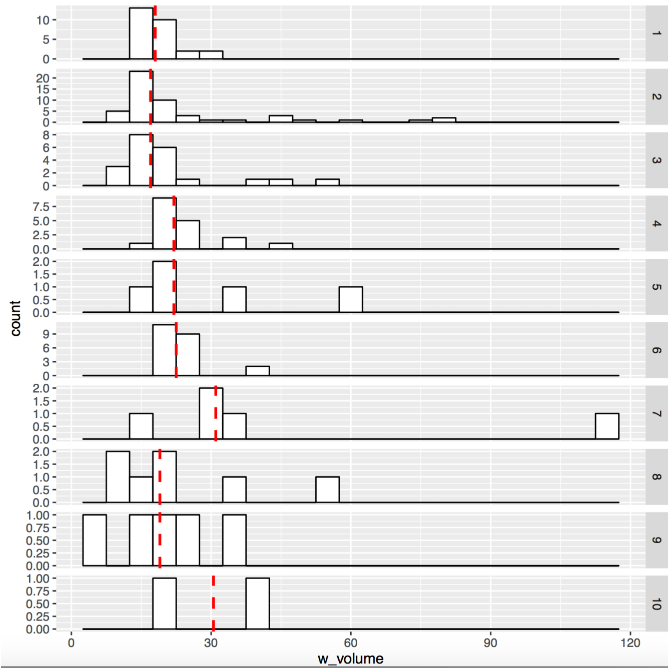
Once an estimate is determined for the number of clusters to look for, the K-means clustering algorithm can be applied to all of the "washer events" at each home separately. Like events are grouped together based on the event characteristics previously discussed; duration, peak power (kW), average power (kW), and total kWh (see figure 16).

Figure 16. Clothes Washer k-means Cluster Analysis



At this point a cluster number, 1-10, has been assigned to each "washer event". Now the whole home water consumption is calculated for between the start and end timestamps of each "washer event". The water consumption distribution for each cluster is analyzed. Notice (see figure 17) that the distributions are skewed towards the minimum (as expected). A minimum can't be chosen because some events will have a volume of 0 gallons if the water meter hasn't reported in or a volume less than the actual volume for the event if the water meter stops updating reads while the event is in progress. The water volume for each cluster was estimated using the median of the distribution for the clothes washer analysis and the 23rd percentile for the dishwasher analysis.

Figure 17. Water Distribution by Clothes Washer Cluster Number



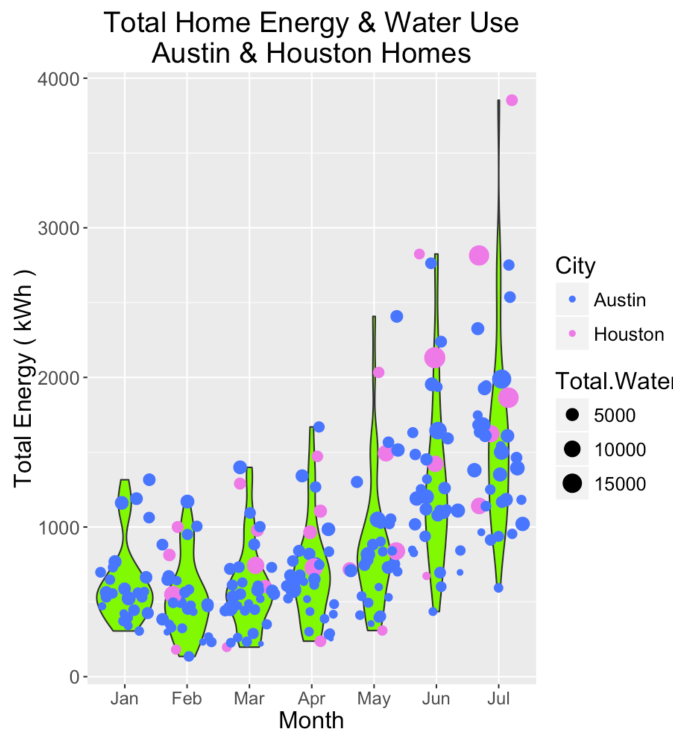
Energy-Water Nexus Analysis

Total Home Energy and Water Use

Understanding water intensity and energy intensity at the residential level first requires understanding of total home energy and water consumption. The total monthly energy and water use for each home in our study can be seen in figure 18. Monthly energy use ranges from a couple hundred to nearly four thousand kWh between January 1st and July 31st, while total monthly water consumption ranges from 545 gallons to 18,890 gallons during the same period. The total monthly water volume is represented by the size of the dot, which represents each home in the study, with Austin homes blue and Houston homes purple. The total water consumption is only shown when a complete month of data is available which is why no Houston homes are shown in January. Water monitoring installation was completed for all but one Houston home during the first two weeks of January, with the final home installation completing mid-February.

The distribution of the total home energy consumption for all of the homes in the study can be seen in the green violin plots. These are best visualized as a histogram turned on its side, it gives a better understanding of the distribution of whole home kWh in each month. The fattest part of the "violin" represents the median of the distribution, the point where 50% of the values lie above and 50% lie below.

Figure 18. Total Home Energy & Water Use



Breaking out the Austin and Houston home data a few things become apparent. The overall behavior of both groups is similar (see figures 19 & 20). The energy distributions stretch as the homes enter the spring and summer months while the minimums increase. The primary driver for this movement is the increase in temperature which directly correlates to an increase in power consumed by HVAC systems. The stretching of the energy distributions is likely due to the variation in the size of the homes in the study, more specifically, the variation in the volume of air being cooled.

The total energy and water consumption of the Austin homes is less than the Houston homes. This could be due to the small sample size of Houston homes. The majority of the 29 Austin homes are located in the Mueller neighborhood and active participants in Pecan Street, many of whom actively work toward or have achieved or exceeded parity with respect to the amount of energy they consume and the about of energy they produce. These homes tend to skew toward minimal energy and water consumption.

Figure 19. Total Home Energy & Water Use Austin Homes

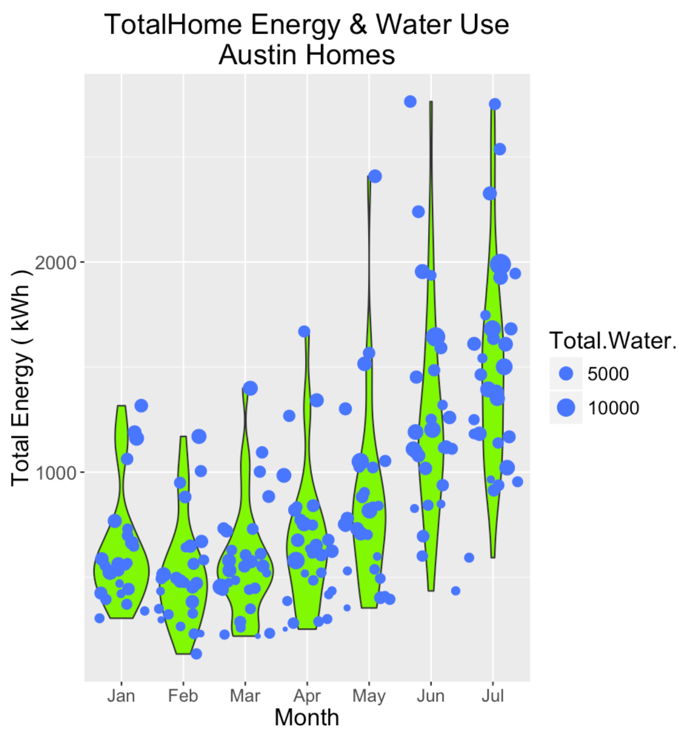
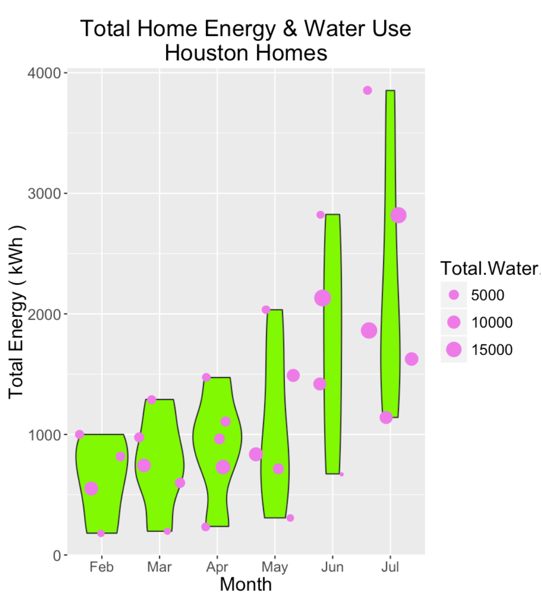


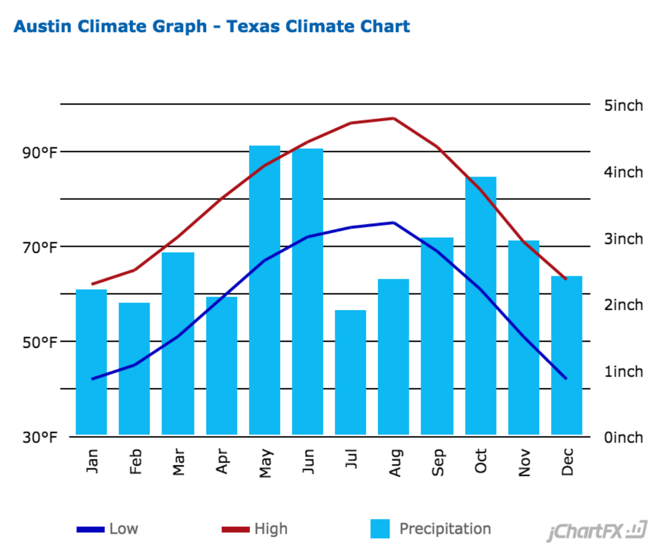
Figure 20. Total Home Energy & Water Use Houston Homes



Energy Consumption

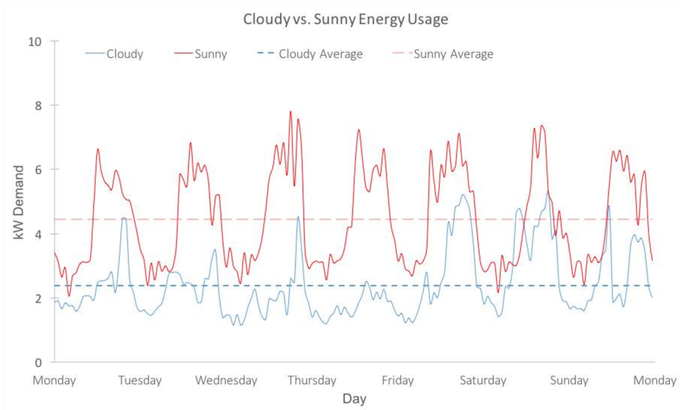
The slight dip in monthly energy consumption followed by the sharp non-linear increases in Figure 19 are primarily due to the total HVAC electricity consumption. Total HVAC includes compressors, fans, and furnaces so when the furnace or compressors are working harder and turning on more frequently the total electricity consumption increases. This makes sense for homes in Texas (see Figure 21) where temperatures in January and February are cold enough to have heaters on, with March and April temperate enough to not require heating or cooling, and finally a steady climb in overall temperature from May to July when we see air conditioners come on, resulting in an increase in consumption.

Figure 21. Austin Climate Graph (4)



May and June typically bring the most rain of the year which also tends to bring temperatures down and require less energy for cooling. Austin had an exceptionally rainy May with 7.09" falling, while June was below average with 3.08". Figure 22 compares the power demand at one of the Austin homes during two weeks in August, one a sunny week and the other a cloudy week. A difference in average power demand of 2kW means 48kWh per day, or 18 gallons a day. The total energy consumption of the home plotted in Figure 22 is well above the average in this study. It had an average daily water intensity in July of 34.9 gallons, the third highest water intensity of all the homes in this study.

Figure 22. Power Demand Comparing Cloudy and Sunny Days – Austin Home August



Water Intensity Calculations

Per Home Water Intensity Calculation

The total water intensity for the 34 homes between January and July 2016 is 81,733 gallons, with July accounting for 26.3% of the total at 21,487 gallons. February accounted for only 8% (6,512 gallons) of the total water intensity. The average monthly water intensities range between 203.5 and 632.0 gallons, with the first four months of the year averaging below 300 gallons per month.

Water Intensity of Appliances

To understand water intensity at an appliance level, a disaggregated account of how electricity is used in the home must be determined. As previously mentioned, the homes selected for this study have their electric sub panel circuits monitored by eGauge monitoring systems. This allows the total energy consumed for each monitored appliance at any interval, daily, weekly, monthly, etc., to be pulled and recorded. The resolution of the energy data is 1-minute intervals. Analysis was restricted to available appliances directly related to water use or those which consumed large amounts of power.

For each appliance, the average of all of the homes with data available was calculated for each month. Homes with no reported data were ignored as were homes with zero use reported were included in the average. For example, homes report zero or near zero use consumption on air conditioning circuits in January were included in the average to reflect the behavior.

The top four appliances with respect to water intensity are HVAC, electric car charger, refrigerator, and electric dryer. Two very distinct groups emerge in the tables below (see figure 23). The bottom six appliances maintain water intensities below 7 gallons in each month, while the top four appliances vary considerably and even swap ranking throughout the months. The most volatile being HVAC which shifts rankings from 3rd to 5th then back to the 3rd position and finally holds the 1st position from April through July. In July the average HVAC water intensity of 399 gallons is a staggering 525% higher than the 2nd ranked appliance, electric car.

For the purposes of this comparison only the main appliance in each category was used. In other words, when multiple similar appliances were monitored like two refrigerators or two ovens, only the primary appliance was used. This will be revisited this at the end of the report when the total appliance activity per home per month is averaged and compared to overall consumption per appliance category. Total HVAC is the one exception, it has been treated as one "appliance", all air circuits, which contain air compressors, as well as all furnace circuits, which contain the furnace and air handlers, are included in the water intensity calculation.

Figure 23. Monthly Average Water Intensity per Appliance

Monthly Average Water Intensity Per Appliance

January	
Appliance	Water Intensity (Gallons)
Electric_Car	67.3
Total_HVAC	32.7
Dryer_Electric	24
Refrigerator	21.9
Dishwasher	6.1
Oven1	6
Range	4.7
Microwave	3.7
Dryer_Gas	2.3
ClothesWasher	1.7

February	
Appliance	Water Intensity (Gallons)
Electric_Car	58.3
Refrigerator	20.7
Dryer_Electric	19.9
Total_HVAC	19.7
Dishwasher	5.7
Oven1	5.7
Range	4
Microwave	3.3
Dryer_Gas	1.7
ClothesWasher	1.5

March	
Appliance	Water Intensity (Gallons)
Electric_Car	63.2
Total_HVAC	37.5
Refrigerator	24
Dryer_Electric	19
Oven1	6.4
Dishwasher	5.2
Range	3.9
Microwave	3.4
Dryer_Gas	2
ClothesWasher	1.7

April	
Appliance	Water Intensity (Gallons)
Total_HVAC	76.8
Electric_Car	69.4
Refrigerator	25.3
Dryer_Electric	18.2
Oven1	6.1
Dishwasher	5.3
Microwave	3.3
Range	3.2
Dryer_Gas	1.7
ClothesWasher	1.4

May	
Appliance	Water Intensity (Gallons)
Total_HVAC	143.1
Electric_Car	45.9
Refrigerator	25.8
Dryer_Electric	18
Oven1	6.4
Dishwasher	5.2
Microwave	3.2
Range	3.1
Dryer_Gas	2.6
ClothesWasher	1.7

June	
Appliance	Water Intensity (Gallons)
Total_HVAC	298.2
Electric_Car	70.4
Refrigerator	25.8
Dryer_Electric	17.4
Oven1	5.6
Dishwasher	5.3
Microwave	3.1
Range	2.6
Dryer_Gas	2.2
ClothesWasher	1.8

July	
Appliance	Water Intensity (Gallons)
Total_HVAC	399
Electric_Car	62.8
Refrigerator	29
Dryer_Electric	18.7
Oven1	6.7
Dishwasher	4.9
Range	3.4
Microwave	3
Dryer_Gas	2
ClothesWasher	1.6

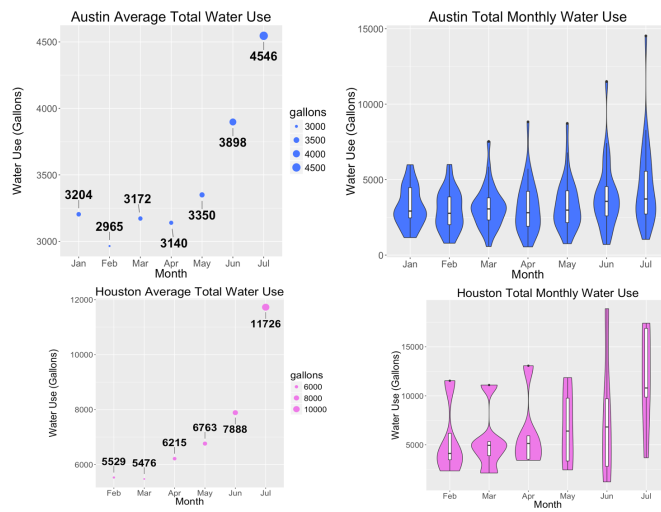
Sample Size	
Appliance	Sample Size (n)
Total_HVAC	35
Refrigerator	23
Microwave	22
ClothesWasher	22
Dishwasher	20
Dryer_Electric	18
Oven1	15
Electric_Car	10
Range	7
Dryer_Gas	7

Total Monthly Water Consumption

The total water consumption for the 34 homes between January and July 2016 is 916,399 gallons (or an energy intensity of 1,540 kWh), 20% (212,414 gallons or an energy intensity of 308 kWh) from the Houston homes and 80% (703,985 gallons or an energy intensity of 1,232.0 kWh) from the Austin homes. July accounted for 20.5% of the total water consumption at 190,468 gallons, however, 30.8% (58,630 gallons) from the Houston homes and 69.2% (131,838 gallons) from the Austin homes. In fact, the monthly water consumption of the Houston homes was between 1.7 and 2.6 times that of the Austin Homes (see figure 24). February accounted for only 11.8% (108,086 gallons) of the total water consumption between January 1st and July 31st, with Houston contributing 17.6% (22,117 gallons) and Austin contributing 82.4% (85,979 gallons).

Figure 24. Total Water Use by City

Total Monthly Water Use

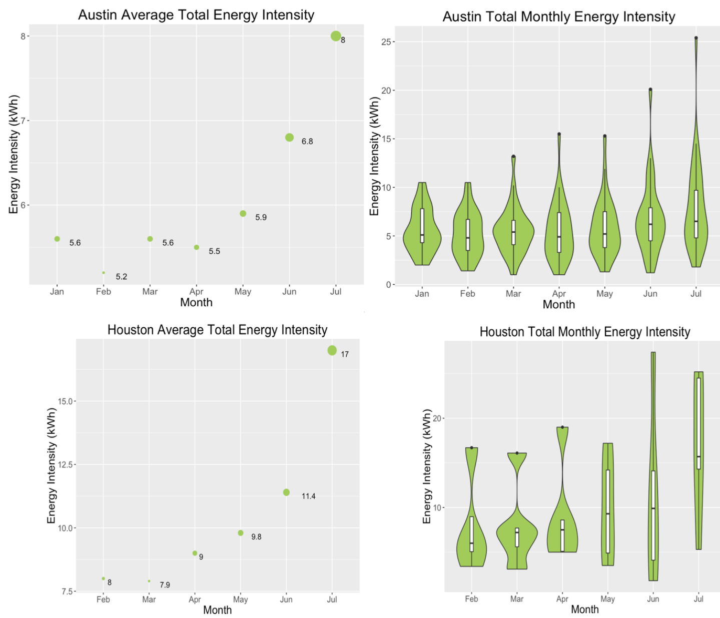


The impact of flooding in the Houston area on water consumption is clear in figures 24 and 25, notice the total water and average total energy intensity in February and March are the lowest value by quite a bit (Houston's graph starts with February).

Energy Intensity Calculations

The average daily energy intensity for the homes in Austin range between 5 and 6 kWh from January through April, then increase to 7 kWh in June, and 8 kWh in July. In Houston, homes start around 8 kWh in February and March, then increase approximately 1 kWh per month between April and June, and finally increase 5.6 kWh from June to July ending up at 17 kWh. In fact, both Austin and Houston show significant increases in energy intensity between May and July. This should sound familiar, the increasing temperatures and heavy rain in June followed by little rain in July that drove significant increases in energy consumption by the HVAC system are driving increases in water consumption.

Figure 25. Average Monthly Energy Intensity per Household



Energy Intensity of Water Events

Irrigation Systems

Irrigation Systems are the HVACs of the energy intensity world. No other water use comes close to the volumes of water used by sprinklers, which in many cases is an order of magnitude greater the biggest indoor water uses like toilets, faucets, and showers. The average monthly irrigation water use and energy intensity numbers in figure 26 represent 6 to 13 homes in the Austin area. The non-linear increase observed is due to climate and weather which influences how much and whether home owners water.

Figure 26. Average Irrigation Use per Household

Average Irrigation Use Per Household		
Month	**Water Use Gallons**	**Energy Intensity (kWh)**
Jan	1120.8	1.96
Feb	1113.0	1.95
Mar	1175.9	2.06
Apr	1410.2	2.47
May	1630.4	2.85
Jun	2496.1	4.37
Jul	2940.8	5.15

Clothes Washers

The homes in the study used an average of 535 gallons of water per month (see figure 27), for washing clothes (20 homes). The average daily water use for clothes washers in our study is 17.7 gallons.

Figure 27. Clothes Washer Average Water Use

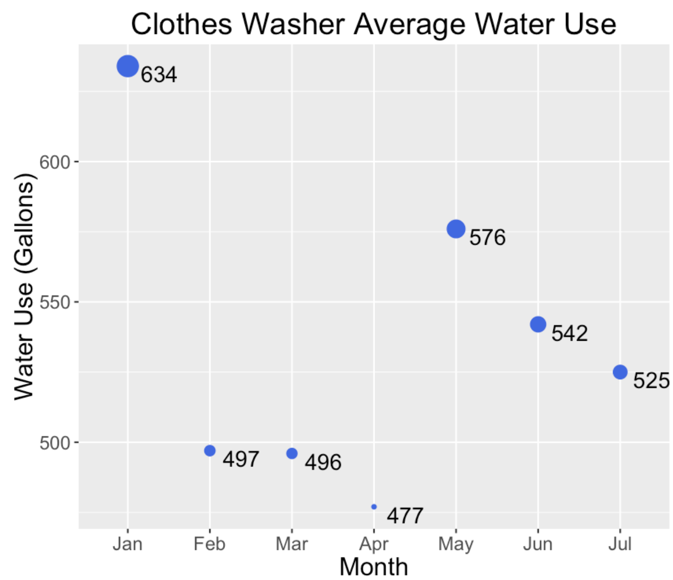
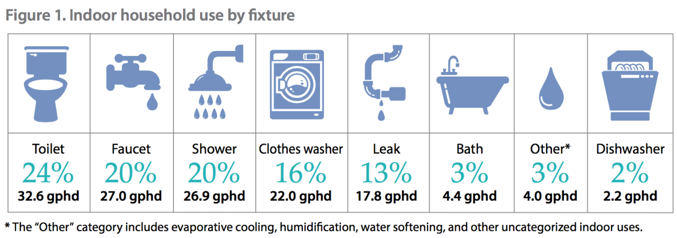


Figure 22

In April, 2016, the Water Research Foundation published a follow up to the 1999 report, *Residential End Uses of Water* (REU1999), (Mayer et al. 1999). The new report, *Residential End Uses of Water, Version 2* (REU2016) (DeOreo et al. 2016)(5), encompassed approximately 1,000 homes randomly selected from 23 utilities, 22 in the United States and 1 in Canada. The study was divided into two categories for analysis, indoor household use and outdoor household use. The study found that the national average water consumption for clothes washers was 22.0 gphd (see figure 28), 4.3 gallons higher than the average for the homes in Mueller. One possible reason for this a higher ratio of high-efficiency, and more specifically front-end loading high efficiency washers.

Figure 28. Daily Indoor Household Use by Fixture



According to a recent survey conducted by Pecan Street, approximately 71% of the homes in this study said they had a front-end loading clothes washer. Consumer Reports advises that front-end loading clothes washers, "as a group these typically clean better than HE top-loaders and use less water …. most scored excellent in water efficiency meaning they used about 13 gallons of water or less to wash an 8-pound load."(6)

Clothes washers monitored in the homes have an average energy intensity of just under 1 kWh (940 watt hours) per month (see figure 29). The monthly energy intensity distribution range from 0.03 kWh to 3.3 kWh a month (see figure 30).

Figure 29. Clothes Washer Average Monthly Energy Intensity

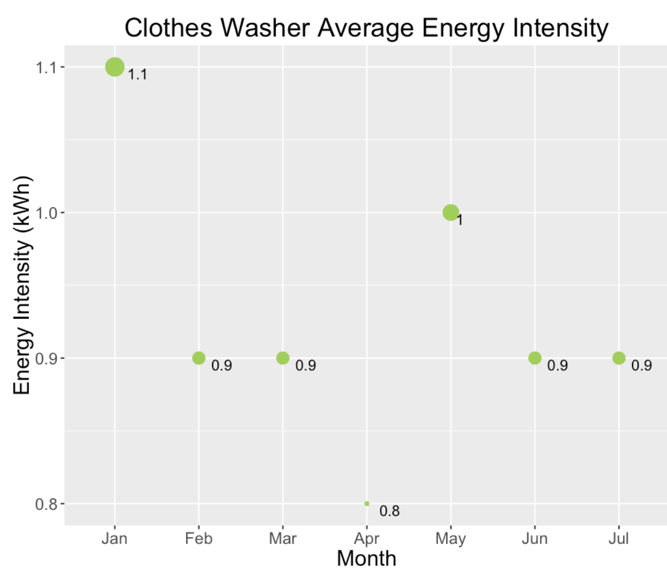
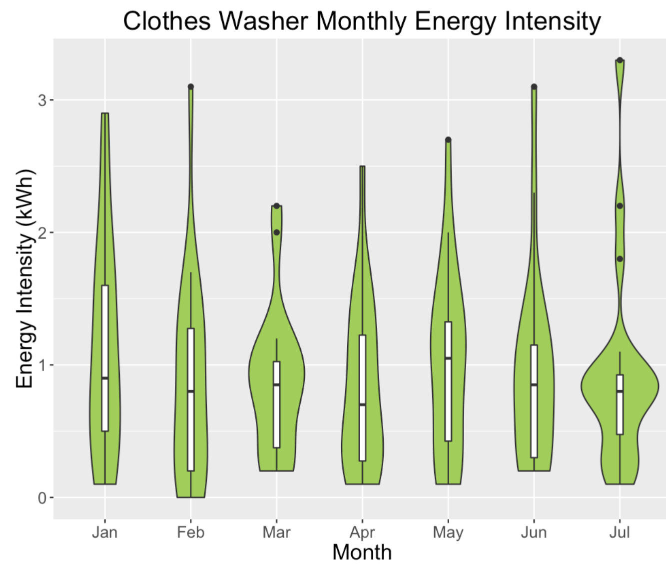


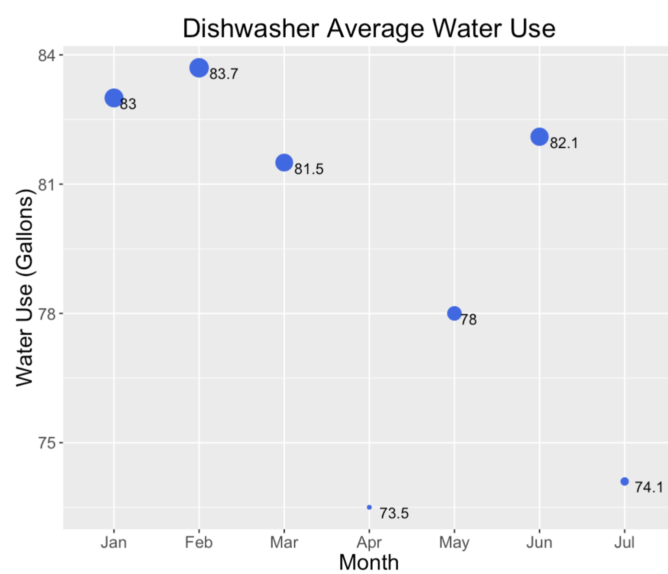
Figure 30. Clothes Washer Monthly Energy Intensity Distribution



Dishwashers

The dishwashers monitored in the study used an average of 79.4 gallons of water per month, or 2.6 gallons per household day (see figure 31), just 0.4 gallons over the national average reported in *Residential End Uses of Water, Version 2* (REU2016).

Figure 31. Dishwasher Monthly Water Use



The average energy intensity of 139 watt hours per month (see figure 32) is very stable. Juxtaposing the clothes washer and dishwasher energy intensity distributions, additional variability can be observed in clothes washer data (see figure 33). This is likely due to two things, clothes washers have a wider range of water consumption and some smart clothes washers adjust cycles and water use based on feedback such as load balance. The monthly energy intensity distribution ranges from 0.02 kWh to 0.45 kWh a month with a slight stretching in July.

Figure 32. Dishwasher Average Monthly Energy Intensity

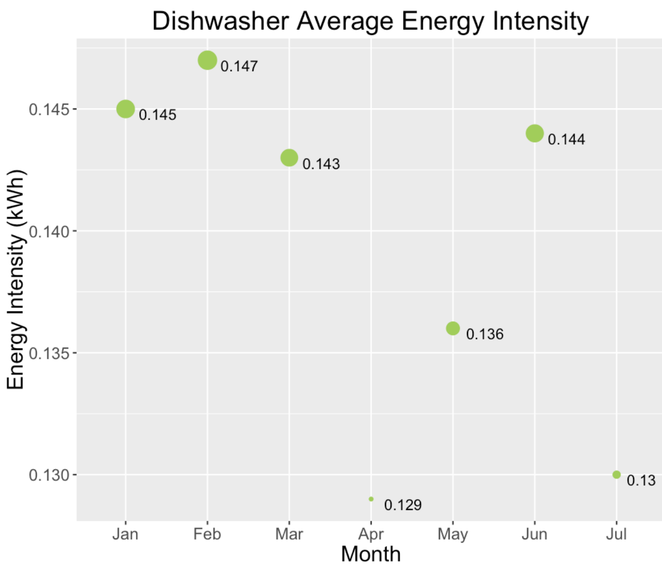
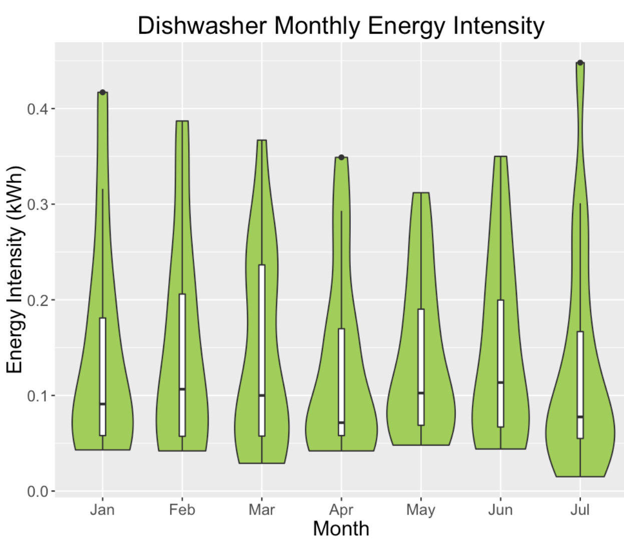


Figure 33. Dishwasher Monthly Energy Intensity Distribution



Other Water Events

Water events like toilets, faucets, and showers have been extrapolated based on the results of the clothes washer disaggregation work and the results of the *Residential End Uses of Water, Version 2* report representing the nation averages of select indoor water events (see figure 34).

Figure 34. Extrapolated Water Use for Toilet, Faucet, and Shower

	Water Research Foundation	PecanStreet	
	National Average (gphd)	Extrapolated (gphd)	Extrapolated (gphm)**
Toilet	32.6	26.2	786.8
Faucet	27	21.7	651.7
Shower	26.9	21.6	649.3
Clothes Washer	22	**17.7***	[redacted]
*Based on dissagregation of PecanStreet Data ** gallons per household month			

Energy-Water Nexus, Bringing it All Together

Whole Home and End-Use Analysis

The total energy and water cost calculation for a given appliance-level event requires four values.

For a given event,

$$\begin{aligned}&\textit{Total energy and water cost}\\&= \textit{total direct energy use} + \textit{total direct water use}\\&+ \textit{total energy embedded in direct water use}\\&+ \textit{total water embedded in direct water use}\end{aligned}$$

This can only be done after a specific event for a given appliance in the database has been identified and then the total directly consumed energy and water over time for that event can be calculated. After those values have been determined using the appropriate energy and water intensity value for the given home, we can compute the energy and water embedded in the use.

Let the following functions represent the identification and calculation of water and energy for a given appliance performing a given end-use.

Figure 35. Total Energy and Water Cost Functions

Function	Description
$\omega(i)$	For appliance, i, this function returns the total water used for a given activity
$\varepsilon(i)$	For appliance, i, this function returns the total energy used for a given activity
$\omega \rightarrow \varepsilon(i)$	For appliance, i, this function returns the total water embedded in the energy used for a given activity
$\varepsilon \rightarrow \omega(i)$	For appliance, i, this function returns the total energy embedded in the water used for a given activity

Using these functions, total energy and water cost equation becomes,

$Total\ energy\ and\ water\ cost = \varepsilon(i) + \omega(i) + \varepsilon \rightarrow \omega(i) + \omega \rightarrow \varepsilon(i)$

Some residential activities are the combination of several appliance-level activities. For example, "doing laundry" typically involves two activities, washing clothes and drying clothes. To understand the total energy and water cost of "doing laundry" the total energy and water cost for washing clothes and for drying clothes must be combined. "Doing laundry" can be mathematically represented by first representing the appliances needed to complete the task in a set.

Let *clothes washer* be represented as *CW* and *electric clothes dryer* be represented as *CDe.*

Let A = $\{CW|CDe\}$, here A represents the set of appliances used in the activity of "doing laundry".

To calculate the total water and energy cost of "doing laundry", start with the set of appliances required to complete the task and sum over the set.

Given A = $\{CW|CDe\}$

Total water cost = $\sum_{i \in A} \omega(i) + \omega \rightarrow \varepsilon(i)$

Total energy cost = $\sum_{i \in A} \varepsilon(i) + \varepsilon \rightarrow \omega(i)$

Where,

$Total\ Water\ Cost\ of\ doing\ laundry = \sum_{i \in A} \omega(i) + \omega \rightarrow \varepsilon(i) \Rightarrow \omega(CW) + \omega \rightarrow \varepsilon(CW) + \omega(CDe) + \omega \rightarrow \varepsilon(CDe)$

and,

$Total\ Energy\ Cost\ of\ "doing\ laundry"$

$= \sum_{i \in A} \epsilon(i) + \varepsilon \rightarrow \omega(i) \Rightarrow \varepsilon(CW) + \varepsilon \rightarrow \omega(CW) + \varepsilon(CDe) + \varepsilon \rightarrow \omega(CDe)$

Since no water is used when drying the clothes, the following functions evaluate to zero.

$\omega(CDe) = \epsilon \rightarrow \omega(CDe) = 0$, and

$Total\ Water\ Cost\ of\ doing\ laundry = \omega(CW) + \omega \rightarrow \varepsilon(CW) + \omega \rightarrow \varepsilon(CDe)$

$Total\ Energy\ Cost\ of\ "doing\ laundry"$

$= \varepsilon(CW) + \varepsilon \rightarrow \omega(CW) + \varepsilon(CDe)$

This makes sense, the total water cost of "doing laundry" is the water used to wash the clothes plus the water embedded in the energy used to run the clothes washer plus the water embedded in the energy used to dry the clothes. The total energy cost of "doing laundry" is the energy used to run the clothes washer plus the energy embedded in the water used to wash the clothes plus the energy used to run the electric dryer.

Total Water & Energy Cost

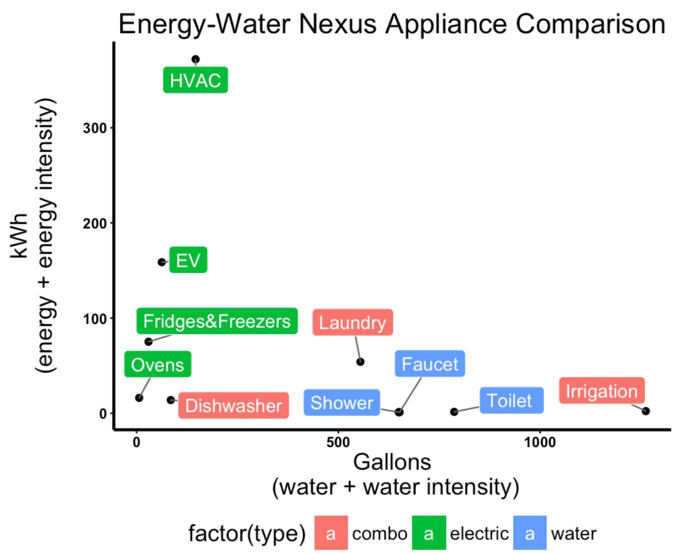
Using the methodology described above, the total water cost and total energy cost have been calculated for various appliances and appliance-level activities. All available data for each home was used to calculate the average monthly energy (kWh), water intensity (gallons), average monthly water use (gallons), and energy intensity (kWh) for each appliance.

Toilet, faucet, and shower water use and energy intensity were calculated based on the extrapolated gallons per household day (gphd) discussion previously using Austin's energy intensity factor of 0.00175 kWh/gallon.

Homes with multiple monitored appliances such as refrigerators and ovens were calculated using the total energy consumed by all monitored appliances. For example, one home has 2 refrigerators and 1 freezer monitored, so all three were included in that home's monthly calculation.   Laundry combines the clothes washer average monthly data and the electric dryer average monthly data.

Figure 36 shows the total demand each appliance or event places on our energy and water infrastructures. Averaged over the full seven months of the study, HVAC and Irrigation are the primary consumers of energy and water respectively. Doing laundry with an electric dryer has a fairly significant impact on both water and energy demand, ranking 4th with respect to both water and energy when electric vehicle charging and irrigation are present. In the absence of electric vehicle charging and irrigation, laundry ranks as the 3rd highest consumer of both energy and water.

Figure 36. Total Water & Energy Cost Comparison by Appliance & Household Event



1. Copyright © 2011 by the author(s). Published here under license by the Resilience Alliance. Stillwell, A. S., C. W. King, M. E. Webber, I. J. Duncan, and A. Hardberger. 2011. The energy-water nexus in Texas. Ecology and Society 16(1): 2. [online] URL: http://www.ecologyandsociety.org/vol16/iss1/art2/
2. E.A. Martin, B.L. Ruddell, Value intensity of water used for electrical energy generation in the Western U.S.; an application of embedded resource accounting
3. 11 Dec 2009 DRAFT City of Austin Community Inventory Report
4. http://www.usclimatedata.com/climate/austin/texas/united-states/ustx2742
5. Residential End Uses of Water Version 2, Executive Report, Water Research Foundation, April 2016, ISBN 978-1-60573-236-7
6. http://www.consumerreports.org/cro/news/2015/04/washing-machines-that-save-water-and-money/index.htm
7. http://www.afdc.energy.gov/data/10308
8. In a 2008 report, Argonne National Lab estimated that the efficiency for producing gasoline of an "average" U.S. petroleum refinery is between 84% and 88% (Wang, 2008), and Oak Ridge National Lab reports that the net energy content of oil is approximately 132,000 Btu per gallon (Davis, 2009). It is commonly known that a barrel of crude oil generate approximately 45 gallons of refined product (refer to NAS, 2009, Table 3-4 for a publication stating so). Thus, using an 85% refinery efficiency and the aforementioned conversion factors, it can be estimated that about 21,000 Btu—the equivalent of 6 kWh—of energy are used per gallon of gasoline refined: