Characterizing the Urban Water-Energy Nexus

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INTRODUCTION

What is the WEN? It's the symbiotic ***relationship between water and energy*** which this project aims to characterize in two ways: in terms of energy generation and its influence on the outdoor environment, and at a fundamental physical level.

Water for cooling machinery in power plants accounts for the largest withdrawal of freshwater in the United States. Princeton's power plant uses 97 million gallons of water a year for cooling. We are particularly interested in cooling towers, where on hot water is pumped above ground, aerated and cooled with large fans (Figure 2). Since there are thousands of power plants nationwide, ***we want to know if they influence local humidity levels. Is vapor emitted from cooling towers sensible and can it be tracked?***

Solar radiation tends to become trapped in dense cities, creating urban heat islands**.** ***In characterizing this natural phenomenon during wet conditions,*** we focused on Andlinger Center's sunken courtyards, which can represent two types of urban heat islands; those with more "grey" concrete land surfaces and those with more "green" vegetative land surface cover (Figure 3). In urban areas both of these issues are important because local ***outdoor conditions influence thermal comfort*** and air conditioning usage, an extremely energy-intensive household appliance.

METHOD & PROCEDURES

Cogeneration Plant Experiment

- In five separate experiments, four to six ***RH/DBT (relative humidity/dry blub temperature) sensors*** (Figure 1) were placed on and around the cooling tower platform (~15m high), at ground level, and at ground locations ~110m to the north, south, east and west.
- We later improved the accuracy of our sensor data by programming a ***GPS sensor in combination with a RH/DBT sensor, installing them on a bicycle*** and cycling a ~1 km circumference around the cooling towers. This method yields continuous sensing in a full 360 degree circumference around the towers and exactly corresponding latitude/longitude positions (Figure 2).
- ***Wind direction and speed was recorded*** every ten minutes from Princeton's campus weather station (970m away) and a dominant direction is determined. This allows us to determine a direction we expect to see increased humidity levels for a particular duration of time.

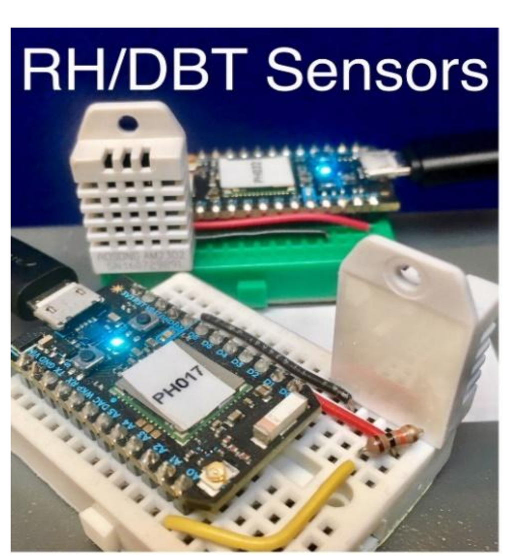

Figure 1. Arduino Protons, inexpensive RH/DBT distributive sensors used in both experiments.

Sunken Courtyards Experiment

- Over five experiments, two to six ***RH/DBT Sensors*** were placed in each courtyard for an average of 4 hours, especially on days of rain followed by sun.
- On wet days ***infrared images were taken hourly in both courtyards with a FLIR e60*** to observe mean radiant temperature as wet surface water evaporated. On dry days infrared images were taken in both courtyards to observe any difference between MRT in a more green or more grey surface space.
- DBT and RH in the courtyards is ***then compared to local weather data***, obtained from the campus weather station (560m away).

RESULTS & DISCUSSION

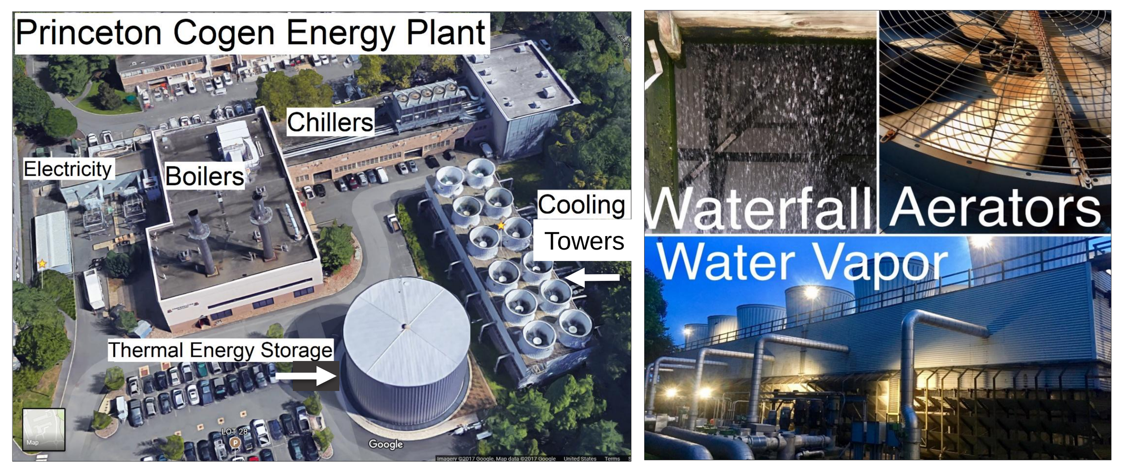

Figure 2. Left side: Overview of Princeton's energy plant. **Right side:** A dozen cooling towers use aerators and a waterfall perimeter to reduce the temperature of hot water from ~95°F to surrounding air temperature, emitting water vapor in the process.

Cooling Towers: At the cogeneration plant on campus, five experiments were preformed lasting on average 12.5 hours. In two instances, higher humidity levels corresponded with wind direction. Three instances produced inconclusive results. For example, in one experiment Princeton's weather station recorded average winds blowing from west to east, however the sensors at the towers showed greater levels of humidity east *and* west of the cooling towers. The experiment would benefit from more frequent trials and use of the more accurate GPS/sensor method exclusively.

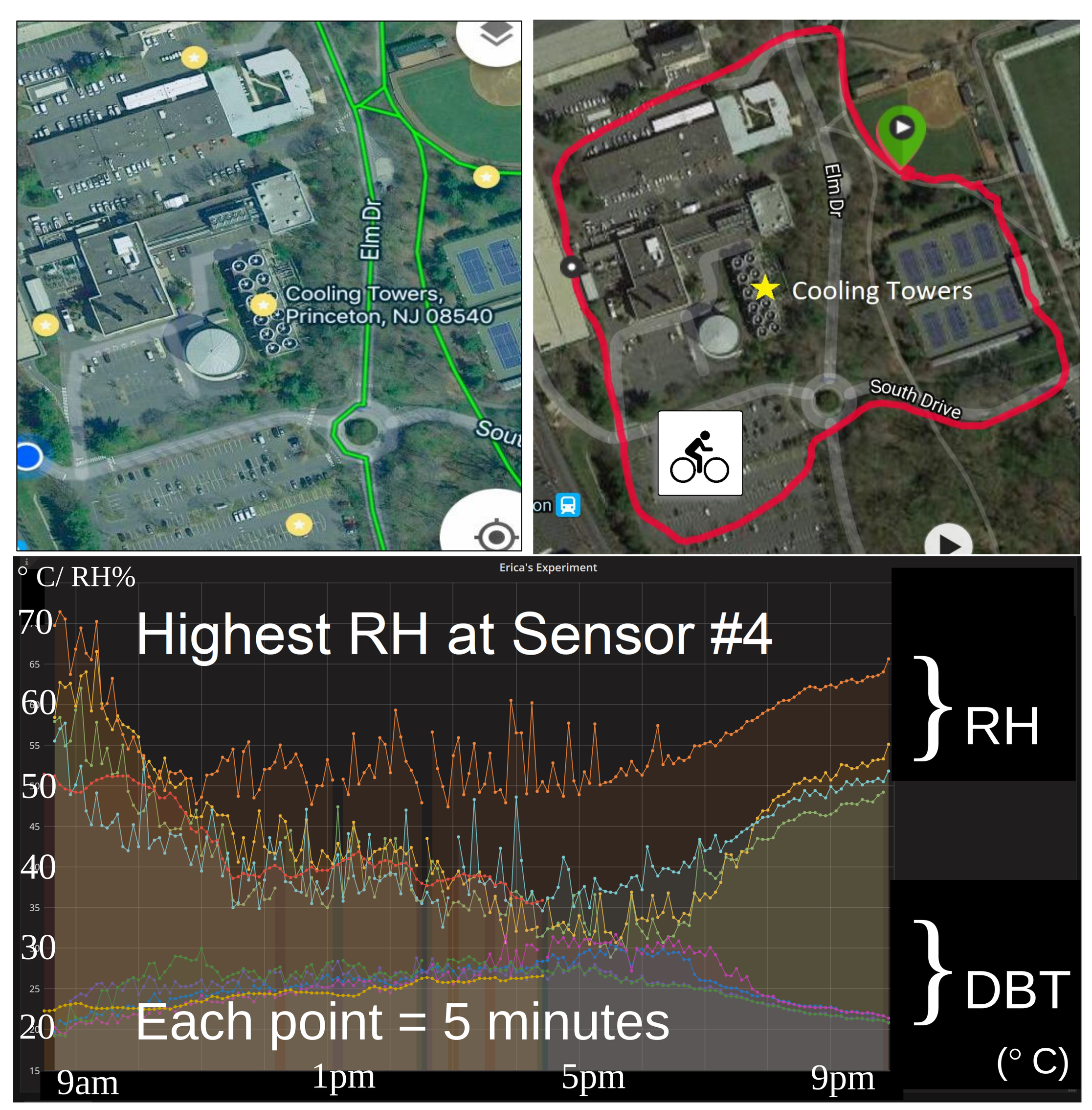

Figure 3. Top: Two data collection methods: stationary sensor placement (left) and GPS circumference of a path cycled around the cooling towers. **Bottom:** Data is available in real-time, shown is screenshot data from four electron sensors. In this instance wind direction agreed with the location of sensor #4, which recorded the highest levels of humidity.

In addition we recorded local data for comparison purposes including RH, DBT, and wind direction at ten minute intervals. We compared average wind direction against average humidity levels over periods of time ranging from 6-12 hours. Higher dry bulb temperatures suppress relative humidity levels, therefore, ideal conditions for the experiments were during the hottest part of the day. This means we had a larger RH window within the psychrometric chart to measure additional humidity emitted by the cooling towers.

All data was taken using inexpensive distributive sensors. Two different types of sensors were made and programmed in CHAOS lab: Arduino *Protons* operating on Wi-Fi and *Electrons* operating by cellular tower. Protons were programmed to record sensed data every 5 seconds and Electrons every 5 minutes.

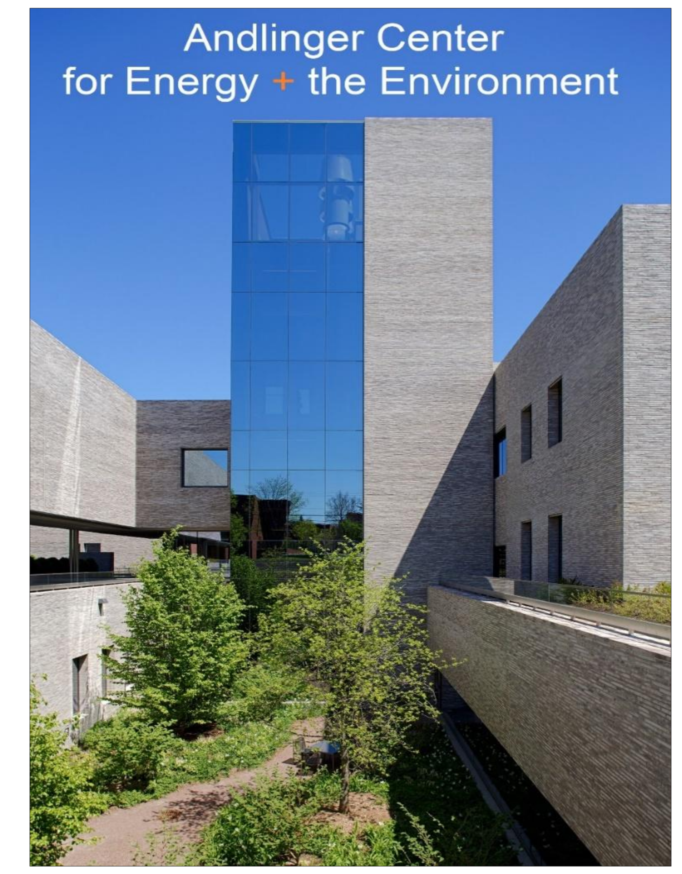

Figure 4. The Andlinger Center for Energy and Environment at Princeton University and one of several sunken courtyards.

Sunken Courtyards: The Andlinger Center, (left) built in 2015 is a modern structure with several sunken spaces and gathering sites. Five experiments were preformed in two courtyards at equivalent latitudes and receiving the same amounts of sunlight each day, three times in wet conditions and twice when dry. The grey canyon consistently had higher MRT and DBT than the green canyon, and both courtyards recorded higher DBT than the campus weather station less than 600m away (Table 1 & 2).

Images were taken above the courtyards and at ground level while maximizing view of ground surface area. Figure 5 shows images taken at the same time, with the grey canyon a significant 22 °F higher in MRT.

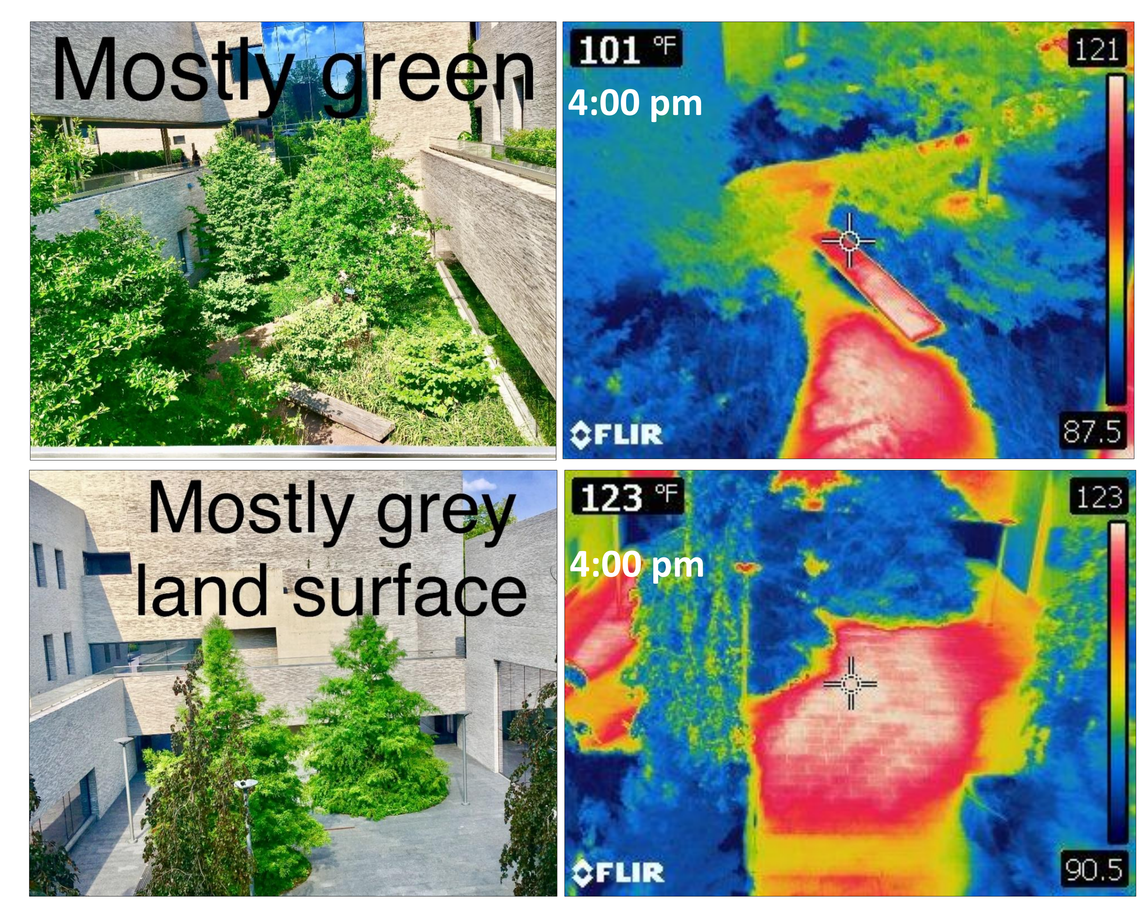

Figure 5. Difference in MRT at the same point in time on a day when temp is 93°F. Both courtyards are viewed from upstairs, looking down from the south side.

In addition, hourly comparisons of MRT was made during wet conditions in the grey canyon. Of the three wet-condition experiments, following rain the DBT increased in one case (shown in Figure 6), decreased in another, and stayed the same in the third.

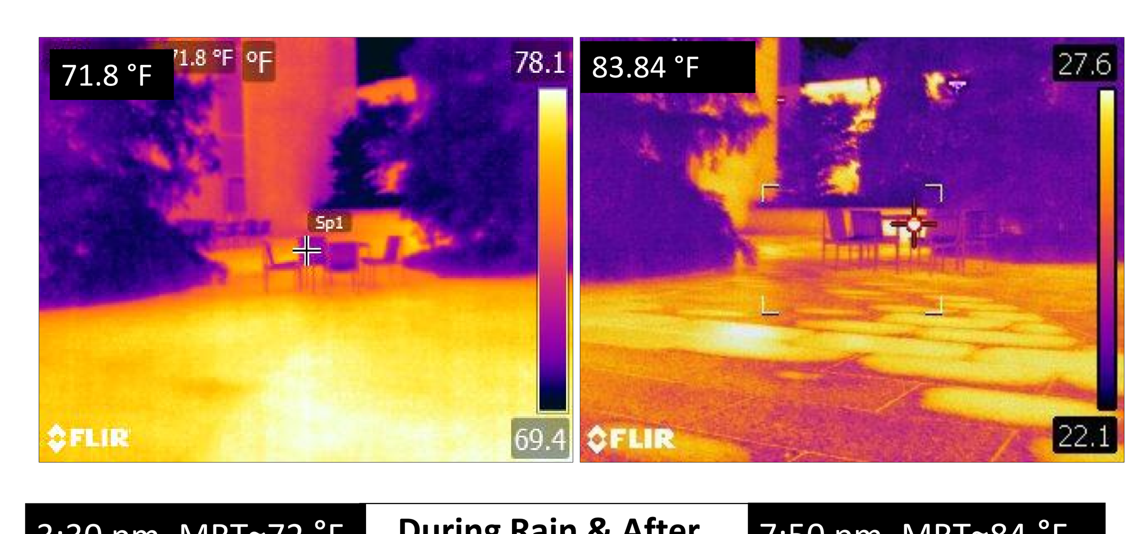

Figure 6. Difference in grey canyon MRT during very wet (raining) conditions and over four hours later. Viewed from grey canyon's ground level. Results are not typical.

Green Vs. Grey					
Experiment #	1 dry	2 wet	3 wet	4 wet	5 dry
Higher MRT	Grey	Grey	Grey	Grey	Grey
Higher DBT	Grey	Equal	Equal	Equal	Grey
Higher RH	Green	Green	Equal	Green	Green

Table 1. Experimental trends show the sunken courtyard with granite land surface area (grey) sustains higher temperatures overall than the courtyard with green landscape and gravel footpath.

Canyon Temperatures Compared to Local					
Experiment #	1	2	3	4	5
Green	Higher	Higher	Higher	Higher	Higher
Grey	Higher	Higher	Higher	Higher	Higher

Table 2. Sunken spaces surrounded by "grey" surfaces like concrete and granite can be characterized as warmer compared to spaces open to air flow, even spaces with vegetative ground covering. The canyons or sunken spaces are representative of urban heat islands in this experiment.

CONCLUSION

Whether a power plant's cooling towers can have an effect on local humidity levels remains partially unanswered. ***A subsequent study of cooling towers and their influence on immediate surroundings*** might build on ours, employing minor changes for more meaningful results. Sampling should be more frequent over at least the same amount of time and obstacles to air flow, while complex, must be accounted for. Also, further studies should use the later method of data collection, GPS programmed in tandem with RH/DBT sensor for more accurate and distributive data than four to six stationary sensors alone.

In the green and grey sunken courtyards our study ***confirms a trend: solar radiation trapped in our built environment can effect outdoor thermal comfort by means of increased DBT and MRT*** in comparison to the surrounding suburb. While DBT is commonly reported, MRT is one of several important metrics to be considered in a discussion of outdoor thermal comfort which influences how we condition and dehumidify our indoor air spaces. The significance is that outdoor thermal comfort influences ***how people condition indoor airspaces*** – what is currently in the U.S., still an ***energy-intensive*** process.

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