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# Modeling peak load reduction and energy consumption enabled by an integrated thermal energy and water storage system for residential air conditioning systems in Austin, Texas

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ABSTRACT

This paper discusses the development of a model for evaluating peak load reduction and change in overall energy consumption for a residential air conditioning (AC) compressor with and without condenser-side thermal storage. Stored rainwater (or any other type of on-site water storage) could be utilized as a heat sink for the condenser during peak hours, allowing for more efficient and lower power compressor operation, then re-chilled at night during off-peak hours. The system evaluated in this manuscript is referred to as 'integrated thermal energy and rainwater storage' (ITHERST).

The model used simulated cooling load data for a typical home in Austin, Texas, based on summer 2011 historical and typical meteorological year (TMY) datasets. The analysis suggests that the ITHERST system with 3785–18,925 l of water could reduce on-peak compressor power demand by approximately 29–53%, as compared to a traditional AC with an air-cooled condenser. However, total compressor energy consumption increases 5–15% because of the inefficiencies of re-cooling the thermal mass, but this additional energy consumption occurs during low demand off-peak hours. System performance varied depending on weather data, the individual compressor, and thermal storage volume.



## 1. Introduction: motivation and scope

### 1.1. Motivation: energy and water issues in Texas

Electricity generation capacity and water resources in Texas are under increasing strain due a variety of factors: a growing population, historic drought, and aging infrastructure [1–4]. The Electric Reliability Council of Texas (ERCOT), the operator of the Texas electricity grid, has expressed concerns about meeting the peak demand in future years while maintaining sufficient reserves [3,5,4]. There are two primary options for addressing peak demand: (1) build more capacity to generate more electricity, or (2) reduce on-peak demand. The summer peak demand on the ERCOT grid is primarily driven by concurrently operating residential air conditioning (AC) systems during hot summer afternoons. Thus, reducing residential AC load could be a major factor in reducing peak demand [6,5].

One method of reducing peak electricity load for AC systems is to couple the system with an active thermal energy storage (TES) system. For this approach, the thermal mass in a TES system is pre-cooled off-peak so that it can be used on-peak to reduce (or replace) the compressor portion of the AC system by supplementing (or fully meeting) the cooling load [7–10]. While active TES for large commercial HVAC applications is an established industry, there is not yet a market for single-home residential thermal storage systems. Residential TES systems are not yet widely available because of the high capital costs for a dedicated system, and lack of financial incentive for residential peak energy reduction since most residential consumers do not pay time of use rates [11–13]. Pre-cooling the house itself and/or temporarily cycling the air conditioning unit off can be effective at reducing on-peak load [14], and are the most commonly employed methods of reducing residential peak load, but the duration and effectiveness of these methods becomes limited due to increased discomfort on very hot days.

Concurrently, the Texas Water Development Board (TWDB) is also seeking means to increase water availability by: (1) reducing water consumption (e.g. water efficiency measures), and (2) exploring the construction of new water resources [2]. Rainwater collection, a practice that has fallen out of widespread use in Texas

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and the US, has been one proposed method to, "…generate additional water supplies in Texas…particularly in urban and suburban areas" [15]. One of the current barriers to entry for rainwater collection has been the high capital cost for the system compared to low utility water rates, leading to long payback periods [15–17].

To potentially improve the utility of rainwater collection systems, the stored rainwater could theoretically be used as a thermal storage medium in a residential air conditioning system. This combined system concept, referred to herein as ITHERST (for *I*ntegrated *Th*ermal *E*nergy and *R*ainwater *St*orage), could potentially increase the economic viability of both residential rainwater collection, as well as residential thermal storage. Since the motivation for this work is to reduce peak electricity demand from residential air conditioning systems in Texas, this model and analysis are focused on residential air conditioning systems. While beyond the scope of this paper, the ITHERST concept could be adapted and implemented in larger scale for commercial buildings, as well as to other types of air conditioning systems (such as chilled water systems). The hypothesis is that the combined value of on-peak electricity demand reduction and water savings from an ITHERST system will out-weigh the energy penalty and associated equipment costs, especially since redundant parts could be avoided. However, before a full economic analysis can be performed, a thermal system model of an AC system with and without thermal storage is needed to accurately assess system performance over varying real-world conditions. Thus, this analysis attempts to quantify the electric demand reduction and energy penalty portion of that hypothesis.

### 1.2. Rainwater thermal energy storage literature review

The concept of thermal storage is a well-established means of reducing on-peak cooling load and maximizing the cooling system's utilization [7–10]. Likewise, the concept of rainwater collection for reduction of potable water consumption is also well-established [15]. However, the utilization of rainwater for thermal storage has not been a deeply explored topic [18–21]. Below is a summary of relevant literature, and discussion of how the proposed ITHERST configuration and analysis fill a knowledge gap in the literature.

Upshaw et al. described a conceptualization of the integrated thermal energy and rainwater storage system, as well as the development of a thermodynamic model to estimate system performance based on tank size [18]. In that analysis, the theoretical model assumed the compressor operated as an ideal compressor with a constant 75% isentropic efficiency [18]. The purely theoretical model provided a first-cut assessment of the concept, but was limited in that it did not capture the real-world inefficiencies of off-design operating conditions. The present analysis describes an updated model that utilizes empirical compressor performance curves to estimate compressor energy consumption, which will be discussed in detail in Section 3. Additionally, while the Upshaw 2013 paper only estimated peak load reduction for a single summer day, this analysis expands the model to calculate the average performance over the entire summer.

Kalz et al. describe the design and experimental testing of a heating and cooling system utilizing rainwater cisterns in a highly efficient German house [19]. The system included two 11 $m^3$ rainwater cisterns as part of a thermo-active building system that uses radiant heating and cooling to maintain building thermal comfort, while a ventilation system provides fresh air [19]. The cooling system is limited to circulation of cold water through the thermo-active building structures, which cools the walls and absorbs heat from the air, which is then deposited in the colder rainwater cistern. The cooling system does not use any sort of air conditioning for space cooling. The cooling system is operated continuously when needed, without cycling or tank re-cooling. Heat removal from the tank is limited to the natural heat loss from the tank to the surrounding ground. Gradual warming of the rainwater cistern was an issue; it was noted that, attention has to be paid to the operation of the entire system, since permanent cooling and heating results in a fast depletion of the energy reservoir [19]. The heating mode of the Kalz system uses the rainwater for the heat source for a heat pump, but the system is not actively re-heated [19]. The Kalz paper also identified the relative lack of literature on the topic of utilizing rainwater as a heat source and sink [19].

Gan et al. describe the simulation and experimental testing of a heat pump coupled to an in-ground rainwater tank with an array of heat exchanger arms for exchanging heat with the surrounding soil [20]. The tank-soil heat exchanger was meant for enhanced thermal interaction between the tank and soil, which allowed for better absorption of heat form the soil during heating operation, and better dissipation of heat to the soil during cooling mode operation. Gan describes the system as an enhancement to normal ground source heat pumps by avoiding costly drilling of deep boreholes to attain a steady ground temperature source [20]. However, their focus in system design was entirely heating; there was no mention of air conditioning or cooling, and their primary concern was the tank freezing [20]. Like the Kalz system [19], the Gan system is a passively recharged system, meaning the rainwater thermal storage is not actively re-charged (re-cooled or re-heated).

While not rainwater or thermal storage, Liu et al. discuss the modeling and prototype testing of a heat pump with both air and graywater-cooled condenser coils for both space conditioning and water heating [21]. Liu discusses the cooling system performance gains by utilizing the gray water for condenser cooling, but the system is not operated in an active thermal storage manner to maximize peak load reduction [21]. The multifunction gray water source heat pump tested in Liu paper analysis was originally conceived and designed with the goals of reducing overall energy consumption and water consumption, and was first described and modeled in Ni et al. [22]. This system differs from the ITHERST concept proposed in this paper because it was designed and operated for overall energy savings, rather than peak load reduction.

In summary, the present analysis improves and expands upon the concept of using rainwater as the thermal mass in an active thermal storage system for peak electric load reduction. The ITHERST configuration of the present analysis differs from the systems described by Kalz and Gan because the primary goal is active, diurnal peak shifting of cooling load, rather than serving as a passive thermal sink to improve heat pump efficiency [19,20]. Lastly, this analysis addresses some of the limitations of original Upshaw model by increasing the analysis period to the entire summer, as well as incorporating more realistic, empirically derived performance curves for the compressor [18].

### 1.3. Scope

This analysis of the ITHERST concept is limited to typical residential direct expansion (DX) air conditioning systems. For input to the present analysis, cooling demand for a typical residential building in Austin, TX was modeled based on averaged data from local energy audits [6]. The model was built in BEopt, a building energy modeling software published by the National Renewable Energy Laboratory (NREL) [23]. The BEopt model was executed with 2011 historical data, and typical meteorological year (TMY) data, to obtain simulated house cooling load data. The cooling load data and weather data were then used as input for a MATLAB model, which used bi-cubic empirical compressor curves to estimate the compressor electrical power demand and energy consumption necessary to meet the load (Section 3). The model calculates the power demand and energy consumption for a DX system with and without the thermal storage system. The outputs of the two scenarios were used to calculate comparative performance metrics, such as