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Modeling electric load and water consumption impacts from an integrated thermal energy and rainwater storage system for residential buildings in Texas

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HIGHLIGHTS

- Hydronic integrated rainwater thermal storage (ITHERST) system concept presented.
- ITHERST system modeled to assess peak electric load shifting and water savings.
- Case study shows 75% peak load reduction and 9% increase in energy consumption.
- Potable rainwater collection could provide ~50–90% of water used for case study.

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ABSTRACT

The United States' built environment is a significant direct and indirect consumer of energy and water. In Texas, and other parts of the Southern and Western US, air conditioning loads, particularly from residential buildings, contribute significantly to the peak electricity load on the grid, straining transmission. In parallel, water resources in these regions are strained by growing populations and shrinking supplies. One potential method to address both of these issues is to develop integrated thermal energy and auxiliary water (e.g. rainwater, greywater, etc.) storage and management systems that reduce peak load and freshwater consumption. This analysis focuses on a proposed integrated thermal energy and rainwater storage (ITHERST) system that is incorporated into a residential air-source chiller/heat pump with hydronic distribution. This paper describes a step-wise hourly thermodynamic model of the thermal storage system to assess on-peak performance, and a daily volume-balance model of auxiliary water collection and consumption to assess water savings potential. While the model is generalized, this analysis uses a case study of a single family home in Austin, Texas to illustrate its capabilities. The results indicate this ITHERST system could reduce on-peak air conditioning electric power demand by over 75%, with increased overall electric energy consumption of approximately 7–9%, when optimally sized. Additionally, the modeled rainwater collection reduced municipal water consumption by approximately 53–89%, depending on the system size.

1. Introduction and literature review

Energy and water resource consumption are underlying many major global stresses, and the combination of climate change and an increasing population might exacerbate them. The built environment (residential and commercial buildings) are major direct and indirect consumers of energy and water. In the United States, approximately 40% of all primary energy, and about 75% of all electricity produced, are consumed within buildings [1]. While direct water consumption by the built environment is only about 12% of US water withdrawals, the indirect water footprint of the electricity consumed in the built environment equates to another 34% of all US water withdrawals, bringing the combined direct and indirect total to just under 50% [2]. Water is necessary for cooling most thermoelectric power plants that provide electricity to buildings, and electricity is also needed to treat and move water for residential use [3]. This interdependence of energy and water is the source of many potential supply and availability issues, but

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Nomenclature

Acronyms and abbreviations

ITHERST	integrated thermal energy and rainwater storage
HVAC	heating, ventilating, and air conditioning
TES	thermal energy storage
AC	air conditioning
UT	University of Texas
TUM	Technische Universität München
DX	direct expansion
DOE	US Department of Energy
NREL	National Renewable Energy Laboratory
AHRI	Air conditioning, Heating and Refrigeration Institute
TMY3	Typical Meteorological Year (3rd edition)
ARCSA	American Rainwater Catchment Systems Association
ASPE	American Society of Plumbing Engineers
AWWA	American Water Works Association
PLR	peak load reduction
ECC	Energy Consumption Change
cc	cooling capacity
amb	ambient (outdoor temperature)
s	supply
HP	heat pump
Load	house cooling load
HL	hydronic loop
HLP	hydronic loop pump
FCU	fan coil unit
TSP	thermal storage loop pump
Tot	total of all system components
D	thermal storage discharge
R	thermal storage recharge
HX	heat exchanger
TS	thermal storage loop
Env	environmental (heat gain)
Conv	convection
FFD	first flush diverter
Cap	capacity (volume)
GW	gray water
BW	black water
ppl	people in household
bs	bathroom sink
sh	shower
ks	kitchen sink

it might also be the solution to most effectively addressing these issues as well [4].

In many southern states, air conditioning loads drive the overall peak load and wholesale market price of electricity on the electric grids. During the summer in Texas, the cumulative electric demand from residential air conditioners alone can exceed 40% of the peak load on the electric grid [5]. Because most of these power plants use water for cooling, water scarcity can force them to reduce their power output or turn off entirely [6,7]. If power plants do not have the water available to produce power, price could significantly increase, and/or the supply could become less reliable [6,7].

The Texas population is projected to grow by 80% in the next 50 years; that growth coupled with projected warming temperatures could lead to both increasing residential water demands and air conditioning loads increasing [8]. This paper proposes addressing both electricity demand and water availability through an integrated approach combining active peak load reduction and significant water savings, with a focus on single-family residential housing, which consists of over 5.7 million units out of 8.5 million total housing units in Texas [9].

There are many technologies available to address water scarcity and electric load challenges, including water efficiency and electricity efficiency measures such as low flow toilets and more efficient air conditioners. While these reduce instantaneous demand, they cannot eliminate consumption (in the case of water) or on-peak demand (in the case of cooling load).

Active water source replacement, such as rainwater harvesting, can significantly reduce or eliminate residential demand for municipal water [10–13]. There has been much research into the water savings capacity of such systems in different configurations, and in different climates around the world [14–23]. Additionally, research in the United States has shown that rainwater collection and greywater re-use could potentially save energy on the utility side by reducing energy spent pumping and treating water and wastewater [24].

There are also many strategies available to manage residential building cooling load, including: demand response and centralized control, building pre-cooling and passive thermal storage materials, and active thermal energy storage (TES) systems. Demand response is the temporary interruption (turning off) of an electric load to reduce demand, and there are also similar centralized control strategies that adjust thermostat set-points to delay the rate of air conditioner power cycling [25–27]. Building pre-cooling and other passive thermal storage concepts shift cooling load off-peak by cooling the thermal mass present in the building at off-peak times, and then let the buildings' natural thermal inertia maintain thermal comfort [27–29]. Thermally active, or homeostatic, building concepts actively manage energy flowing in and out of the thermal mass of the building via low energy hydronic systems [30–32]. Active thermal energy storage (TES)—the focus of this paper—is a method of reducing peak electricity load for AC systems by coupling the system with a thermal mass, usually a tank of water or ice, but could also be a phase change material (PCM) [33–37]. This mass 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 by warming the pre-cooled water or melting the ice or PCM [33–37].

TES and rainwater harvesting systems usually have higher upfront costs than conventional systems that do not have on-site storage. However, they recoup costs over time by reducing utility bills (electricity, in the case of TES, and municipal water, in the case of rainwater harvesting). However, these technologies have traditionally been limited to larger-scale applications (in the case of TES) for the commercial and industrial sectors and/or remote or water-scarce locations (in the case of rainwater harvesting for potable use). Because TES and rainwater harvesting systems traditionally benefit from economies of scale, these technologies generally have yet to be adopted en masse at the residential household level in the continental US [14,16,17,19,20,23,24,38–40].

One way to potentially improve the economic viability of both rainwater harvesting and thermal energy storage is to integrate the two systems such that they share components. The proposed combined system concept, referred to herein as ITHERST (*Integrated Thermal Energy and Rainwater Storage*), could potentially increase the economic viability of both systems beyond that of two separate systems. The hypothesis is that the combined value of on-peak electricity demand reduction and water savings from

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