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Reducing a semiarid city's peak electrical demand using distributed cold thermal energy storage

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HIGHLIGHTS

- Distributed CTES addresses utility scale electrical demand management problems.
- CTES capacity of 7791 MW h would shave peak demand during a Phoenix, Arizona heat wave.
- Shaving peak air conditioning electrical demands reduces peak citywide demand by 13%.
- 454,034 residential CTES units achieve the target, with installation over roughly 10 years.

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ABSTRACT

Several changes to the world's electrical power systems and grids threaten to require massive infrastructure investment and cost to power utilities, especially increasing population and electrical energy demands, especially peak summertime air conditioning demands, and mismatches between timing of supply and demand due to increases in renewable energy and/or large demands from new technologies. Existing power grid systems are generally under-utilized with low load factors during most times of day and year, but demand strains capacity during peak hours. Brownouts and other grid failures are projected to become more common as peak demands approach grid capacities, with negative economic and public health consequences resulting. Meanwhile a financial barrier exists for the financing of grid improvements, because utility revenues are proportional to total power sales, whereas utility costs are driven largely by capital and maintenance for the fixed infrastructure.

An alternative to active demand management or electrical energy storage is to shift thermal demands to off-peak hours, allowing the utility's power grid to meet much larger total demands using a fixed capacity. Thermal energy storage is a mature, energy-efficient, and possibly cost-effective technology that can be applied to buildings of all sizes, and is particularly well-suited to shift afternoon peak cooling demands to off-peak hours in hot summertime months. This simple technology, if distributed widely, can make a dramatic impact on power grid load factors in hot cities.

This paper utilizes a utility-scale model of the Phoenix metropolitan area to simulate the air conditioning portion of the electrical demand during a summertime heat wave. The electrical demand by air conditioning during peak hours is incrementally shifted to off-peak hours using distributed thermal storage technology. The aggregated thermal storage capacity and operating hours required to reduce the peak load by incremental fractions are established, along with the size of the gross electrical energy cost savings potentially realized by electrical power consumers during heat wave events, at current electricity prices.

1. Introduction

Several changes to the world's electrical power systems and grids threaten to require massive infrastructure investment and cost to power utilities, especially increasing population and electrical energy demands, mismatches between timing of supply and

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demand due to increases in renewable energy and/or large demands from new technologies, and an aging and increasingly obsolete power grid. Existing distributor scale power systems are generally under-utilized during most times of day and year, but are already under stress with demands stretching capacities during peak hours. Brownouts and other grid failures are projected to become more common as peak demands approach grid capacities [1]. In many cases peak load factors will exceed the 15% margin between grid capacity and demand that is generally considered the minimum to maintain all-important power grid reliability [2]. In the United States alone up to 120 GW of new generation and distribution capacity may be required in the coming decades in order to maintain reliability [3]. The areas of greatest concern globally are those that are growing the fastest or which have older infrastructure.

The average load factor is the average percentage of the power grid's capacity that is being utilized over a period of time. The peak load factor is the maximum percentage of the capacity that is utilized. Power utilities generally benefit by maintaining a 'flat' load profile over time with high average load factors and peak load factors that are as close to the average as possible. Such a profile maximizes the employment of capital invested in the power grid infrastructure, and maximizes the ability of the utility to utilize efficient and low-cost baseload capacity.

Average load factors are declining in the US, and peak load factors are increasing [2]. The decline in average load factors is driven largely by increased summertime afternoon peak loads from air conditioning (AC) that raises peak load factors, combined with capital-intensive installation of peak load generation transmission capacity that is under-utilized and reduces average load factors. Declining average load factors will be increasingly expensive for the public in terms of power rate increases, and will require escalating and increasingly unaffordable investments in capital infrastructure.

If retail electricity prices increase too sharply, it will impact the most vulnerable first, potentially exacerbating a public health crisis associated with heat related illness during heat waves [4,5]. If the necessary investments are not made, the all-important reliability of the power grid may be compromised when peak loads exceed the grid's capacity resulting in brownouts or blackouts, with even more severe economic and public health consequences. The highest demands on the power grid now occur during mid-afternoon hours during dangerous summertime heat waves, threatening blackouts and a failure of power system reliability and resilience [6–9].

AC electrical energy use represents between 40% and 50% of the summertime peak demand originating in both residential and commercial buildings in the US [2]. Because most of the growth in electrical demand is occurring in hot regions where summertime AC is standard [2,3], managing growth in the peak summertime AC electrical demand may be the single biggest target for grid-scale load factor management.

There are several ways to reduce peak load factors, including: (1) add peak utility power generation and distribution capacity, (2) manage/suppress demand or increase efficiency to avoid adding capacity, (3) add distributed peak generation at the points of use, (4) add power storage capacity to shift off-peak generation capacity to on-peak hours, or (5) where possible without compromising services, shift some electrical demands at the point of use to off-peak hours to avoid adding capacity using 'load-shifting' methods.

Demand-side management (DSM) has been an important cornerstone of electrical utility planning and incentive programs since the 1980s, when it became understood that peak electrical loads were a major problem for the power grid [10]. In response to the challenge of matching increasingly variable electrical supplies and demands, the 'smart grid' (e.g. [11] is an idea that is coming of age. This new power grid uses anticipatory controls and information networks to manage transmission and distribution systems and to control both generation systems and system demands to ensure that the power grid remains reliable and balanced under all conditions. Energy Storage Systems (ESS) are an important part of this solution [12,13] because they hold the potential to match time-variable loads to steady-state generation capacity (e.g. summer peak cooling loads and nuclear base generation), or to match time-variable generation capacity with the system (e.g. wind or solar).

Pumped hydroelectric systems, electrochemical systems such as batteries, mechanical systems such as flywheels, hydrogen fuel cells, and Thermal Energy Storage (TES) are the common methods of energy storage on the power grid [14]. TES has been applied in the USA since the 1970s as a type of DSM that combines energy storage and load shifting [15]. Energy storage and load shifting are particularly valuable solutions because they allow utilities to reduce peak load factors while simultaneously increasing average load factors [16].

TES has not been widely utilized, or implemented at smaller scales such as in residential buildings, and it has not been widely adopted outside of the USA. TES may currently be the most cost-effective demand management option [17,18], as compared with electrical energy storage methods and active demand responses. This paper does not directly address the cost-effectiveness of TES technology, but rather the market potential for the technology to be used to manage electrical demand in a hot, semiarid city.

The typical TES application is 'diurnal', shifting loads from one time of day to another, but 'seasonal' TES is able to shift thermal loads from winter to summer, or vice versa [80]. Although seasonal TES may be effective for some applications, this paper and most research emphasizes diurnal applications.

Most existing solutions have been utility-oriented and operate in a regulated market, with energy storage technologies (e.g. pumped hydroelectric) operating with central control and connected to the power grid in an optimal and centralized fashion. Distributed Energy Storage Systems (DESS) have advantages over centralized storage systems in that they can be controlled by either utilities via 'virtual power plants' (e.g. [19] or by individual end-use customers, and they can also be used to balance loads across a power distribution system's many sectors [20,21]. Furthermore, uniquely effective and efficient Distributed TES systems (DTES) such as those for Heating Ventilation and Air Conditioning (DTES-HVAC) technologies explored in this paper can only be implemented at the point of use in a distributed system.

DTES-HVAC may currently be the most mature and cost-effective of all energy storage and load shifting technologies [17,22–24]. DTES-HVAC has been utilized on a wide scale for decades, especially in the market for stored wintertime heating energy [15,25] and concentrating solar power [26]. Increasingly DTES-HVAC is being utilized for peak AC cooling energy, especially in larger scale commercial applications [27]. This air conditioning application is often referred to as 'cold' TES or CTES [28], and it is an inherently distributed type of TES application. As a result, this paper will use the acronym CTES in reference to distributed refrigeration air conditioning thermal energy storage applications.

The most common implementation of the AC application utilizes a compressor to make water ice during off-peak hours, usually at night, and substitutes circulation of refrigerant through tanks of ice water for the use of the compressor during on-peak hours. This application has been demonstrated to achieve 100% or greater effective energy efficiencies based on a comparison of a TES-augmented AC unit with a standard unit [29,14,27,30–33]. This is because the compressor runs more efficiently against a lower thermal gradient at night than during peak daytime outdoor air