Available online at www.sciencedirect.com
ScienceDirect
Current Opinion in Chemical Engineering

Energy intensification using thermal storage

Thomas F Edgar[1,2] and Kody M Powell[1]

Thermal energy storage (TES) is a cost-effective technology that can greatly improve the performance of energy systems that have dynamic supply or demand. In solar thermal systems, TES plus controls enables the power output of the plant to be intensified and effectively regulated, despite fluctuating solar irradiance. In district energy systems, TES can be used to shift loads, allowing the system to take advantage of variable energy prices. The benefit of TES can be significantly enhanced by dynamically optimizing the complete energy system. The ability of TES to shift loads gives the system new degrees of freedom that can be exploited to yield optimal performance and improve thermal efficiency.

Addresses
[1] McKetta Department of Chemical Engineering, University of Texas, 200 E. Dean Keeton St., Austin, TX 78712, USA
[2] Energy Institute at the University of Texas, 2304 Whitis Avenue, Austin, TX 78712, USA

Corresponding author: Edgar, Thomas F (edgar@che.utexas.edu)

Current Opinion in Chemical Engineering 2015, **9**:83–88

This review comes from a themed issue on **Energy and environmental engineering**

Edited by **Rakesh Agrawal** and **Vasilios Manousiouthakis**

For a complete overview see the Issue and the Editorial

Available online 7th December 2015

http://dx.doi.org/10.1016/j.coche.2015.11.002

Introduction

EPA's recently proposed Clean Power Plan represents a major push to reduce greenhouse gas emissions and to increase energy security. Significant focus has been given to energy efficiency improvements and to the development of renewable energy such as solar PV, wind, and biomass. Although renewable energy penetration and energy efficiency have grown considerably during the past two years in the power sector, the majority of the electrical energy in the United States still comes from coal and natural gas.

Although renewable energies are abundant, their intermittency puts them at a disadvantage compared to fossil fuels. With energy storage, energy can be accumulated during periods of excess and then dispatched as necessary to meet demands, which alleviates the intermittency issue and makes renewable resources like solar and wind much more viable [1•]. Many different forms of energy storage exist including battery storage, pumped hydro, compressed air, and thermal energy storage, but this introduces a dynamic aspect to energy management, in order to intensify the energy available for delivery.

Energy storage can intensify renewable energy systems, but also conventional systems. Because energy storage allows a system to shift times of energy production or consumption, it has shown great potential in improving the overall efficiency of conventional energy systems as well. The grid demand for power can vary during a 24 hour period by a factor of two. Thus energy storage gives a baseload system the ability to store excess energy when production capacity exceeds demand, then use this stored energy dynamically for periods of higher demand, thereby reducing the required size of the system and yielding operational cost savings.

Thermal energy storage (TES) is the storage of thermal energy as latent heat, sensible heat, or chemical heat. In warmer climates TES is often used for storing 'cooling' in the form of chilled water or ice, usually in a large tank. This tank can be used to store cold water when demand is low, and then the water can be discharged when demand is high in order to meet cooling loads. Though not as versatile as battery storage, TES is much cheaper with costs ranging from \$6 to 43/kWh [2,3]. Battery costs range from \$74 to 1484/kWh [4]. TES is a promising technology due to its low cost, particularly in comparison to battery storage [5•]. TES has been used in a wide array of applications including concentrated solar power (CSP), electric grid storage, space heating and cooling, and combined heat and power (CHP). Although successful implementations of TES in multiple sectors have proven this technological and economic viability, performance can be improved by focusing on optimal dynamic management of the resource.

Combined heat and power (CHP, also called cogeneration) is the simultaneous production of heat and electricity. These power plants use gas and steam turbines in a combined cycle to generate electricity. CHP currently produces about one-fourth of the power in the process industries. CHP systems typically have very high efficiencies (~70–80%) compared to electricity-only steam turbine systems (~35%) and can be integrated with building climate control systems by using chillers. CHP systems most often include a natural gas turbine, but systems such as fuel cells, reciprocating engines, and microturbines are also ideal CHP candidates [6•].

District cooling allows a centralized chiller plant to provide cooling to a number of facilities in a single geographical area and benefit from economies of scale. The cooling district can comprise industrial facilities, commercial facilities, residential facilities, or any combination of the above. District cooling (and heating) networks can generally improve overall system efficiency when compared to a distributed cooling system [7,8]. However, they do require significantly more infrastructure than distributed systems. Solar district heating can also be done on a seasonal basis, where solar energy is collected in the summer months, used to heat an underground storage system (such as a section of earth), then extracted in winter months for space heating [9].

Electricity generation systems are required to vary their power output to match consumer demand. Systems relying on intermittently available energy, such as solar and wind power, are heavily influenced by the varying energy source. Thus, for determining optimal operation of the system, it becomes critical for these types of systems to employ forecasting to predict and account for major exogenous disturbances. These forecasts could include: weather, pricing, and demand, which are important when longer time scales of optimal operation are considered. Typically a day-ahead forecast is sufficient, but longer periods may be required in certain cases. When accurate forecasting models are combined with dynamic systems-level models of energy systems with storage, many opportunities arise for dynamic optimization. The extra degrees of freedom that accompany energy storage can then be fully exploited [10••].

Two vignettes illustrating dynamic optimization for energy storage are presented here. The first system, solar thermal power with storage, follows a distinct diurnal cycle. By using modeling and control of storage, an intermittent input can be converted into a constant power output. Additionally, storage can be further exploited by adding in storage bypass, solar radiation forecasting, and hybrid solar/gas operation and using these features in a dynamic optimization solution. A second example involves the University of Texas CHP plant combined with a TES system. Here the cooling loads are forecasted using empirical models which are developed from historical load and weather data. The campus meets all of its own electrical, heating, and cooling needs and is the largest microgrid (125 MW) in the U.S. Because the cooling system requires large amounts of electricity, the cooling/TES and CHP systems are highly interdependent. This will require forecasts of electrical, heating, and cooling loads with the objective being to minimize the campus energy usage and operating costs.

Modeling and control of a solar thermal plant with storage

Solar thermal energy makes effective use of solar energy by converting it directly to heat. The ease with which energy can be collected and stored via TES makes solar thermal processes viable for power production. Because of its ability to act as a buffer for intermittent renewable resources, high temperature TES is an enabling technology for concentrating solar power (CSP) systems used for electricity generation [11]. The high temperatures are achieved by concentrating the solar radiation to heat a fluid with parabolic collectors, then using this fluid to generate steam, which is then fed to a turbine, ultimately converting sunlight into electricity [12,13•,14,15].

If constant (baseload) power generation is the objective, the low cost of TES gives CSP a current advantage over photovoltaic (PV) systems, which must rely on expensive battery storage to achieve the same baseload level as CSP systems. However, the costs of batteries such as lithium-ion are projected to decrease over the next 10 years. In addition, the cost of PV generation has been decreasing rapidly over the past several years, and as of 2015 has declined to under 4 cents/kWh for utility-scale PV (on the basis of news reports). Therefore PV plus battery storage will probably be the preferred option for baseload solar power generation in 2030.

A first principles model of a solar thermal power plant with high temperature TES was developed by Powell and Edgar [16••]. The model uses a two-tank direct configuration for energy storage, where a fluid such as Dowtherm is used for heat collection and storage (see Figure 1). The temperatures of the hot and cold tanks are 390 °C and 250 °C, respectively.

The study considered several scenarios: with and without energy storage on both a sunny day and a day with sporadic cloud cover. The study demonstrated the value of TES for operation of a solar thermal power plant. Despite using a relatively simple control system (a feed-forward plus feedback controller for solar field temperature control by manipulating the flowrate and a feedback-only controller for power control), the power output of the plant can be controlled to a constant rate. By contrast, a system without thermal energy storage undergoes large fluctuations in output power because it is entirely subject to availability of solar energy. The storage system, therefore, provides an invaluable buffer between available solar energy and energy demand. With the addition of a feedback plus feedforward control system for the fluid temperature by manipulating the flowrate, the system is able to maintain a constant power output. This allows the system to operate much more stably without having to attempt to rapidly ramp the backup energy source up and down to make up for any power discrepancy, thereby using less natural gas.

TES helps increase the solar share (fraction of energy provided by solar) of the plant. Using simulation [16••], on clear days the solar share is much larger for a system with TES, which requires 43% less supplemental energy. The