Principles of saving energy with dynamic thermal storage

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Keywords

energy, economic, savings, thermal, storage, system, buildings, cooling, heating, dynamic, optimal operating conditions

Abstract

This paper describes the interaction between thermal storage and various sources of variation in heat supply and demand, to promise overall thermodynamic work within a temperature span of 20°C or less. This allows coefficients of performance (COP) of 6.0, twice that of conventional heat pumps and in many cases free cooling without heat pumps. Variation in ambient air temperature, solar radiation or patterns of energy usage, optimised in conjunction with heat pumps and dynamic thermal energy storage (DTES), promise to save large amounts of energy used for the heating and cooling of buildings. For example, cooling at night at 24 °C, rather than in warm afternoons at 34°C will remove 45% of the thermodynamic load. Economic savings are further improved where off-peak tariffs for electric power exist. Variation from various sources, combined with thermal storage, promises to become an attractive source of renewable energy and economic savings. Furthermore, a dynamic thermal energy storage (DTES) may be combined with borehole thermal energy storage (BTES) to allow summer heat to be used for heating in wintertime, whilst cooling during summer. A DTES is constructed in practice as a below-ground 'well' adjacent to a (new or existing) building. The area on top is available for other use. Typical size for a single-family home is a volume of 5-7 m³ and a cross-section of 2-3 m². The technology promises to be cost effective in mass application, in particular for commercial buildings.

Introduction

Large amounts of energy are presently used to maintain suitable indoor conditions; figures of some 35-40% of total energy use are commonly cited. This means opportunities for extensive improvement by achieving and maintaining suitable conditions while using much less energy. This "Not-Used-Energy" (NUE) is in effect creating the same end-result as the provision of extra electric power, or purchased supplies of fossil fuel. Moreover, NUE is renewable and sustainable, and, once paid for, becomes an almost "free lunch" as long as a building remains operational. There is no element of renunciation; no "saving" with reduced standards or comfort. General surveys of thermal storage are given by McQuiston et al (2000) and by Dincer and Rosen (2002).

One should keep in mind that improved energy efficiency eliminates upstream costs and losses. This involves societal improvements such as decentralised energy generation, less need for pylons, grids and infrastructure, less thermal generating capacity and capacity running in stand-by mode. The overall result is increased systems efficiency, reduces costs and reduced CO_2 emissions.

Dynamic thermal energy storage (DTES) uses variation in outdoor temperature and other conditions, to obtain heat and cold when readily available and cheap and for use when most valuable. It promises a substantial contribution to NUE. In fulfilling this promise we believe that thermal storage should be seen not just as storage, but in an overall role integrated with the functioning of the building. This means handling of both heat and cold, transport of heat within the building, and heat exchange within the building and with the outdoors. The interaction with the outdoors may take several forms, most typically liquid-to-air heat exchange and solar heating.

There are three main criteria as to the functioning of suitable DTES installations. These relate to:

1. Sufficient effect to meet the requirements for heat input or –removal to/from the building
2. Sufficient heat capacity to match the time constant of the variation (e.g. 24 hours for day/night variation)
3. Sufficiently fast response to follow requirements for heating or cooling

The physical construction may most directly take the form of two tanks (cf. below) with cool water in one and warm water in the other. A particular construction utilising the same volume for both warm and cool water, and allowing use of the top surface for e.g. greenery or parking was described by Gether et al (2006).

Integrating thermal storage with buildings

The central focus is on suitable indoor conditions while compensating for variation in outdoor weather and the effects of normal operation of the building, and to do this with a minimum use of energy. A first integrative issue is that this task becomes easier as the building shields its interior through insulation and protection against incipient radiation. All active, compensating tasks become easier when these passive measures are in place. There is thus not competition between, say, insulation and active measures in the real world, although there may be competition for available funding. The task for thermal storage is made easier the more demand efficient the building is.

A second integrative issue is transport of heat throughout a building. While in homes and smaller buildings this may be handled on a passive basis, in larger buildings some active form of transport of heat is normally required, for both heating and cooling. This generally involves a mass flow, with the amount of heat transferred:

$$Q = c_v * m * (t_2 - t_1) \quad (1)$$

where

c_v = spec. heat of transfer medium
m = mass of transfer medium
(t_2-t_1) = temperature drop from transfer medium to receiving medium

Two situations appear to circumvent the temperature drop, although just seemingly so. The first is passive storage like interior walls with appreciable specific heat. Secondly, A/C units with the compressor outside and expansion valve and cooling inside, utilize the phase change of the working medium from liquid to vapour. In all other cases, transport of heat relies on a temperature drop in such a way that, for a given amount of energy, half the temperature drop means twice the amount of transfer medium. Although basic, this seems often to be forgotten.

Heat transfer normally operates with a heat exchanger supplying heat to the transfer medium (e.g. water) that in turn delivers heat to one or more radiators. These perform a key function, and their proper construction and operation are important. With a drop in temperature across the transfer medium of 10°C for transport of heat proper, temperature drops across each exchanger of 3°C implies a loss of 60% of net transferred energy. While not a direct part of the present work, it is evident that heat exchangers should be designed with care.

We consider the role of thermal storage in this overall setting. It needs to be dynamic; to transfer heat into and out of storage as required. An idealised solution would be two tanks, each starting half filled, one with warm and one with cold water, and thermally well insulated from each other. A need for heating is met by pumping water from the warm tank, through a radiator in the building, and to the cold tank. Cooling is likewise met by pumping water the other way. The temperature difference is set by the return side not being colder than indoor temperature plus the temperature drop across the radiator, and the high temperature as low as possible to minimise energy consumption by heat pumps. Room temperature at 21°C, 3°C drop across the radiator and 10°C for heat transfer lead to a low temperature of 24°C and a high of 34°C. Storage and distribution in this way mean that we use the temperature drop required for heat transfer, also for dynamic thermal storage.

Saving energy under variable usage conditions

This concerns day/night variations, the passage of weather systems, annual variations and variation in energy usage. Some of these require significant effects, which the current proposal can provide. Where a dynamic storage facility is available all of these types of variation may be integrated and play together for optimal results with present-day information technology under the control of a computer. The system may take advantage of weather forecasts, schedule of usage, and keeping critical components at optimal running conditions.

An example of variation in outdoor temperature is given in Figure 1.

Figure 1 shows three dominating mechanisms behind variation in outdoor temperature: annual variation, passage of weather systems, and day/night variation. Passage of weather systems dominates in winter, with day/night (diurnal) variation becoming significant from early March onwards. Annual variation has a time constant of half a year, passage of weather systems 3-5 days, and diurnal variation 12 hours. A fourth factor in Figure 1 is workdays differing from weekends. Even in cool Scandinavian climates there is also substantial need for cooling for many types of buildings.

Systems for thermal storage need to match these time constants, with larger capacities to match longer intervals of time. Where electric power is used for either heating of cooling, dynamic thermal energy storage promises to make this much more efficient. The basic principle of shifting available energy in time is shown in Figure 2.

Figure 2 gives an example of one way dynamic thermal energy storage (DTES) may be used to obtain energy from natural variation in outdoor temperature. The principle is simple: the heat pump is run at full capacity in mild weather when all of its capacity is not required to heat the building. In a following cold spell heat is obtained from the DTES while the heat pump is turned off. The same reasoning applies to cooling, and in

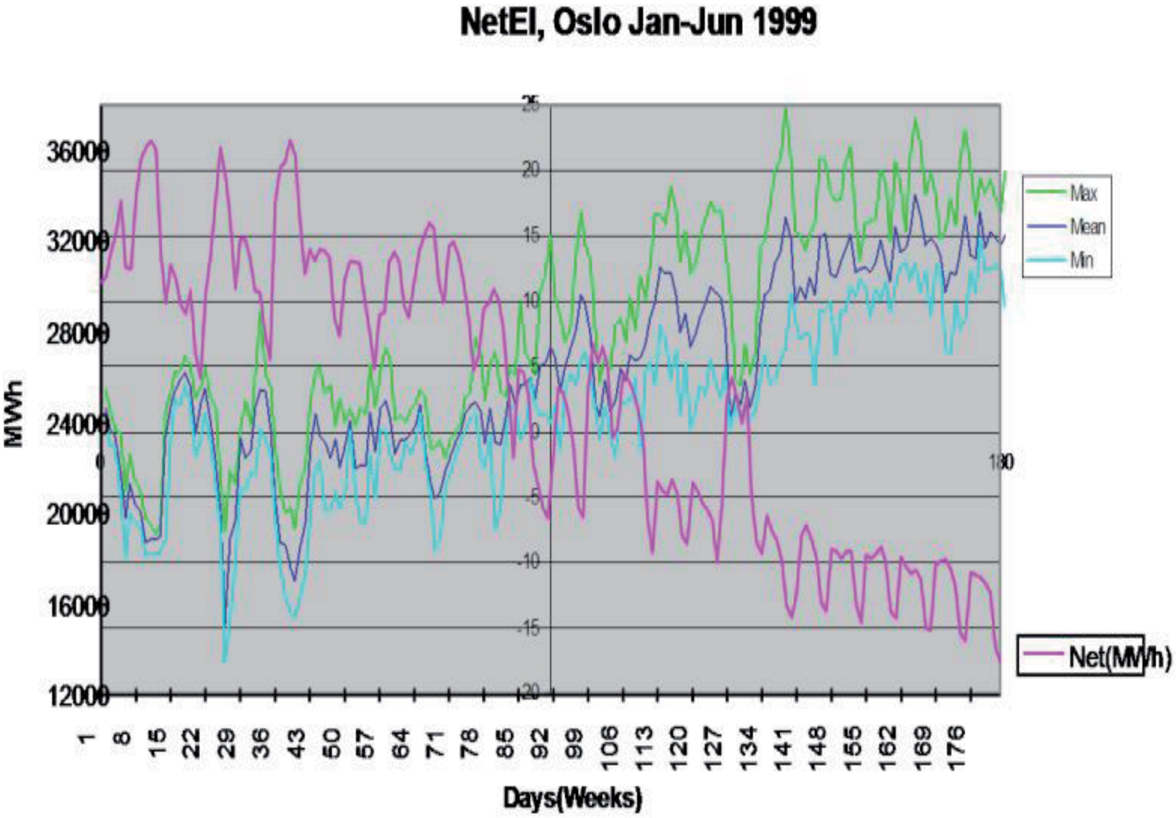

Figure 1. Example of temperature variation and consumption of electric power (The Norwegian Meteorological Institute, Oslo. Electricity data from the local transformer station)

particular to running heat pumps at night rather than in hot summer afternoons, as illustrated in Figure 3.

Figure 3 illustrates the benefits of operating the DTES based systems at night, compared to ordinary operation in the afternoon. Assuming a night temperature of 20°C (for 3-5 hours), if used in the afternoon at 36°C it gives a 67% improvement in Carnot efficiency, at 30°C in the day the improvement is about 45 %, and at 24°C about 25%. If the night temperature goes down to about 17°C, then the heat pump may be switched off altogether, with a reduction in energy demand of some 90%. These numbers apply at the site of cooling (they also obviate all upstream losses up to the excavation of coal in the case of coal-based electricity).

These energy savings result in economic gains following the reduced thermodynamic work needed to meet desired conditions in buildings. In addition there are further economic gains following particular characteristics in most thermal based electricity systems. This is discussed in the next section.

Economic savings (from off-peak tariffs)

Peak load categories and tariffs for commercial actors are based on peak demand at the end use site. The reduced peak demand from the DTES by reducing and shifting load may improve the classification category for the commercial enterprise and thereby lead to substantial savings.

Furthermore, in thermal based electricity generating systems where nuclear- and coal generating capacities play a significant role, there is significant price variation from day/night due to the combination of varying demand and the slow response of the aforementioned technologies. This is illustrated in Figures 4 and 5.

The EEX exchange in Germany (line with dots) is dominated by thermal generation, where plants either run at less than optimal load or are kept on standby – consuming fuel in order to deliver on short notice, but not actually generating. The Nordpool is flatter as it is much more influenced by hydro-power.

Typical patterns of demand with diurnal variation between countries and for summer/winter conditions are illustrated in Figure 5. The result is a price level at night less than a third of that of daytime. This has significant influence on economic performance made possible by the DTES.

In the next section we discuss systems where there are long time constants and need for larges capacity.

Synergy between dynamic- and borehole-based thermal storage

A DTES facility as discussed above, typically has fast response and high effect (power), but limited capacity for matching summer/winter variation and also passage of weather systems. Borehole-based thermal storage on the other hand has much larger capacity, but the effect is limited by the overall length of boreholes, and this is a major cost factor.

BTES is a well established technology based on 150-200 m deep holes drilled in bedrock. Clusters of boreholes may be constructed so that warm water is introduced or taken out from the centre of the cluster and cool water at the rim (or vice-versa in warm climates) to allow such clusters to act as thermal storage for annual variation. By combining these technologies the BTES may extract heat (store cold) 24 hours a day and save

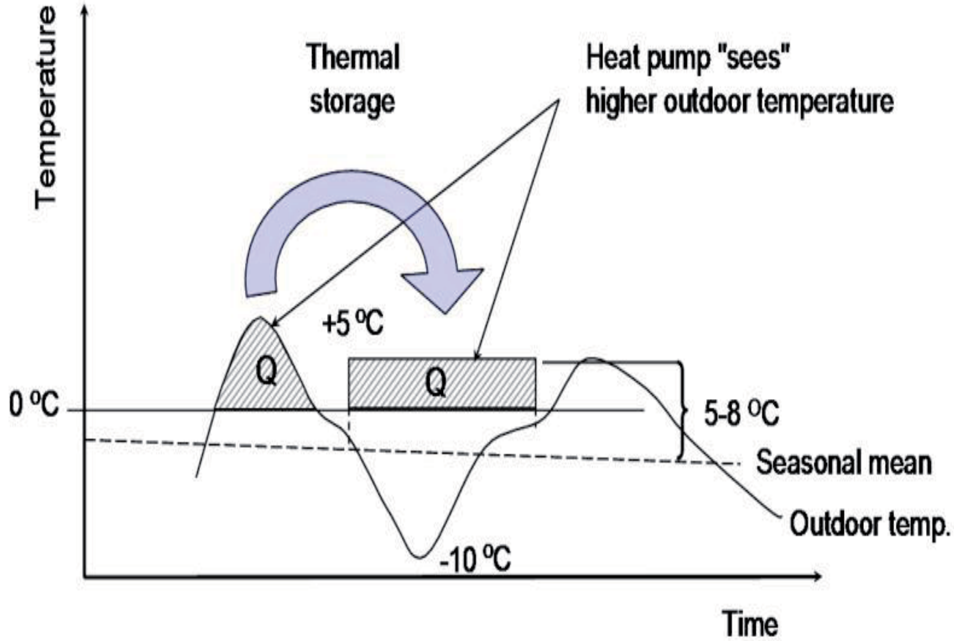

Figure 2. Illustrating the gaining energy from variation in outdoor temperature

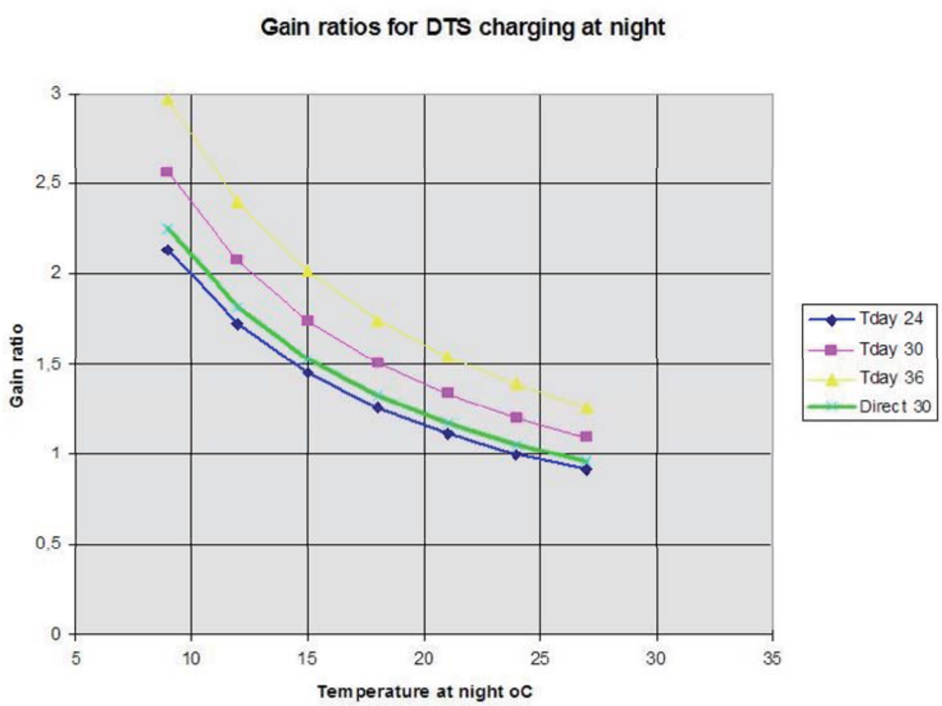

Figure 3. Improved Carnot efficiency from cooling at night with a DTES based system

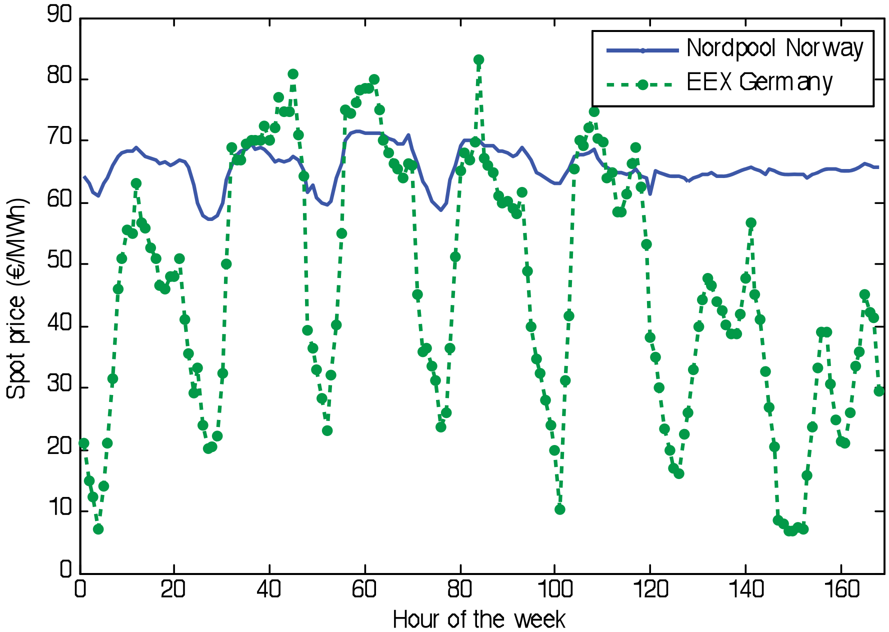

Figure 4. Electricity prices from Nordpool (Norway) and EEX (Germany) between 04.09.2006 and 10.09.2006. (Data provided by Energinet.dk. Nordpool is the Nordic Power Exchange, EEX is the European Energy Exchange)

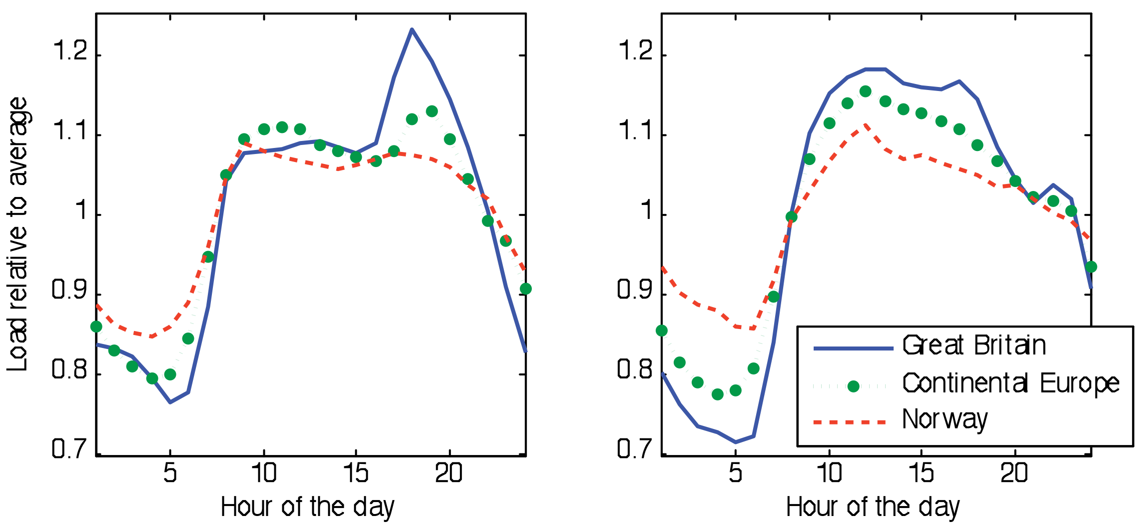

Figure 5. Typical intraday load variation in continental Europe (UCTE), Norway and Great Britain. (Data provided by UCTE, Statnett and National Grid)

this in a DTES for use while the building (say an office building) is being actively used, or while there is a cooling load in daytime. Another instance of synergy is where input of heat, say in a greenhouse, is too high in sunshine to be mastered by the BTES, and where a DTES may take up the slack.

Architectural freedom

The DTES and/or the combined BTES/DTES allows considerable architectural freedom for using large glassed surfaces in buildings, where efficient storage and retrieval of heat/cold allows operation of the glassed surfaces to act as solar heaters. The amounts of heat gained in this way may considerably exceed the energy used to move the heat around. Furthermore, indoors/outdoors may be visually integrated without the costs for cooling in warm climates becoming excessive.

Conclusions

The introduction of thermal storage opens a number of opportunities for obtaining of heat or cold by time-wise shifting demand from when it is needed to when it is available. Further opportunities are gained by combining BTES and DTES facilities. From study and evaluation carried out thus far, heat pumps may mostly work with a thermodynamic lift in temperature of not much more than 20°C, and when run, will operate near optimal operating conditions. Much cooling may furthermore be shifted from the heat pump to free cooling, also increasing overall efficiency. As far as may be judged now, this points to specific efficiency factors (overall "COP"-values) of 6, which is about twice the efficiency of traditional heat pump installations. Further studies are required for proper evaluation of costs.

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