Review and Comparison of Centralized and Decentralized Seasonal Thermal Energy Storage within Net-zero Energy Communities

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Abstract

The role of seasonal thermal energy storage systems within net-zero energy communities is explored. Seasonal thermal energy storage systems have been of interest in recent years, due to prospective benefits in areas of efficiency, economics and environmental impact. Depending on the composition and characteristics of a community, the most appropriate community thermal storage may differ from that for a single building. This study compares features of centralized and decentralized community-level seasonal thermal energy storage. Centralized and decentralized seasonal storage use is compared based on efficiency, economics and environmental impact, and associated benefits and shortcomings of each are identified. Overall both decentralized and centralized systems offer benefits but centralized systems are often better suited for communities.

Keywords: Thermal energy storage, net zero, community, efficiency, economy, environment

Résumé

Dans cette étude, on examine le rôle des systèmes de stockage saisonnier d'énergie thermique dans les communautés à consommation énergétique nette zéro. Ces systèmes ont suscité un certain intérêt au cours des dernières années, car ils présentent des avantages potentiels sur les plans du rendement, de l'économie et de l'impact environnemental. Selon la composition et les caractéristiques d'une communauté, le système de stockage thermique le mieux adapté peut différer de celui utilisé pour un bâtiment donné. Cette étude établit une comparaison entre les caractéristiques d'un stockage saisonnier d'énergie thermique centralisé et celles d'un stockage thermique décentralisé au niveau de la communauté. Les systèmes de stockage saisonnier centralisé et décentralisé font l'objet d'une comparaison en ce qui a trait au rendement, à l'économie et à l'impact environnemental; on énumère aussi les avantages et inconvénients des deux modes de stockage. Bien que dans l'ensemble, les systèmes centralisés et décentralisés offrent des avantages, le stockage centralisé est souvent mieux adapté à une communauté.

Mots-clés : stockage d'énergie thermique, consommation énergétique nette zéro, rendement, économie, environnement

1. Introduction

A community can be considered as a collection of buildings. Examples of different types of communities include residential, commercial and industrial. In Canada the built environment, consisting of houses, buildings, and the communities they form, account for approximately 50%

of all energy consumed in Canada [1]. Since the beginning of the 20th century the distribution of Canadians who live in urban communities has increased from 38 percent to 80 percent in 2009, with a projected increase to 85 percent by 2020 [2]. The Canadian population is also increasing, and it is estimated that the population will approach 43 million by 2050 [2]. The combination of high overall energy consumption in buildings, increasing population and community distribution suggests that there will be an increase in community population and an associated increase in their contribution to the national energy consumption. Natural Resources Canada estimates that the energy use within communities will grow non-linearly in the future [2]. Figure 1 illustrates the estimated increase in energy use for a variety of community related sectors; sectors of importance include industrial, commercial and residential.

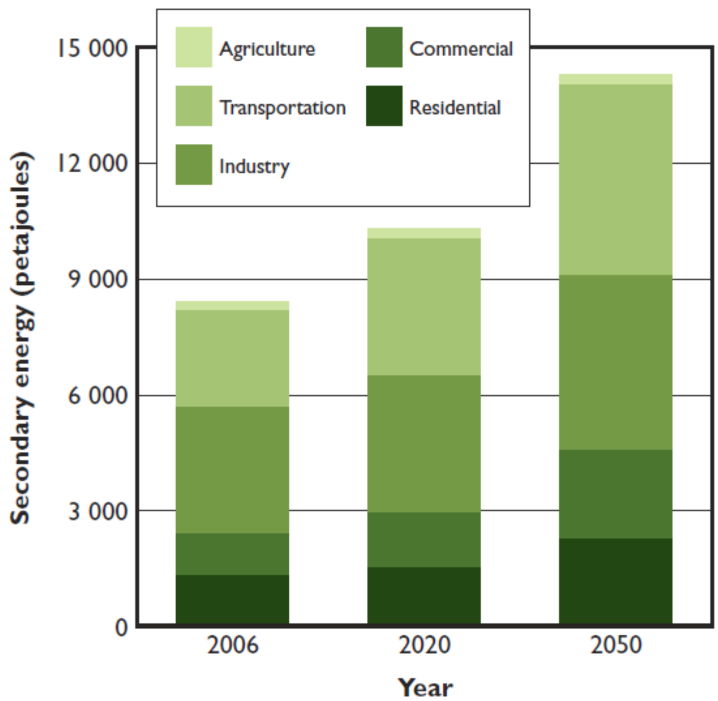

Figure 1: Forecasted growth in community energy use [2]

Measures are needed if the increases in energy use and related greenhouse gas emissions for communities are to be mitigated. Net-zero energy communities can contribute in this area. A net-zero energy community is a community that produces as much energy as it consumes, averaged over a year. Many enabling technologies/processes for net-zero communities are being investigated, including advanced building design and control, renewable energy integration, high efficiency energy systems, and energy storage.

Thermal energy storage (TES) has good potential for assisting communities in becoming net-zero energy. TES typically involves short-, medium- or long-term storage of thermal energy at high or low temperatures (i.e., above or below the environment temperature) for use later. Examples of TES applications include the storage of solar energy during the day for overnight heating, of summer heat for use in winter, and of winter ice for summer cooling.

TES serves various purposes, including energy conservation and substitution, and energy peak shifting. TES systems can provide reduced energy costs, reduced energy consumption, improved indoor air quality, increased flexibility of operation, reduced initial and maintenance costs, reduced heating and cooling equipment size, more efficient and effective utilization of equipment, conservation of fossil fuels, and reduced pollutant emissions [3]. Reducing energy consumption through storing waste or surplus heat, or storing off-peak energy for later use, can offset in whole or part the need to purchase additional equipment for heating or cooling applications and can reduce equipment size [3].

In a seasonal thermal energy storage (STES) system, waste heat from a building or industrial process and/or energy from solar gains during the summer, charge a storage via a heat exchange system, for discharge and use in the winter [4]. Thermal storage systems can also be used to store below ambient energy; ambient cold can be used to cool a storage media and the low-temperature energy can be used for space conditioning during summer months [5]. STES has been demonstrated to be able to provide significant benefits in terms of efficiency and utilization of renewable energy. For example, when combined with solar thermal technology, in a residential setting, STES allows for a solar fraction in a typical range of 50 to 70 percent for space heating and domestic hot water [6,7]. The concept of combining renewable energy technology and seasonal thermal energy storage has been demonstrated before, one well known project that illustrates this combination is the Drake Landing Solar Community in the town of Okotoks, Alberta, Canada. The Drake Landing Solar Community combines solar thermal systems with seasonal underground TES and achieves solar fraction of 90 percent [8]. The main reason for the high solar fraction is that the seasonal time shift between irradiance and heat demand is compensated by storing unused solar energy in a STES [9].

There are essentially two methods of implementing STES for the creation a net-zero energy community: decentralized, where separate TES units are installed in each building, and centralized, where multiple buildings use a common TES system [4]. The objective of this study is to qualitatively compare centralized and decentralized STES within a community setting. Centralized community-level and decentralized building-level seasonal storages are compared, in terms of storage media, efficiency, economics and environmental impact, and associated benefits and shortcomings of each are identified.

2. Storage systems/media

A variety of storage systems are currently being utilized globally. High capacity storage systems are necessary for STES do to the extended storage duration, accounting for thermal losses, and reduced charging potential during use; reduced above and below ambient temperature charging during winter and summer respectively [10]. High capacity storage is implemented mainly through storage types employing either water or ground as the storage media. Except for the use of above-ground water tanks, storage techniques tend to be subsurface [10]. Subsurface storage techniques are typically referred to as underground thermal energy storage (UTES). With UTES the storage volume is naturally filled with substances including ground water and soil.

If the storage requirement is less than a few thousand m^3, or < 100 MWh, which is typically the case for a single building, then above-ground storage systems are usually the cheapest alternative [10]. Above-ground seasonal storage tanks are typically constructed of steel or concrete. The volume of the storage tank for typical single-family high-efficiency home in a northern climate is approximately 80 m^3 [11], which would account for a significant amount space within a home or property. Within a community this would account for a significant amount of space that could otherwise be used for other community developments. Alternatively UTES systems can be installed within single buildings to reduce the visible footprint, but this may not be an appropriate option if the individual property dimensions, within a community, are not large enough to accommodate such systems. Also there may be additional installation costs associated with small scale UTES which may prove to be uneconomical. The total storage volume for multiple buildings or homes increases correspondingly compared to the volume for a single house.

For larger volumes, different subsurface storage concepts become interesting due to much lower costs. Thus the best thermal energy storage technology may change with the capacity needed. The thermal requirements of a community, as a whole, can be quite large in comparison to a single building, often leading to the use of TES systems with very high capacities within centralized arrangements. With conventional TES systems, an increase in storage capacity directly correlates to an increase in system size and storage media volume [4]. The use of above ground systems for centralized STES can be obtrusive due to their size, for many applications, and the cost of manufacturing the storage system must include a container to accommodate the storage media. In general the most appropriate method of centralized seasonal thermal energy storage is thought, by some, to be underground thermal energy storage [11]. Examples of UTES systems include borehole TES, aquifer TES, cavern TES, and earth-pit TES [12, 13].

3. Efficiency/performance

One aspect of the performance of a TES system can be measured by comparing the amount of energy recovered from a system to the amount of energy originally input. The main factor that detracts from the performance and efficiency of a thermal storage system is thermal loss over the storage duration. A well designed TES system should allow for reasonably low thermal energy losses and high corresponding energy savings, while permitting the highest reasonable storage efficiency [3].

A basic definition of energy efficiency for a thermal energy storage system is:

$$\eta = \frac{Energy\ in\ product\ outputs}{Energy\ in\ inputs} \tag{1}$$

where the denominator represents the amount of energy supplied to a thermal storage system and the numerator is the amount of energy that is recovered from the storage system after a period of time.

For seasonal storage, larger storage volumes often offer improved efficiency and other advantages compared to smaller systems [10]. A significant advantage of large volume storage systems is that the relative heat losses decrease with increasing size; the relative heat losses to the surroundings are proportional to the surface area-to-volume ratio (A/V) [10], where

$$\frac{A}{V} = \frac{Storage\ surface\ area}{Storage\ volume} \tag{2}$$

The A/V ratio is important in thermal energy storage because, as the size of an object increases for a constant shape, the volume increases faster than the surface area.

Combining numerous small thermal energy storage systems into a single large system, with an equivalent total volume, typically reduces the total associated surface area, which leads in turn to a decrease in the heat transfer rate from the storage media to the surroundings. This normally results in improved efficiency for large centralized systems compared to small single building systems. The benefit of using a larger system for multiple buildings is a reduction of the required initial energy supplied to the system for storage as well as the potential for an increased storage duration [10]. In the context of net-zero energy communities, the use of integrated centralized storage has the potential to reduce energy use and corresponding emissions compared to smaller, less efficient systems employed in every building.

Seasonal underground thermal energy storage systems may offer efficiency benefits compared to above-ground storage tanks in terms of thermal losses and efficiency. Depending on the location and design of an above-ground storage tank there is the potential for increased thermal losses which are associated with changes in season and related ambient conditions [14]. For example a poorly insulated storage tank that is located outside is exposed to low temperatures in winter when it is storing above warm ambient thermal energy. As winter progresses an increased temperature difference would promote heat transfer from the storage unit and induce unwanted losses. In the case of underground thermal energy storage variations in season do not affect ground temperatures to a significant extent [15].

4. Economics

Buildings are generally subject to long term variations in heating and cooling loads due to seasonal changes, especially in high latitude locations. Typical buildings require little heating during the summer and little cooling during the winter. Long term energy storage permits high temperature energy obtained during summer months to charge a storage for use during winter months. During winter, low temperature energy can be stored for cooling during the summer. The ability to store energy seasonally creates an opportunity for a reduction in operational costs, compared to systems without storage. Energy storage also offers the opportunity to store high and low temperature energy at times when it is inexpensive to generate or harness. When the heat or cold is derived from an energy source that has low operating costs, i.e. solar energy and winter ambient cold, building HVAC operating costs can be low.

When considering the economics of seasonal storage for a community and a single building, economies of scale are significant [8, 16], as larger systems notably benefit from economies of scale [5]. Fisch et al. [7] found that the when seasonal storage is combined with solar thermal energy systems the investment cost per unit collector area for larger systems is between 20% and 30% of the cost for single houses; well designed larger sensible storage systems are generally more efficient than smaller ones of the same energy density since larger sizes result in smaller area/volume ratios and therefore in lower relative heat losses, as pointed out by Kozlowski et al. [17].

Schmidt and Mangold [18] reviewed 65 solar heating plants with more than 500 m^2 of installed collectors in Europe, concentrated mostly in Germany, Austria, Denmark and Sweden. Schmidt et al. [9] reported investment costs, per equivalent water storage volume, for storage systems using four different storage methods (see Figure 2, where solid symbols represent realized projects and hollow symbols represent projects that were only studied). The trend that emerges is that larger systems cost less per equivalent storage capacity, suggesting that large centralized, community based, thermal energy storage systems are economically advantageous.

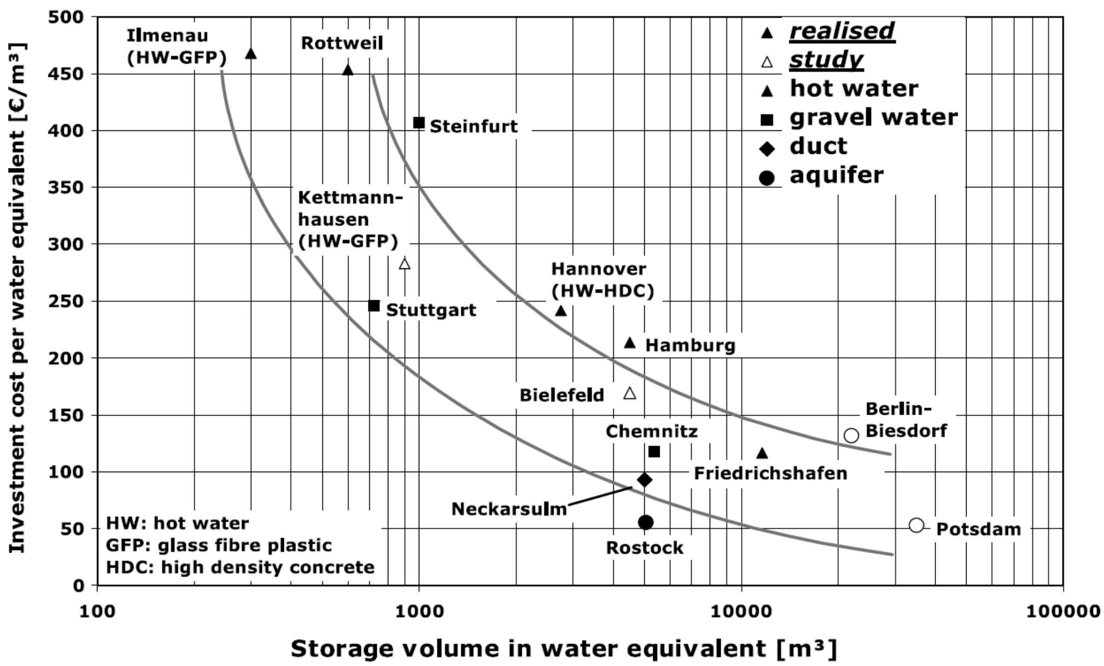

Figure 2: Investment cost of seasonal heat stores in Germany [9]

A significant challenge for seasonal storage is commonly the high capital cost associated with system construction and installation. Seasonal thermal storage systems require enhanced designs and large equipment, both of which result in high capital costs. Access to funds or the ability to raise funds at reasonable interest rates may hinder potential TES installations. Access to funds does not constitute a major barrier for TES technology overall [3], but the projected payback periods are often not appealing to many.

When considering the installation of a seasonal TES system into a single building the owner of that building will most likely be the main financier. To encourage positive economic scenarios, for the owner initializing the installation, ownership should continue through the duration of the payback period and efforts should also be made in promoting the economical benefits of the TES system to potential building purchasers. This may discourage many installations within individual buildings, especially where there is a high turnover rate in ownership.

With the installation of a large scale centralized TES system the capital cost is typically shared between numerous parties [8]. Large scale TES facilities sometimes offer the opportunity for a financial consortium. Such Consortia may include local, provincial and federal authorities, and energy utilizes, which can usually obtain funding [3]. End users can also contribute funds through the implementation of user fees for thermal energy supply services and as is the case in the Drake Landing Solar Community [8]

National, provincial, and municipal incentives and subsidies can reduce initial cost of STES systems [8]. A review of the current and past national incentive programs in Canada shows that there are numerous incentives for medium and large scale projects that reduce energy consumption and promote the use of environmentally friendly technology and practices [19]. Examples of such programs include the Technology Early Action Measures (TEAM) program [8], the Sustainable Development Tech Fund [20], the EQuilibrium™ Communities Initiative [9], the Green Infrastructure Fund [21] and the Green Municipal Fund [8]. For these programs, eligible projects are of large scale and offer energy and environmental benefits. Given the broad eligibility of these programs, centralized STES community projects often have high potential for receiving funding.

Incentives also exist for individual buildings and small scale projects. A review of national, provincial, and municipal programs in Canada demonstrates that the rules for eligibility are more defined in these situations. Overall the programs offer financial assistance to cover a portion of the associated cost of specific technology upgrades, for example upgrading to high efficiency appliances, compact fluorescent or LED lighting, and R-2000 homes [19]. Given past and current programs and their rules for eligibility it may be difficult for individuals to acquire financial assistance when implementing a STES within a single building, especially when it is of small scale such as residential.

5. Environmental impact

Seasonal thermal energy storage can reduce environmental impacts of energy systems, by reducing fossil fuel consumption and associated greenhouse gas and other emissions and increasing system efficiency. The Drake Landing Solar Community uses a central solar heating plant with seasonal storage to reduce annual fossil fuel consumption by 89% and GHG emissions by more than 5 tonnes per home [16].

Centralized STES can have lower environmental impacts than decentralized systems. This can be observed by considering two communities that utilize underground STES, one with a centralized system and the other with a system for each building. Underground systems can affect the local ecology. There is likely to be better monitoring for large centralized system than for smaller systems, allowing problems (e.g. leaks, soil drying) to be identified and remedied. Such vigilance may not occur with decentralized systems, as small scale systems often do not receive the same monitoring as larger systems, with longer periods between inspections or neglect of inspections.

When underground STES is utilized thermal interactions between the storage system and the soil occur, which causes the local subsurface temperature to change [22]. When energy losses from an underground system are high there is an associated increase in the area that experiences a temperature change. Small single-building STES systems have high surface area to volume ratios; therefore the losses from these systems typically are relatively high compared to larger systems [10]. The additional energy being transferred to the surroundings leads to a larger affected area per unit volume of storage. If many small, decentralized, systems are spread across a community, the amount of energy transferred to the surroundings is multiplied. Therefore multiple decentralized systems may exhibit a greater affected area than a single centralized system, meaning multiple small systems could potentially cause larger variations from background soil conditions

6. Conclusions

Centralized and decentralized arrangements of seasonal thermal energy storage within communities can provide numerous common benefits: reduced energy consumption, reduced energy costs, improved indoor air quality, increased flexibility of operation, reduced initial and maintenance costs, reduced heating and cooling equipment size, more efficient and effective utilization of equipment, conservation of fossil fuels, and reduced pollutant emissions. But a comparison of centralized and decentralized seasonal thermal energy storage suggests that a centralized setup is likely to be most advantageous for net-zero energy communities. Possible benefits of large centralized systems over current building-based systems include:

- Increased efficiencies due to reduced relative heat loss in large systems
- Reduced emissions through increased efficiency
- Reduced specific investment cost through capital cost sharing among multiple users
- Reduced operating costs

The present study discusses centralized and decentralized seasonal thermal energy storage systems through a qualitative comparison using information found in previous studies, general trends and national statistics. For a complete understanding of the most appropriate seasonal TES system, for a community, a detailed analysis should be performed. Future work in this field may include quantitative investigation into scenarios where centralized and decentralized systems become efficiently, economically, and environmentally competitive. Other potential work may include investigation into possible centralized/decentralized hybrid TES system arrangements.

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