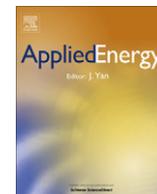


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Applied Energy

journal homepage: [www.elsevier.com/locate/apenergy](http://www.elsevier.com/locate/apenergy)

## Low-energy buildings and seasonal thermal energy storages from a behavioral economics perspective

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### HIGHLIGHTS

- The state and potential of the STES technology is presented.
- STES and 5 conventional heating alternatives are compared for standard and passive houses.
- The relative competitiveness of STES is found to be higher when it is used with passive houses.
- Behavioral economics theory is used to analyze investments and market barriers in STES.
- The combination of passive houses and STES could avoid individual discount rates from rising.

### ARTICLE INFO

#### Article history:

Received 30 September 2012  
Received in revised form 20 March 2013  
Accepted 21 March 2013  
Available online xxxx

#### Keywords:

Seasonal thermal energy storages  
Passive houses  
Behavioral economics  
Solar energy

### ABSTRACT

The seasonal thermal energy storage technology for domestic heating applications is not enjoying the same increasing market penetration as the smaller diurnal thermal energy storage technology. Although high efficiencies are to expect with seasonal thermal energy storages, high up-front costs are likely to constitute an efficient market barrier, impeding the growth of this technology. This paper analyses the application of seasonal thermal energy storages and other, more conventional heating alternatives on passive houses and standard houses from a behavioral economics perspective. The results show that when the seasonal thermal energy storage technology is applied to passive houses, more competitive investment and annual costs can be offered.

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### 1. Introduction

The harnessing of renewable solar energy is of great importance in order to secure the energy supply to an increasing population on the earth while reducing the emissions of CO<sub>2</sub> for a mitigation of climate change. Solar technology has had tough competition from low prices of oil and natural gas during the 20th century, which has resulted in a low market penetration. However, the prices of oil and natural gas are believed to increase and solar energy offers a way out of the dependence on these fuels. In order to increase the use of solar energy, thermal storages can be used to make excessive heat available at a later time when there is a heating need. The size of the storage is adapted to the time-scale of the application, which can vary from a diurnal to a seasonal scale. While diurnal thermal storages have enjoyed an increasing market penetration over the world, seasonal thermal storages have not shared the same increase in use. Consequently, there is an

untapped potential for solar energy in combination with the seasonal thermal energy storage technology.

Putting it in perspective – ways to increase the use of renewable solar energy with STES has been available for a long time. The ‘MIT Solar House #1’, which was built in 1939, used solar energy together with a seasonal storage for domestic heating applications [1]. The ‘Heating Ventilating and Air Conditioning’ community shares the opinion that one of the most important factors for an increased adoption is the development of economically competitive alternatives for seasonal storage of thermal energy [2]. In particular in high latitude countries like Sweden, where the space heating need and solar radiation are out of phase. The Swedish energy agency submits that the problem of reaching an increased market diffusion is not caused by a lack of knowledge of STES, which is considered to be high, but by the high cost [3].

Even though high economic and technological efficiencies can be reached with the large-scale seasonal thermal storages, high investment costs, logistical challenges and risks follow which are likely to impede the growth of the technology. However, if STES is applied on low-energy buildings instead of standard houses,

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each household will face a lower up-front investment cost since more households can share the storage, or, smaller storages could be built for the same number of households. The diffusion of an innovation is influenced by many variables such as institutions, economic structures, actors and societal subsystems, and changes first occur on a large scale in the society when the adoption rate of a technology together with the feedback from the evolving dynamics has gained a certain momentum. [4], [5] If the technologies of STES, solar energy and low-energy buildings are used together, it could help them reach stronger market competitiveness faster since the success of each of them could create positive feedback for the other technologies.

In order to bring new understanding in how STES can reach a higher market penetration and how it should be developed, it is of importance to study not only the technical aspects of the innovation but also its application from a higher system level, including other, non-technical aspects. With a focus on Sweden, this paper aims to analyze and discuss the diffusion and application of seasonal thermal energy storages (STESs). Based on the seasonal heat storage in Anneberg, Sweden, built in 2001/2002 for standard houses, this paper analyses the competitiveness of this technology and how an application on passive houses changes the competitiveness. The seasonal thermal energy storage technology is compared with other, more conventional heating alternatives, both for passive houses and standard houses. Thereafter, insights from Behavioral economics are used to discuss the diffusion of the STES technology and why it is not enjoying a satisfactory market penetration.

## 2. Methodology

In this paper a literature survey of the current state and potential of the seasonal thermal energy storage technology is carried out. With a focus on Sweden and Germany, built examples are studied from a techno-economical perspective. Additionally, the passive house concept is explained and applied to seasonal thermal energy storages. With the purpose of identifying eventual changes in the competitiveness, the different heating alternatives are analyzed for standard and passive houses. These alternatives are then discussed from a behavioral economics perspective, which is important since an investment is a result not only of techno-economic aspects but also of emotional, cognitive and societal factors. This perspective can therefore provide explanative resources for decision-making and investing behavior.

## 3. Seasonal thermal energy storages

Heat is usually stored in sensible, latent or chemical heat storages. Of these, the most developed technology is the sensible, which is “well demonstrated, clearly understood and cheaper than the alternatives” [2]. Therefore, the focus lies in this paper on the sensible heat storage technology. Seasonal thermal energy storages are used to store heat from summer to winter but can also be used to store cooling from winter to summer. Due to the long time-scale of seasonal storing, the temperature difference between the inside and outside of the storage will contribute to leakage from the storage that is hard to avoid even with a high degree of insulation. The use of thermal energy storages opens up for the possibility of using excess heat from nearby industries or buildings to help heating the storages. For residential applications, which this paper focuses on, water is commonly used as storage medium due to its: high heat capacity, low cost and good properties in the temperature span between 20 and 80 °C. Most commonly, the water is stored in water tanks, aquifers, solar ponds and boreholes or in rock beds, gravel or soil. However, the storage method best suited varies from case to case since it depends on the properties of the area such as capacity,

temperature of storage medium, and climate and the condition of the soil.

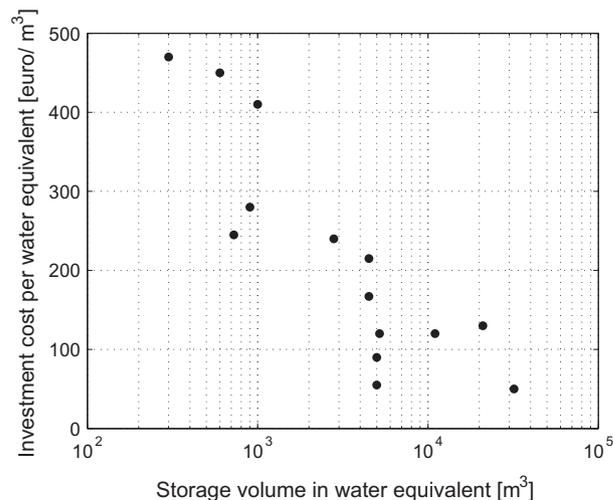
Large-scale seasonal storage systems have been studied in the IEA SHC Programme Task 7 [6], in the Solarthermie2000 [7] and Solarthermie2000plus [8] programmes. Leading countries in the STES technology have been Canada, Germany and Sweden [9]. Ref. [10] submits that for boreholes, averaged costs in general are competitive or better than district heating. In Europe, the seasonal thermal energy storages usually reach a solar fraction of around 30–60%, this with energy storages sizes of around 300–4000 MW h/year and these storage systems result in investment costs per water equivalent of around 50–500 €/m<sup>3</sup>, see Table 1. The first generation of storages in Germany resulted in costs between 1.2 and 3.2 Million € and the following second and third generations could offer solar system costs between around 0.26 and 1.7 Million €. Additionally, calculated values for long-term operation resulted in values of 160–420 €/MW h.

Fig. 1 below shows the investment cost per volume €/m<sup>3</sup> as a function of storage volume (m<sup>3</sup>) of water equivalent in German seasonal heat stores. The x-axis has a logarithmic scale and there is an increased energy-efficiency that comes with an increased storage size.

For Sweden, the solar energy technology began during the oil crisis in the seventies. However, back then the technology did not meet desirable quality and the investment costs were too high [13]. Thereafter, Swedish solar energy has during some decades improved and produced large-scale solar collector fields in Kungälv, Säter, Nykvarn, and the solar plant in Falkenberg which at the time it was put into use (1989) was the largest array of solar collectors in the world. Eleven large-scale solar thermal projects that were built in Sweden during 1979–2000 have reached results around; 300–370 kW h/m<sup>2</sup>, cost per energy between 5.6 and 24 Ct/kW h, costs per area of 220–800 €/m<sup>2</sup> and the areas have varied be-

**Table 1**  
German seasonal thermal energy stores [8,11].

Parameter	Value
Heat demand	300–4000 MW h/year
Investment cost	50–500 €/m <sup>3</sup>
Solar fraction	30–60%
Cost of system	0.26–3.2 Mio. €
Solar heat costs	160–420 €/MW h



**Fig. 1.** Investment costs per volume (€/m<sup>3</sup>) as a function of storage volume (m<sup>3</sup>) of water equivalent in German seasonal heat stores [12].

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