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The Sundsvall hospital snow storage

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Abstract

During the summer, the regional hospital in Sundsvall in central Sweden requires 1000 MW h of cooling with a maximum cooling power 1500 kW. From the summer of 2000, seasonally stored snow will be utilised to meet the cooling demand. A storage area of 140×60 m with a capacity for 60,000 m^3 (40,000 tons) of snow was constructed in 1999. Initially, about half of this volume will be stored. The storage consists of a shallow pit made of watertight asphalt. A layer of wood chips covering the snow reduces the natural melting to 20–30% of the total volume. Meltwater from the snow storage is pumped to the hospital. After cooling the hospital, the heated meltwater is re-circulated to the snow storage. When all the snow has melted, the wood chips will be burnt in a local heating plant. Luleå University of Technology is responsible for the scientific evaluation of the project. This paper describes the construction and the simulated operation of the snow storage system.

Keywords: Snow; Cooling; Energy storage; Renewable energy

1. Introduction

Ice storage for cooling was used already in ancient Greece. Ice was harvested from lakes and rivers and stored in barns that were thermally insulated by sawdust (Taylor, 1985). This technique was common in Europe and North America until the beginning of the 20th century, when cooling machines were introduced (MacCracken and Silvetti, 1987). During the last decades, however, new techniques using snow and ice for both comfort cooling and food storage have been developed.

Fabrikaglace is an un-insulated box inside an insulated shelter. Thin layers of water (a few millimeters) are frozen by cold air blown at the water surface, at suitable locations more than 20 m of ice can be formed. To extract the cold, meltwater is pumped to a heat exchanger and then re-circulated to the ice. Flexible walls have been used to manage the problem with ice-creeping and thermal expansion of the ice. The size of existing Fabrikaglaces varies between a few up to 250 MW h with cooling powers from 8 to 1600 kW (Buies, 1985). The coefficient of performance (COP) is about 95 (Abdelnour et al., 1994). The high construction cost requires large-scale

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plants or high cooling power (Morofsky, 1984). The technique has not been widely used so far because of, among other reasons, higher initial cost and lack of awareness and knowledge by architects, engineers and others (Canada, 2000).

Ice ponds are based on the concept to use ponds, or pits, to store snow, ice or slurry. The ponds have a rubber or plastic fabric bottom and some top insulation. The ice/snow is produced with nozzles or snow blowers. Cold is extracted by re-circulation of meltwater. Ice ponds can combine cold storage and water cleaning since impurities are separated from the ice as it freezes. Cold storage capacities vary from 50 to 650 MW h with cooling powers from 8 to 1600 kW (Taylor, 1985). The COP varies between 50 and 2000 (Abdelnour et al., 1994).

Himuros and Yukimuros are traditional Japanese buildings made of stone or wood with one part for ice or snow and another part as a storage for vegetables, fruits, etc. (Okajima et al., 1997). Natural convection and occasionally shutters control the air circulation, resulting in a low and stable air temperature with high relative humidity. Both artificial and natural ice/snow are used. There is no size constraint for Himuros/Yukimuros (Kobiyama, 1987).

The All Air System is another Japanese technique where air is cooled by direct contact with snow. In this system, both temperature and humidity can be controlled (Kobiyama et al., 1997) and pollutants removed from the air (Iijima et al., 1999). This system has mainly been used for food storage, but there are also examples of comfort cooling (Kaneko et al., 2000). There are more than 50 snow and ice storage cooling plants in Japan today. Some of them are test plants while the rest are commercial plants (Kobiyama, 1997).

Seasonal Snow Storage for cooling has been studied in Ottawa, Canada (Morofsky, 1982). The idea was to use snow that has to be removed from streets and squares and transport it to a snow deposit; a deposit of 90,000 m^3 of snow covered with a reflective and insulating cover was investigated. It was found that the best technique for cold extraction was re-circulation of the meltwater. The mean cooling load of 7 MW resulted in an estimated payback of 10 years. It would also be possible to store snow in underground rock caverns where such plants would be constructed in urban areas to reduce the snow transportation cost (Johansson, 1999). To reduce the snow volume, it is helpful to add water before compacting the snow (Vigneault, 2000). One major problem with urban snow deposits is that the meltwater is highly polluted (Viklander, 1994); by using snow storage, this contamination can be controlled and treated.

Short Term (Diurnal) Ice Storage with ice generated by refrigeration systems is another technique that has become increasingly popular in North America, Europe and Japan. This is economically feasible because of the varying electricity cost during the day. In Japan, for instance, the peak price around noon is five times higher than night price (Japan, 2000).

Snow and ice have excellent qualities for the storage of winter cold for cooling because of its 0°C melting temperature and its high heat capacity and heat of fusion. The heat amount required (E) to raise the temperature of ice from T_1 to 0°C, melt it, and raise the water temperature to T_2 is given by

$$E = (0 - T_1) C_{\text{ice}} + L + T_2 C_{\text{water}} \left[\text{kJ kg}^{-1}\right]. \qquad (1)$$

The heat capacity of ice at -5°C, $C_{\text{ice}} = 2.1$ kJ kg^{-1} K^{-1} (Dorsey, 1940); the heat of fusion of water $L = 333.6$ kJ kg^{-1}; and the heat capacity of water at 5°C, $C_{\text{water}} = 4.2$ kJ kg^{-1} K^{-1} (Hobbs, 1974).

2. The Sundsvall snow storage

The Sudsvall Regional Hospital, with a floor area of 190,000 m^2, is located in central Sweden. National regulations and environmental targets made the County Council of Västernorrland to look for new solutions in comfort cooling. The hospital's cooling demand is 1000 MW h a^{-1} with a maximum cooling power of 1500 kW. The chosen alternative was to use the nearby snow deposit as a cold source for the cooling system.

2.1. Principle

In seasonal snow storage, a major part of the cold is stored in the phase change from water to ice. Therefore, the heat transfer occurs by circulating the

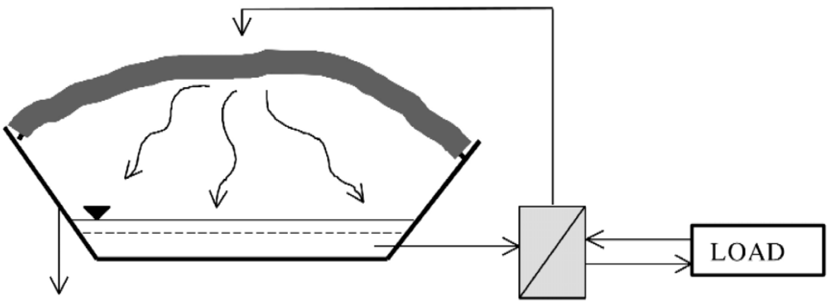

Fig. 1. Snow storage principle. The meltwater is re-circulated through the snow.

cooling media through the storage, melting the snow, Fig. 1. The snow is covered with some type of insulation to prevent natural melting. In the Sundsvall case, a layer of wood chips is used to reduce the heat transfer from air to snow and act as a cooler. This cooling effect is a result of the wood chips' absorption and evaporation of water.

The function of the snow storage was simulated in a feasibility study (Nordell and Sundin, 1998). Resulting snowmelt calculations were roughly verified by a performed small-scale test at the Sudsvall hospital during the summer of 1998.

2.2. Construction

The construction work of the Sundsvall Snow Storage was completed in November 1999 (Fig. 2). Snow was stored during the winter and at the begin-

Fig. 2. Picture of the Sundsvall hospital snow storage, November 1999.

ning of April 2000 the storage was thermally insulated by a layer of wood chips. The system was put into operation in June 2000.

Snow is stored onto a watertight, slightly bowl-shaped asphalt surface with the area 140×60 m. A possible maximum snow depth of 9 m means a storage volume of 60,000 m^3. A covering layer of wood chips (0.2 m) thermally insulates the snow. During the first winter of operation, 30,000 m^3 of snow was stored corresponding to approximately 20,000 tons of snow (snow density ~ 650 kg m^{-3}) and approximately 2000 MW h of cold.

The asphalt surface is slightly sloped to flow the meltwater towards the water outlet at the pump house. Here, the water is cleaned by a coarse meshed filter and an oil and gravel filter. It is pumped by two frequency controlled pumps (0.035 and 0.050 m^3 s^{-1}) to the heat exchangers (2×1000 kW). Between the pumps and the heat exchangers are automatically rinsed fine filters.

The meltwater leaves the storage at a temperature close to 0°C. In the heat exchangers, where the warm side is cooled from 12°C to 7°C, it is heated to 10°C. At the present maximum cooling power demand of 1500 kW, a water flow rate of 0.045 m^3 s^{-1} is required. The meltwater is then re-circulated to the snow storage to be cooled down and form more meltwater. This re-circulated water is distributed over the storage area by 36 individually adjustable valves (Fig. 3). The cooling power is controlled by the meltwater flow rate. This type of snow storage has no limit in extraction power, but its limitations are in the capacities of the pumps, heat exchangers, etc. As long as there is snow in the storage, the temperature of the meltwater will be close to 0°C. To avoid an increasing water level in the pit, part of the meltwater is occasionally diverted from the system.

Both natural and artificial snow will be used. The Sundsvall storage will be filled from December to February by urban snow transported from the clearing of streets and squares of the surroundings. During snow deficient winters, artificial snow will be produced by snow blowers.

The snow required to meet the cooling demand of the hospital is approximately 10% of all snow removed from the city. The overall cost of the project is 1.6 M EURO; however, this sum also includes costs that are not directly part of the snow cooling system. In a recent study (Näslund, 2000), based on experience from the Sundsvall snow storage, it was concluded that the construction cost of a similar storage of 120,000 m^3 snow ($\sim$ 6,000 MW h) would be about 0.8 M EURO. The estimated technical lifetime of the snow storage plant is 40 years. The estimated pay back time is approximately 3 years for a snow storage with the same basic conditions as Sundsvall hospital system, which are typical for space cooling in Sweden. A greater cooling power

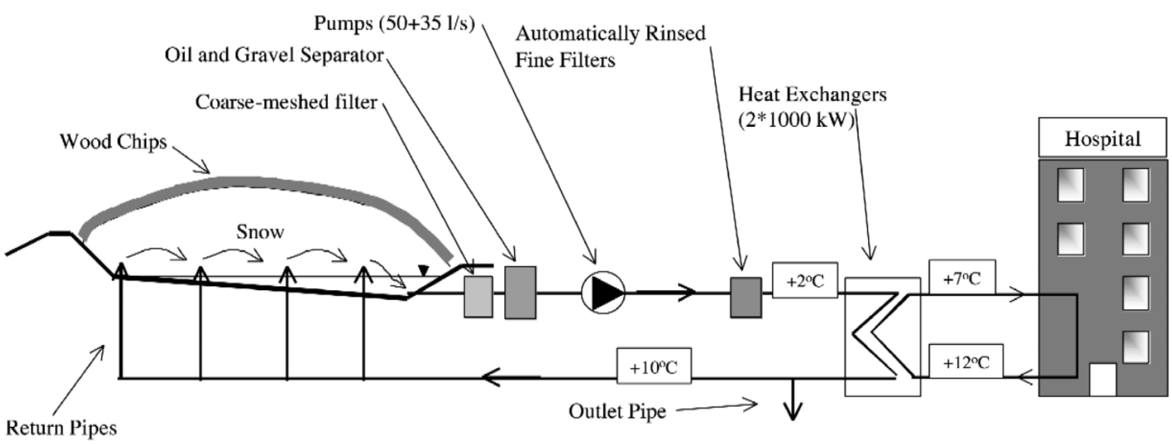

Fig. 3. Outline of the Sundsvall snow storage system.

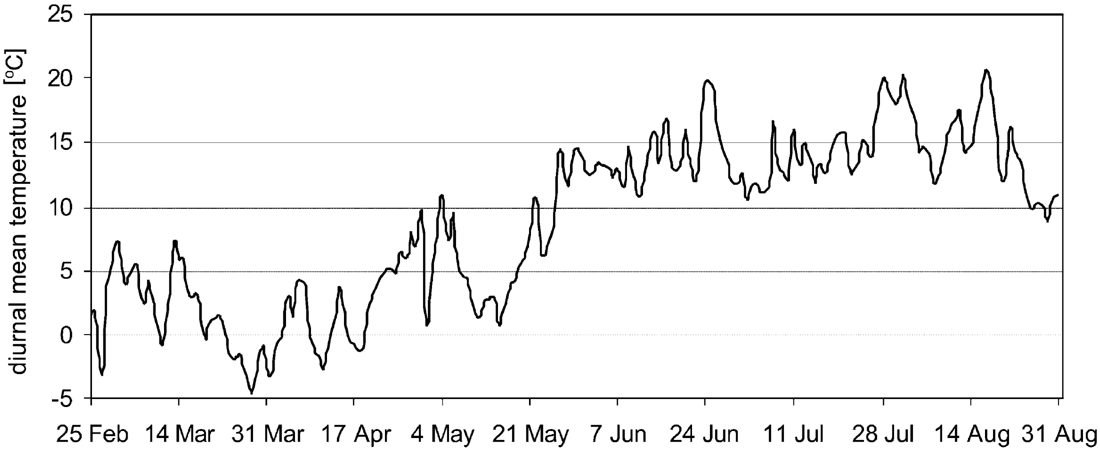

Fig. 4. The temperature series used in snow melt simulations.

would reduce the pay back time. For a large-scale system (5000 MW h, 5 MW) the pay back time is about 2 years.

3. Snowmelt simulations

Snowmelt simulations for a 30,000 m^3 snow storage, without insulation and with 0.10 and 0.20 m of sawdust, were performed to estimate the necessary sawdust thickness. Melting was divided into forced melting caused by cold extraction and natural melting caused by heat transfer from the environment. The forced melting was based on the estimated cooling demand of the hospital.

3.1. Natural melting

Natural melting occurs by heat exchange between the snow pile and its environment. Consequently, natural melting depends on climate, geometry of the storage, and thermal insulation.

The natural melting was divided into three parts: heat transfer from the air, from ground, and from rain. Heat transfer from the air and the ground is a function of the snow pile area, while heat transfer from rain only depends on the size of the storage area. In the simulations, the storage geometry was simplified by the shape of a cut cone with an initial height ($h = 4.0$ m), diameter ($d = 105.6$), and side slope angle ($\beta = 26.6°$). The ratio h/d was kept constant throughout the melting. The air temperature series used in the simulation is shown in Fig. 4. The snow density was assumed to be constant at 650 kg m^{-3} (Viklander, 1994).

Two different models were used to estimate the snowmelt from the air. In the un-insulated case a degree–days (DD) model was used. In the insulated case, heat conduction was assumed to control the heat transfer through the sawdust.

The DD model is the most common method for snowmelt modelling and gives satisfactory results (Sundin, 1998). It only requires mean diurnal temperature, snow density, and initial values of pile geometry (length, width, and height).

The DD model can be expressed as

$$\dot{V} = k\bar{T}_{\mathrm{air,diurnal}} A \qquad (2)$$

where $\dot{V}$ is the meltwater flow rate [m^3 d^{-1}], k is the degree day constant [m K^{-1} d^{-1}], $\bar{T}_{\mathrm{air,diurnal}}$ is the diurnal mean air temperature above freezing point [°C] and A is the snow pile area facing air, $A = f(V)$ [m^2].

The meltwater flow rate can also be written as

$$\dot{V} = \frac{\rho_s}{\rho_w} \Delta V_0 \qquad (3)$$

where ρ_s is snow density [kg m^{-3}], ρ_w is water density [kg m^{-3}] and ΔV_0 is diurnal snow volume decrease [m^3 d^{-1}].Eqs. (2) and (3) gives

$$\Delta V_0 = \frac{\rho_w}{\rho_s} k\bar{T}_{\mathrm{air,diurnal}} A. \quad (4)$$

Before the meteorological spring (defined as when $\bar{T}_{\mathrm{air,diurnal}}$ is roughly stable above ± 0°C, based on meteorological records (SMHI, 2000)), $k = 0.003$ m K^{-1} d^{-1} was used and from April 4th, $k = 0.011$ m K^{-1} d^{-1}. These k-values were empirically decided (Sundin, 1998).

In the insulated cases, the heat conduction equation was used to determine the heat transfer through the area facing the upper surroundings (from the air). Thermal conductivity of dry sawdust (12% water content) varies from 0.08 to 0.14 W m^{-1} K^{-1}, depending on the density. Thermal conductivity of water is 0.60 W m^{-1} K^{-1}. In these calculations, a thermal conductivity of 0.35 W m^{-1} K^{-1}, the mean value of 0.10 and 0.60 was assumed for wet sawdust. The natural snowmelt because of the heat flow from the air is then given by

$$\Delta V_1 = \frac{\lambda_{\mathrm{ins}} A_{\mathrm{top}} \dfrac{\Delta T_{\mathrm{top}}}{\Delta z}}{F\rho_s} 86{,}400 \quad (5)$$

where ΔV_1 is the natural snow melt volume [m^3 d^{-1}], λ_{ins} is thermal conductivity of sawdust [W m^{-1} K^{-1}], A_{top} is the top area of remaining snow [m^2], z is the thickness of sawdust layer [m], ΔT_{top} is the temperature differences $\bar{\mathrm{T}}_{\mathrm{air,\ diurnal}} - T_{\mathrm{snow\ surface}}$ [K], Δz is the thickness of sawdust [m], F is the latent heat of snow [J kg^{-1}] and 86400 is the number of seconds per 24 h [s d^{-1}].

The heat transfer from the ground was simplified as a one-dimensional heat flow from the ground water under the snow pile, by heat conduction from the 6°C ground water to the 0°C bottom of the snow pit. The ground water level at this location is about 1 m below the pit surface. Since the ground water flow is high, it was assumed that its temperature was constant. This resulted in a heat flow of 2.4 W m^{-2}, which is at the upper limit of the ground heat flow. The total snowmelt depends on the bottom area of the snow, which decreases with time.

Approximately one-third (240 mm) of the annual precipitation in Sundsvall falls between April and August (Swedish National Atlas, 1995). Assuming that the rainfall is evenly distributed during the summer and that the rain temperature is 10°C, rain results in a snowmelt of 2.1 m^3 d^{-1} or 390 m^3 totally.

4. Results

The calculated natural melting of the snow storage is shown in Fig. 5. The necessity of thermal insulation is demonstrated by the fact that an un-in-

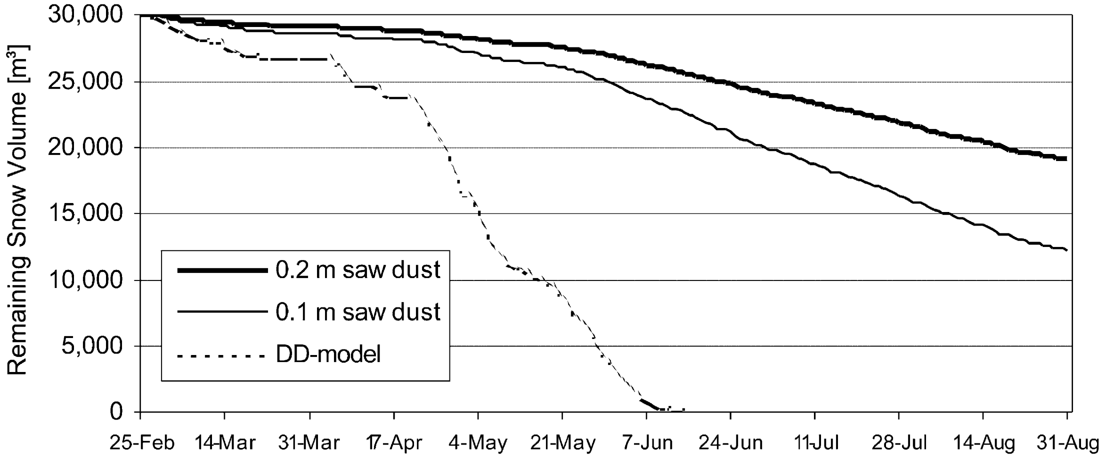

Fig. 5. Natural melting of 30,000 m^3 of snow with 0.1 and 0.2 m of sawdust and without thermal insulation (DD-model).

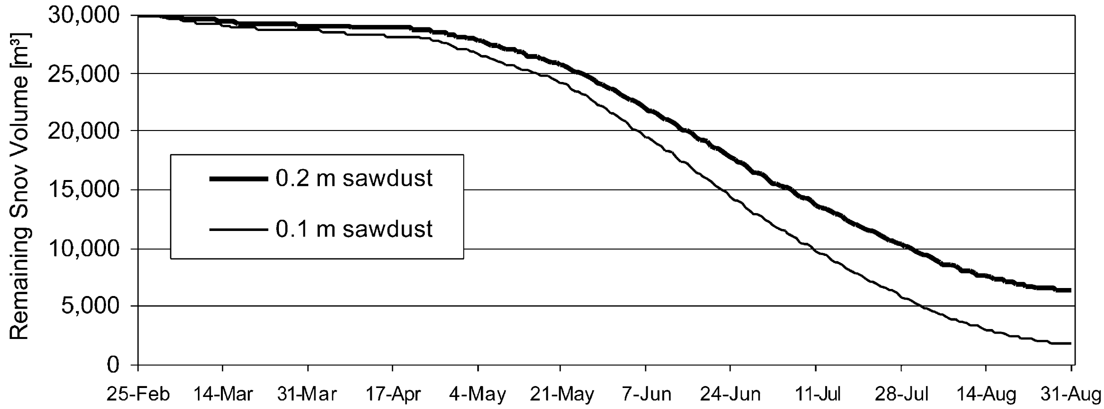

Fig. 6. Total melting for initial snow volume 30,000 m^3 with 0.1 and 0.2 m of sawdust as thermal insulation.

sulated pile would be gone by June 17th, i.e. long before the end of the cooling season. With thermal insulation, the remaining snow volumes were 12,169 m^3 for 0.1 m of sawdust and 19,040 m^3 for 0.2 m of sawdust. For 0.2 m of sawdust the maximum natural meltwater rate is 77.4 m^3 d^{-1} and occurs at the end of June. Heat transfer from the air contributes the major part of the natural melt; 16,128 m^3 with 0.1 m of sawdust and 9149 m^3 with 0.2 m of sawdust. Heat transfer from the ground melts 1313 m^3 of snow with 0.1 m of sawdust and 1422 m^3 with 0.2 m of sawdust. Heat transfer from rain melts 390 m^3 of snow.

When including the cold extraction of 1000 MW h (15,000 m^3 of snow) the total snowmelt becomes 28,181 m^3 for the pile with 0.1 m of sawdust and 23,676 m^3 for the pile with 0.2 m (Fig. 6).

5. Discussion and conclusions

A thermally insulated 30,000 m^3 snow storage covers the cooling demand (1000 MW h, 1500 kW) at the Sundsvall hospital over the summer (May–August).

The natural snowmelt was calculated for the un-insulated case and for the cases of 0.1 and 0.2 m of sawdust as thermal insulation. By natural melting, the un-insulated snow would be gone by mid-June. With 0.2 and 0.1 m of sawdust approximately 60% and 40% of the snow remained at the end of August. When cold extraction is included, 1800 m^3 of snow remains with 0.1 m sawdust and 6300 of snow remains with 0.2 m of sawdust. The major part of the natural snowmelt, about 83% in the thermally insulated case (0.2 m of sawdust), is caused by heat transfer from the air. Heat transfer from groundwater contributes with 13% and rain with 4%. Since the natural melting is highly dependent on the area facing the air, a more compact shape would reduce the melting significantly.

The storage technique is an example of utilising renewable energy. Since the temperature of the meltwater is constantly 0°C, snow storage has no power limit of cold extraction. However, detain time of the re-circulated water in the pit and the chosen capacity of pipes, pumps, and heat exchangers means a limit of the cooling power.

There is a great potential of snow storage for industrial, agricultural, and comfort cooling applications in large parts of the world. It is a natural technology where local resources are utilised to save prime energy resources. In Sweden, there is a growing interest for large-scale snow cooling. The snow collected from cities is polluted, but with this snow storage technique, the meltwater can be analysed and treated.

Based on the summarised pre-study (Nordell and Sundin 1998), the Sundsvall Snow Storage was constructed during 1999. Snow was stored during the winter 2000 and the storage was thermally insulated by a 0.2 m layer of the wood chips at the beginning of April. The system was put into operation in June. The maximum cooling power of the system is 2000 kW, which means a meltwater flow rate of 0.060 m^3 s^{-1} at an assumed temperature difference of 8°C.

The operation of the Sundsvall plant will be monitored, evaluated and reported. The total construction cost of the plant was about 1.6 M EURO. In a more recent study, it was concluded that the construction cost could be considerably reduced. The estimated lifetime for the snow storage plant is about 40 years. The estimated pay back time is about 3 years for a new project with the same conditions as the Sundsvall hospital system and decreases with increased cooling power and size.

The excellent thermal insulation qualities of wood chips for snow storage is not only because of the relatively low thermal conductivity, but also that absorbed water evaporates, thereby cooling the snow storage. This particular quality of wood chips (and sawdust) will be studied further at Luleå University of Technology. Snow pollution and possible treatment methods of the meltwater will also be studied.

Acknowledgements

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