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Climate Independent Snow Production and Solutions for Snow Storage

Klimauavhengig snøproduksjon og ulike
løsninger for lagring av snø

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Master of Energy and Environmental Engineering
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MASTER THESIS

for

Student Marianne Heimdal

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Climate Independent Snow Production and Solutions for Snow Storage

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Background and objective

In the perspective of increasing global temperatures, there is a challenge having available snow close to the cities and villages in the mountain for a reasonable winter season. The periods of natural snow is shorter and in some areas, the snow in the winter is disappearing. In Europe the facilities is moving to higher locations to be able to arrange winter games.

In the Nordic countries, it is also a tradition for doing winter activities in snow like kinder gardens, schools and for the families to go skiing in weekends and holidays. If the trend with milder winters is going on, the distance the individuals have to go from the homes to areas with snow will increase. To be able to maintain the snow activity close to the cities it will be of importance to produce snow independent of the ambient temperatures. Since this is an energy consuming process, the energy efficiency of the equipment is of importance and the possibility to utilize the heat for space heating or hot tap water, the emphasize on reducing the operational costs will be important. Since this snow is more costly to produce, the management of the produced snow will be important to avoid to high melt down during storage.

This master thesis will be in cooperation with Trondheim Kommune and Norwegian Ski Association within the project, "Snow for the Future", coordinated by SINTEF Energy Research. Trondheim Kommune will in the near future build a center in Granåsen that will give possibilities for future winter games and give the people possibility to enjoy the winter activity in the period from beginning of October to end of March.

The following tasks are to be considered:

1. Literature review of snow making equipment and snow storage
2. Further develop the model to include evaluation of different snow production and storage facilities
3. Define some scenarios on snow production and storage, outdoor and indoor, depending on type of snow production system, energy prices, weather conditions and possible heat recovery
4. Make an evaluation of the different solutions and size of snow storage, including operation and investment costs
5. Make a draft paper of the main results from the master thesis
6. Make proposal for further work

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Within 14 days of receiving the written text on the master thesis, the candidate shall submit a research plan for his project to the department.

When the thesis is evaluated, emphasis is put on processing of the results, and that they are presented in tabular and/or graphic form in a clear manner, and that they are analyzed carefully.

The thesis should be formulated as a research report with summary both in English and Norwegian, conclusion, literature references, table of contents etc. During the preparation of the text, the candidate should make an effort to produce a well-structured and easily readable report. In order to ease the evaluation of the thesis, it is important that the cross-references are correct. In the making of the report, strong emphasis should be placed on both a thorough discussion of the results and an orderly presentation.

The candidate is requested to initiate and keep close contact with his/her academic supervisor(s) throughout the working period. The candidate must follow the rules and regulations of NTNU as well as passive directions given by the Department of Energy and Process Engineering.

Risk assessment of the candidate's work shall be carried out according to the department's procedures. The risk assessment must be documented and included as part of the final report. Events related to the candidate's work adversely affecting the health, safety or security, must be documented and included as part of the final report. If the documentation on risk assessment represents a large number of pages, the full version is to be submitted electronically to the supervisor and an excerpt is included in the report.

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The final report is to be submitted digitally in DAIM. An executive summary of the thesis including title, student's name, supervisor's name, year, department name, and NTNU's logo and name, shall be submitted to the department as a separate pdf file. Based on an agreement with the supervisor, the final report and other material and documents may be given to the supervisor in digital format.

☐ Work to be done in lab (Water power lab, Fluids engineering lab, Thermal engineering lab)
☐ Field work

Department of Energy and Process Engineering, January 30th 2018

Trygve M. Eikevik, Professor
Academic Supervisor

Research Advisor:
Dr. Ignat Tolstorebrov, NTNU, ignat.tolstorebrov@ntnu.no

In agreement with supervisor Trygve M. Eikevik, the description of tasks have been adapted. This thesis focuses on development of a realistic and accurate snowmelt model and different solutions for snow storage. Due to that, the evaluated scenarios, calculations and cost estimations done in this work do not consider different snow production systems. Costs related to snow production are not included.

The tasks are changed to:

1. Literature review of snow making equipment and snow storage.
2. Further develop the model to include evaluation of different snow storage facilities.
3. Define some scenarios on snow storage, outdoor and indoor, depending on weather conditions.
4. Make an evaluation of the different solutions and size of snow storage, including operation and investment costs.
5. Make a draft paper of main results from the master thesis.
6. Make proposal for further work.

OK, 2018.06.26

Trygve M. Eikevik, Prof.

Preface

This is a master thesis written at the Norwegian University of Science and Technology (NTNU), in cooperation with Trondheim Kommune and the Norwegian Ski Association within the project ”Snow for the Future” coordinated by SINTEF Energy Research.

In this thesis, snow storage has been studied as a solution to the lack of snow and shorter winter seasons due to increasing global temperatures. Environmental friendly snow technology will be important to face the future climate challenges, and being able to provide winter sports facilities close to the cities.

I would like to thank my academic supervisor, Professor Trygve M. Eikevik, for valuable guidance and helpful discussions. A special thank also goes to my research advisor, Dr. Ignat Tolstorebrov, for his generous and highly appreciated help.

Trondheim, June 2018

Marianne Heimdal

Marianne Heimdal

Abstract

This thesis studies different alternatives for snow storage in Granåsen (Trondheim). It is planned to improve the arena in Granåsen, which will give possibilities for future winter games and cross-country skiing facilities from October to the end of March. For that reason, it is assumed that 24 000 m^3 snow is to be stored from the beginning of April to the end of September. Both outdoor and indoor snow storage are analyzed.

The snow pile stored outside will be covered with sawdust. This is already practiced in Granåsen, but with a smaller volume of snow. A multipurpose hall will be studied as an alternative for an indoor storage. No such hall exists in Granåsen today, but might be a good alternative that fits the ambition for Granåsen to become a future all-inclusive sports arena. The multipurpose hall will be used for snow storage during the summer, and can be used for indoor training and sports arrangements during the winter.

A snowmelt model has been developed in Excel. The model calculates the amount of melted snow for every hour during the storage season, with respect to weather statistics for Granåsen. The calculations show that approximately 20 % of the initial snow volume will be lost for the outdoor storage. Among the evaluated solutions to reduce the snowmelt, increasing the thickness of the insulation layer gives the best result. A solar shading wall or different snow pile geometries do not lead to any significant melt reduction. When the sawdust thickness is changes from 0.4 m to 0.8 m, the snowmelt is reduced from 20 % to 12 %. However, analysis of the costs proves this to be an expensive alternative. Maintenance of sawdust is therefore concluded to be the most important measure to reduce the snowmelt. This includes necessary drying to maintain the quality and the low thermal conductivity of the sawdust. An insulation thickness of 0.3-0.5 m sawdust can be recommended.

As it can be expected, the melting loss for the snow stored inside will be very small. If the refrigeration capacity of the hall cooling system is set to 20 kW, only 0.21 % of the initial volume will be lost. The snowmelt model demonstrates that there will be great variations in indoor air temperature at different refrigeration capacities. This is a storage alternative with high investment costs compared to the costs for the outdoor storage.

More than 50 % of the annual costs for snow storage will be related to the transportation and distribution of the snow from the storage and to the trails. It will therefore be important to have detailed strategies in advance, regarding the need for snow and how much snow which should be distributed during the winter.

Sammendrag

Denne masteroppgaven tar for seg ulike alternativ for snølagring i Granåsen (Trondheim). Det er planlagt å bygge ut dagens anlegg i Granåsen, som skal gi muligheter for fremtidige vintersportsarrangement og skiløyper fra oktober til slutten av mars. I denne oppgaven er det derfor antatt at 24 000 m^3 snø skal lagres fra starten av april til slutten av september. Både utendørs snølagring og innendørs snølagring vil bli analysert.

Snøen som lagres ute vil være dekket med sagflis. Dette gjøres allerede i Granåsen, men av et mindre volum med snø. En flerbrukshall vil bli undersøkt som et alternativ for innendørs snølagring. En slik hall finnes ikke i Granåsen i dag, men kan være et godt alternativ til Granåsens ambisjoner om å bli et helhetlig hverdagsanlegg for idrett. En slik flerbrukshall vil da kunne brukes til snølagring om sommeren, og disponeres til innendørs trening og sportslige arrangement om vinteren.

En snøsmeltemodell har blitt utviklet i Excel. Modellen regner ut mengden snø som smelter for hver time i løpet av lagrinssesongen, med hensyn til værdata for Granåsen. Beregningene viser at omtrent 20 % av volumet vil gå tapt for snølageret utendørs. Blant de ulike løsningene for å redusere snøsmeltingen, gir økt tykkelse av isolasjon best resultat. Vegg for solskjerming eller ulike former på snøhaugen fører ikke til noen betydelig reduksjon. Når laget av sagflis økes fra 0.4 m til 0.8 m, reduseres snøtapet fra 20 % til 12 %. På en annen side er dette et alternativ med høye kostnader. Vedlikehold av sagflisa vil derfor være det viktigste tiltaket for å redusere snøsmeltingen. Dette innebærer nødvendig tørking av flisa for å bevare kvalitet og lav termisk konduktivitet. Et 0.3-0.5 m tykt lag med sagflis kan derfor anbefales.

Som forventet vil mengden smeltet snø for snølageret innendørs være veldig liten. Dersom hallens kjølekapasitet settes til 20 kW, vil kun 0.21 % av snøen gå tapt. Snøsmeltemodellen viser også at det vil være store variasjoner i lufttemperaturen inne i hallen for ulike kjølekapasiteter. Dette alternativet for snølager vil ha store investeringskostnader sammenliknet med kostnadene knyttet til et utendørs lager.

Transport og distribusjon av snø fra lageret og ut til løypenettet utgjør mer enn 50 % av de årlige kostnadene. Det vil derfor være viktig å ha grundig oversikt over snøbehov og hvor mye snø som skal fordeles til enhver tid i løpet av vinteren.

Contents

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Nomenclature

Abbreviations

ACH Air changes per hour.

Bi Biot number.

COP Coefficient of performance.

DHI Diffuse horizon irradiation.

DNI Direct normal irradiation.

Fo Fourier number.

GHI Global horizon irradiation.

GWP Global warming potential.

ODP Ozone depletion potential.

RH Relative humidity as fraction.

RH% Relative humidity as percentage.

SPF Seasonal performance factor.

TDS Temperature dependent snowmaking.

TIS Temperature independent snowmaking.

WHC Water holding capacity.

wt% Percentage of weight.

Greek letters

α	Solar elevation angle; thermal diffusivity.	[°]; [m^2/s]
$\bar{\Theta}$	Dimensionless temperature distribution.	[-]
β	Solar zenith angle.	[°]
ϕ	Solar azimuth angle.	[°]
ψ	Azimuth angle of surface.	[°]
ρ	Density.	[kg/m^3]
τ	Time.	[s]
θ	Tilt angle of surface.	[°]

Latin letters

Δz	Thickness of insulation layer.	[m]
$\dot{m}$	Mass flow.	[kg/s]
A	Area.	[m^2]
a	Absorptivity.	[-]
c_p	Heat capacity.	[J/kgK]
C_s	Sensible heat factor.	[W/m^3Ks^{-1}]
H	Heat flux.	[J/m^2]
h	Heat transfer coefficient; conductance; enthalpy.	[W/m^2K]; [kJ/kg]
h_{lf}	Latent heat of fusion.	[J/kg]
k	Thermal conductivity.	[W/mK]
L	Length; characteristic dimension; thickness.	[m]
l	Distance.	[m]
m	Mass; weight.	[kg]

N	Number.	[-]
n	Number.	[-]
P	Measured precipitation.	[m]
p	Pressure.	[bar]
Q	Load.	[W]
q	Heat transfer.	[W]
Q_0	Refrigeration capacity.	[W]
r	Reflectivity/albedo.	[-]
T	Temperature.	[K]; [°C]
t	Time.	[s]
T_f	Freezing temperature.	[K]; [°C]
U	Overall heat transfer coefficient.	[W/m^{2}K]
V	Volume.	[m^3]
v	Volume flow.	[m^3/s]
W	Work.	[W]
x	Wall thickness.	[m]

Subscripts

abs	Absorbed.
avg	Average.
cond	Conduction.
conv	Convection.
eq	Equipment.
g	Ground.

i	Indoor.
inf	Infiltration.
int	Internal.
lh	Latent heat.
lwr	Long-wave radiation.
o	Outdoor.
p	Precipitation.
rad	Radiation.
rs	Solar radiation.
rt	Thermal radiation.
s	Surface.
sh	Sensible heat.
sur	Surroundings.
sys	System.
tot	Total.
$trans$	Transmission.
wb	Wet-bulb.

Chapter 1

Introduction

A worrying trend is developing with shorter winter seasons and milder winter temperatures. The increasing global temperatures reduce the periods of natural snow, which threatens the winter sports. The climate changes are making it more difficult and complicated to provide winter sport facilities close to the cities.

In order to face the climate changes and still being able to provide good skiing conditions close to the cities, snow storage and snow production at temperatures above 0 °C will be crucial. Snow production at temperatures above freezing level is an extremely energy consuming process. Increasing the energy efficiency of the snow producing equipment and reducing operational costs will therefore be profitable, as well as developing good methods for utilization of the rejected heat.

In the last years Nordic countries and winter games arrangers have been forced to take action due to poor snow conditions. By focusing on climate independent snow production and snow storage, it is possible to adapt to the warmer winter temperatures.

1.1 Background

”Snow for the Future” is a project coordinated by SINTEF together with Trondheim Kommune, the Norwegian Ski Association and NTNU. The ambitions of the project is to develop environmental friendly snow technologies capable to face the future climate challenges, as well as finding solutions to prolong the winter season for skiing facilities close to the cities. In that way the skiing tradition and recruitment can be maintained, winter sports industry will have a bright future and the risk of arranging winter games due to warm weather conditions can be highly reduced (Gjerland, 2016).

This thesis will focus on snow storage solutions for the skiing arena in Granåsen (Trondheim). It is planned to improve and expand the facility in Granåsen, which will give possibilities for future winter games and give the people a possibility to enjoy winter activities from the beginning of October to the end of March.

Previous master thesis within ”Snow for the Future” have studied methods to increase the energy efficiency of temperature independent snowmaking equipment. The time and work for this thesis have therefore been devoted to snowmelt modelling and snow storage solutions. Since snow production above 0 °C is an expensive and energy demanding process, it will also be important to preserve the snow which has been produced by this expensive technology by minimizing the snowmelt.

1.2 Objectives

The objective of this thesis is to develop a snowmelt model with reasonable results for different snow storage solutions. To do this it will be necessary to get an overview of the principles of snowmelt and snow storage. This will give the opportunity to evaluate different solutions with respect to melting loss, cost and efficiency. The model will also show how weather conditions affect the snowmelt. From this it can be possible to develop strategies for location of snow storage facilities, based on incoming solar radiation and shadow from terrain and vegetation around the storage.

1.3 Structure of Thesis

Chapter 2 and chapter 3 present a literature study of snow production and snow storage. Both temperature dependent snowmaking and temperature independent snowmaking are described in the second chapter, while chapter 3 presents both outdoor ground storage and indoor snow storage.

Chapter 4 and chapter 5 are structured as two independent chapters about outdoor snow storage and indoor snow storage respectively, concerning the arena in Granåsen. Necessary theory and equations for calculations are provided at the beginning of each chapter, followed by the results of the calculations. A discussion of the results and conclusions for each case are provided at the end of the chapters.

Chapter 6 sums up the main finding and general conclusions, as well as proposing suggestions for further work.

Chapter 2

Snow Production

2.1 Natural Snow

Snowflakes is formed by accumulation of packed ice crystals. For ice crystals to form and start growing, water droplets need a nucleus (particles of dust in the air) on which to condense on (Libbrecht, 2007). Once a droplet freezes it will grow into a snow crystal by absorbing water droplets in the surrounding air, forming a crystal-lattice structure. The snow starts to form and fall down when the atmospheric temperature is at or below 0 °C, and there is a minimum moisture amount in the air (National Snow and Ice Data Center, 2017). The snow will hit the ground if the ground temperature is below freezing point, but with the right conditions the snow may also hit the ground even at ground temperatures above freezing. When that happens the snowflakes starts to melt on their path through the higher temperature layer, and create an evaporative cooling effect in the surrounding air which decelerates the melting.

2.2 Artificial Snow

In many cases natural snowfall is not enough to provide good winter sports facilities during a whole winter season. Climate and geography are of importance regarding how long a winter season may last, but for stakeholders in the winter sports industry, such as ski resorts and skiing arenas, the best way to remain popular and profitable is to provide the longest season as possible by producing artificial snow (Alpine Infusion, 2016).

There are several factors impacting on the production of artificial snow. The wet-bulb temperature, including the air temperature and the relative humidity, the wind velocity, the water temperature, the size of the water droplets and the time it takes before the ice crystals reach the ground, will affect the result and the quality of the snow production (Vagle, 2016a). But the major condition is whether the ambient air temperature is below or above 0 °C.

To face the warmer winter temperatures it is beneficial to have equipment that can produce snow independent of the temperature. Snow production above 0 °C is an energy demanding process, but utilization of the surplus heat can make the production more energy efficient.

In the following subsections both temperature dependent snow production and temperature independent snow production will be discussed.

2.3 Temperature Dependent Snowmaking

Temperature dependent snowmaking (TDS) has been the traditional way of producing artificial snow, and includes methods that depend on cold ambient air temperatures and climatic conditions. Usually, water is being spread as very small droplets into the cold air in order to freeze. The droplet shape results in a structure which is more compact than natural snow, giving artificial snow a higher density (Lintzén, 2012). The increased density makes artificial snow more durable and more resistant to wind, water and temperature changes.

Two of the main techniques that dominate the TDS market are presented below.

2.3.1 Fan Guns

Fan guns are spraying water at high pressure from several nozzles and use a fan to blow the water droplets (Eikevik, 2017). The fan gives the water droplets a long pathway which results in a high snow production rate, as well as low energy consumption per square meter of snow produced

(Gjerland and Olsen, 2014). Due to the large capacity fan guns are especially suitable for larger skiing hills, such as alpine ski resorts.

These snowmakers have the disadvantages of being quite expensive, they require more maintenance and are difficult to transport because of size and weight. Heating element in the nozzles is necessary to avoid freezing (Eikevik, 2017). A fan gun and its principle sketch are shown in Figure 2.1 and Figure 2.2, respectively.

Figure 2.1: Fan gun (TechnoAlpin, 2016a).

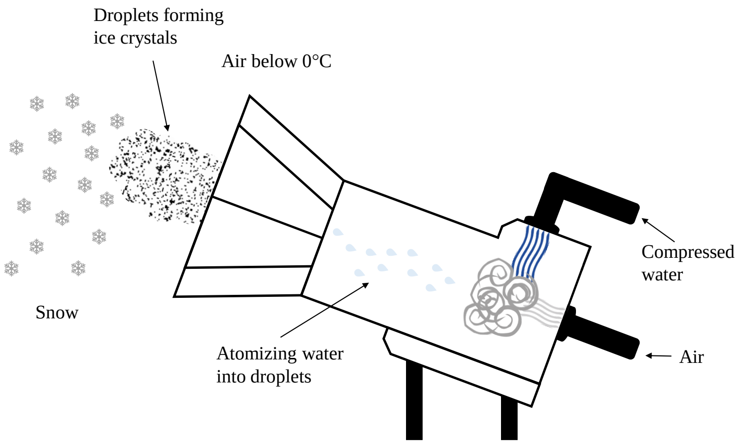

Figure 2.2: Principle sketch of a fan gun.

2.3.2 Lances

Snow lances are supplied with compressed air and spray high pressurized water droplets into the cold air, usually six to nine meters above the ground (Eikevik, 2017). These snow guns consume less compressed air, which reduces the energy consumption and the noise level of the system. The lances require little maintenance, are simple in operation and suitable for targeted snow production supplying cross-country skiing trails.

Due to the height, water droplet pathway and wind sensitivity the lances have a lower production rate compared to the fan guns, as well as limited options to regulate the snow quality (Gjerland and Olsen, 2014). As for the fan guns, it is necessary to have heating element in the nozzles to prevent freezing. A snow lance and its principle sketch are shown in Figure 2.3 and Figure 2.4, respectively.

Figure 2.3: Snow lance (TechnoAlpin, 2016c).

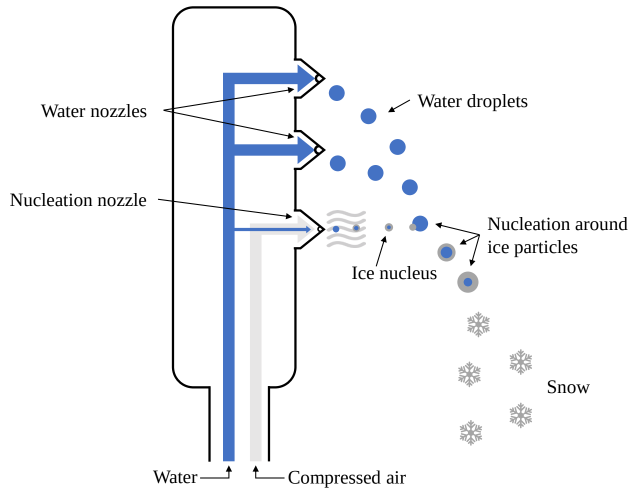

Figure 2.4: Principle sketch of a snow lance.

2.4 Temperature Independent Snowmaking

Temperature independent snowmaking (TIS) makes it possible to produce snow at temperatures above 0 °C, regardless of climate, location or time of the year. This is beneficial for winter sports arenas in order to face the warmer winter temperatures. In 1993 the American company Snow-Magic, Inc. became the first manufacturer of temperature independent snow, and since the early 2000s this type of snow production technology has continued to develop (SnowMagic, Inc., 2015; Gjerland and Olsen, 2014).

The snow produced from TIS is made of ice crushed into very small crystals. The ice may be ice blocks, ice cubes, flake ice, plate ice, ice slurry or vacuum ice, depending on the machine or technique used for the freezing process (Eikevik, 2017). TechnoAlpin, IDE Technologies and SnowTek together with SnowMagic are manufacturers of TIS today, using similar techniques as traditional ice production to produce flake ice, plate ice or ice slurry. These techniques will be further discussed in the next sections.

2.4.1 Ice Production

Ice makers can be classified based on whether dry subcooled ice or wet ice is produced (Graham et al., 1993). The dry subcooled ice is usually produced in machines where the ice is mechanically removed from the cooling surface, while wet ice is produced in machines where the ice is removed during a defrost process. The wet ice is thawed at the cooling surface before it can be removed. Tube ice systems and plate ice systems are examples of wet ice makers, while dry subcooled ice is produced in flake ice systems. Other machines produce an ice slurry, which has a much higher water content than wet ice. In ice slurry makers the ice can be produced and harvested at the same time.

2.4.2 Flake Ice

In a flake ice machine a cooled cylinder drum allows the ice to freeze on its surface, before the ice is being harvested as dry subcooled flakes. The flakes will have a thickness of 2-3 mm and an area of 100-1000 mm^2 (Graham et al., 1993). Figure 2.5 shows a schematic sketch of a flake ice machine. Water is supplied at the top and sprinkled onto the inside surface of the evaporator, the cylindrical container, where ice will start to form. Some designs of this type of ice maker have a rotating cylinder drum with a stationary scraper that removes the ice from the outer surface. In other designs the drum is stationary while the scraper rotates and removes the ice.

The refrigerant temperature, degree of subcooling and speed of rotation are factors which affect the capacity of the machine and the thickness of the produced ice (Graham et al., 1993). Just before the ice is being removed by the scraper, no water is added and the ice temperature decreases. In that way only dry subcooled ice falls into the storage below the scraper. The refrigerant in a flake ice machine has a temperature of -20 to -25 °C. This temperature range is lower compared to other ice machines, but necessary to ensure high production rates and keep the ice machine small and compact. When operating at such low temperatures extra power is needed, but on the other hand there will be no demand for defrosting.

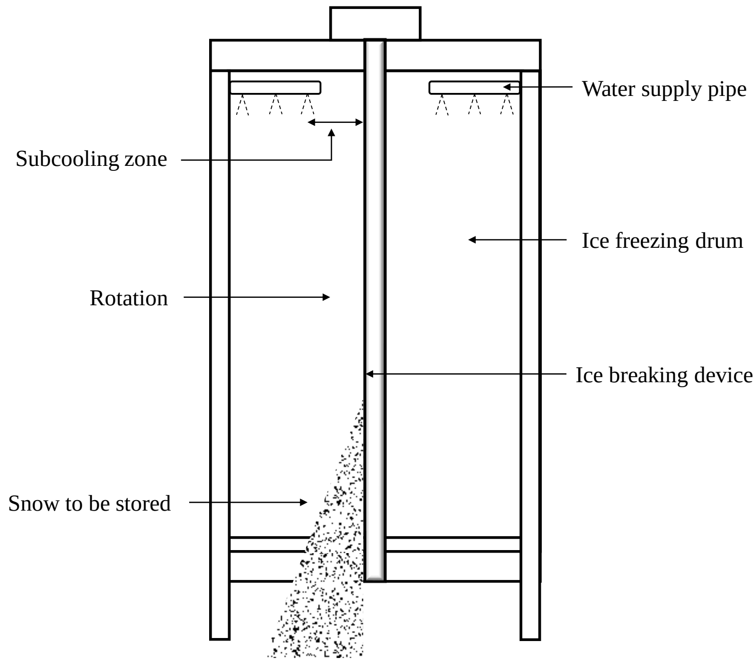

Figure 2.5: Sketch of a flake ice machine. Adapted from Graham et al. (1993).

2.4.3 Plate Ice

In a plate ice machine water is sprayed on the outer surface of refrigerated vertical plates to form ice (Graham et al., 1993). When the ice is ready to be removed, water is run on the other side of the plates for defrosting. Some models use an internal defrost process and ice is formed on both surfaces. The arrangement of several refrigerated plates forms a plate ice machine. By adding or removing plates the capacity of the machine can be adjusted. Figure 2.6 shows a schematic sketch of a plate ice machine.

The ice formed in a plate ice machine has an optimum thickness of 10-12 mm, and must be crushed or broken down into a suitable size for use or storage (Graham et al., 1993). The temperature of the water in the defrost process affects the capacity and cost of the ice production. If the water has a temperature lower than 25 °C heating is needed, or else the defrost process will take too much time and the capacity will decrease.

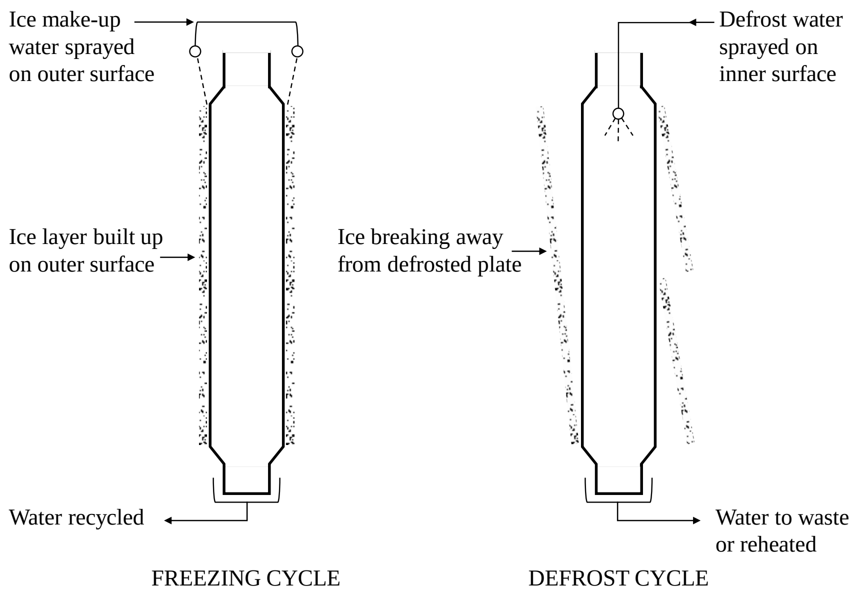

Figure 2.6: Sketch of a plate ice machine. Adapted from Graham et al. (1993).

2.4.4 Ice Slurry

Ice slurry is a mixture consisting of small ice particles and a liquid (Kauffeld et al., 2010). The liquid can be pure water or a binary solution of water and a freezing point depressant. The ice particles has a diameter in the range of 0.1 to 1 mm and the mixture can contain up to 30 wt% water (Graham et al., 1993).

The ice slurry has a high cooling rate because of the large heat transfer surface area of the ice particles (Kauffeld et al., 2010). Due to the latent heat of energy in the particles, ice slurry also has a high energy storage density. These are qualities that make ice slurry beneficial in many applications and industries, such as fish and meat storage, vegetable processing, refrigeration and snow production (IceGen Inc., 2014).

Chapter 3

Snow Storage Classification

Snow storage is another solution to the lack of snow. Storing snow for the next season gives a certain predictability and a guarantee for skiing arenas, users and winter games arrangers. It also reduces the economic risk of not having enough snow. Storage of snow can make it possible to provide skiing facilities at temperatures too warm for TDS equipment.

Figure 3.1 illustrates different ways of snow storage (Skogsberg, 2005). The snow can be stored indoor, on the ground, in open pits or under ground. Outdoor ground storage and indoor storage will be further discussed in the following sections.

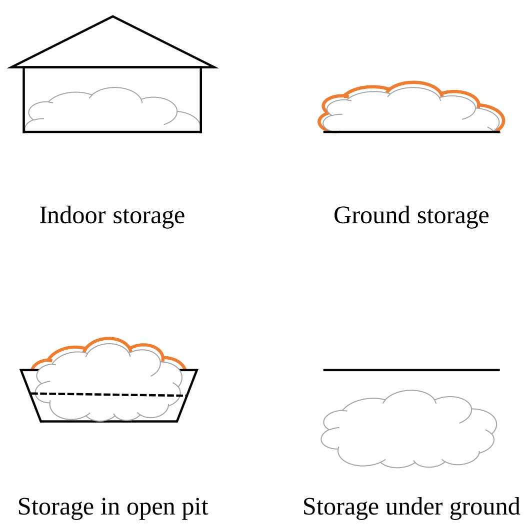

Figure 3.1: Methods of snow storage. Adapted from Skogsberg (2005).

3.1 Ground Storage

Ground storage requires thermal insulation of the snow to shelter and minimize the snowmelt. The snowmelt is a result of rain melt, ground melt and surface melt (Nordell and Skogsberg, 2007). The ground melt is caused by heat transfer from the ground beneath the pile, while heat transfer from the ambient air and radiation causes the surface melt. Rain melt occurs due to precipitation. Today both natural and fabricated materials, such as sawdust, wood chips and geotextile, are used as insulation in snow storage applications.

There are several factors that affect the melting rate of a snow pile stored on the ground. The major factors are the thickness of the insulation layer, the sunlight intensity and the climate conditions such as wind velocity, air temperature and absolute air humidity (Lintzen, 2016). Minor factors such as moisture content in the insulating layer, evaporation, rain and heat from the ground, as well as the geometry of the pile will also influence the melting rate.

3.1.1 Insulating Materials

The most common insulation materials today are natural materials of wood such as sawdust, wood chips, cutter shaving and bark, and fabricated materials such as plastic sheets, geotextile and aluminum folio (Lintzen, 2016). By insulating large snow piles with material such as sawdust, more than two thirds of the initial snow volume can be conserved over the summer (Grünewald et al., 2017).

Important parameters for the performance of the different cover materials are radiative properties, thermal conductivity, permeability, tensile strength, surface roughness and thickness of the insulating material (Olefs and Fischer, 2008). These characteristics affect the components of the energy balance for the sheltered snow.

Figure 3.2 shows a picture of the snow storage in Granåsen from 2016. The snow pile is covered with sawdust.

Figure 3.2: Snow storage covered with sawdust in Granåsen (Vagle, 2017)

Wooden materials

When wooden material, such as sawdust, bark and wood chips, is used as insulation, an evaporative cooling effect is created (Skogsberg and Lundberg, 2005). Most of the melting water will be transported downward through the snow pile, but due to capillary forces and evaporation there will also be some transportation upwards through the insulation layer. The evaporation process requires energy leading to a cooling effect on the insulation layer which reduces the snowmelt.

Wooden materials have good elasticity and will follow the structure and dents in the pile surface. Smaller size of the wood pieces or chips gives better insulating effect as it reduces the air gaps. The snow production guideline published by the Norwegian Ministry of Culture, recommends an insulation thickness of 0.3-0.5 m sawdust (Gjerland and Olsen, 2014). The guideline also advises to use the sawdust every second year, and let it dry in between. This leads to a large space requirement for drying and storage of wooden materials when the insulation is not in use.

Fabricated materials

Fabricated materials, such as blankets and plastic sheets, do not require the same space of storage as wooden materials. These insulation materials are also easier to transport and easier to reuse

(Gjerland and Olsen, 2014). However, snow storage experiments have shown that snow piles covered with fabricated materials have greater melting losses than snow piles covered with wooden materials (Lintzen, 2016).

Physical properties of sawdust

The ability for a specific material to hold water, the water holding capacity (WHC), is defined as

$$WHC = \frac{m_{wet} - m_{dry}}{m_{dry}} \tag{3.1}$$

where m_{wet} is the weight of a sample of the material saturated with water [kg] and m_{dry} is the weight of a dried sample of the same material [kg] (Ødegård, 2013).

From previous studies it has been found that the WHC and the density of sawdust is 3.4 and 240 kg/m^3 respectively. (Ødegård, 2013). The thermal conductivity for dry sawdust is low, which is beneficial for an insulating material. The thermal conductivity depends on the type of tree, the size of the wood shavings and the water content, which will increase the conductivity. Typical values for thermal conductivity of sawdust is 0.03-0.05 W/mK with increasing water content.

3.2 Indoor Storage

Indoor skiing halls produce their own snow and offer excellent skiing conditions throughout the year, regardless of the temperature outside. The same concepts can be applied for indoor snow storage halls where the snow is being produced and stored during the summer, ready to be distributed whenever desired. Indoor snow storage at cold and stable conditions will have reduced melting losses compared to outdoor storage, as the snow is sheltered from solar radiation, rain and the increasing summer temperatures.

Halls for indoor snow storage will have large space requirements, which might be challenging if a hall is supposed to be built in connection with an already existing winter sports arena.

3.2.1 Indoor Snow Centers

Today there exist several indoor snow centers around the world that offer snow for winter sports activities. A typical indoor snow center will have temperatures around -1 °C to -2 °C when it is open to the public, and when it closes the temperature will be reduced to -6 °C for snow production and snow grooming (Clulow, 2006). These snowmaking systems today have high energy demands due to air cooling, floor freezing and harvesting of the snow.

Snow production

The snow can be produced by flake ice machines or by freezing water being sprayed into the hall at low temperatures (Paul, 2003). Figure 3.3 illustrates a snow production system for a conventional skiing hall and a cross-section of the ground including a floor pipe arrangement. The circulation brine (e.g. glycol) and the cold air temperature prevent the snow from melting, and the floor is kept frozen. The floor is well insulated in order to avoid ground freezing.

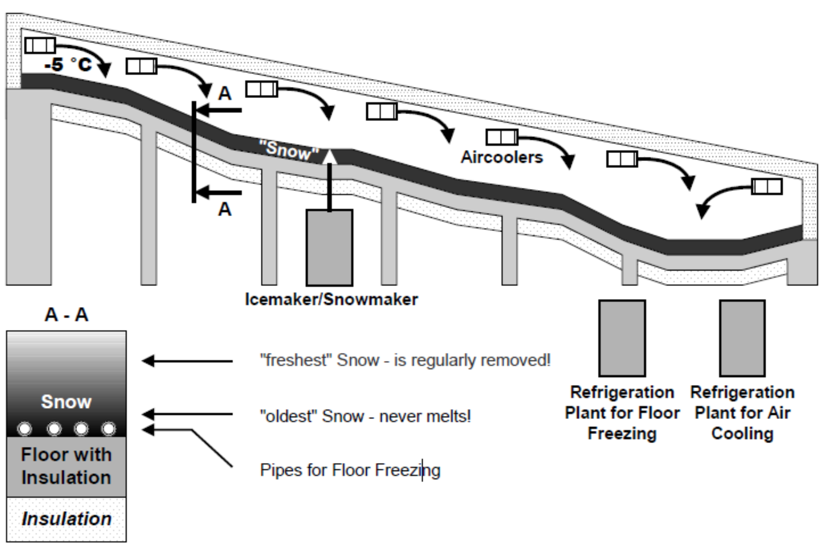

Figure 3.3: Concept of a conventional indoor snow center with floor pipe system (Paul, 2003).

Conventional outdoor snow guns are not suitable for indoor snowmaking applications since the snow produced from these guns will be too wet (TechnoAlpin, 2016b). Since outdoor snowmakers will be exposed to windy conditions they need to produce larger water droplets, usually in a diameter range of 100-250 μm (Clulow, 2006). Indoor snowmakers will not be affected by wind, thus smaller droplet sizes of 10-50 μm can be used. These snowmakers usually have a maximum water flow rate of 9 L/min, and various nozzles can be applied to obtain different snow densities.

An indoor snowmaker will typically use a mix of compressed air and water at high pressure together with a water-jacketed mixing chamber (Clulow, 2006). By circulation of the snowmaking water the water jacket makes it possible for the snowmaker to run below the freezing point without internal freezing. The compressed air/water ratio will determine the water flow into the mixing chamber, hence the size of the droplets and the density of the snow.

Indoor conditions and snow quality

Indoor artificial snow production requires a strict control of the indoor environment (Clulow and Winnett, 2006). The temperature and humidity are crucial for the snow characteristics, and uncontrolled indoor conditions can result in reduced quality. A relative humidity close to 100 % will give inefficient and challenging conditions for snow production. The relative humidity of the air also affects the type of snow which will be produced. A relative humidity between 90 % and 95 % and a temperature around -15 °C are good conditions for producing powder snow, while soft snow can be produced at a relative humidity between 100 % and 95 % and temperatures around -2 °C.

Metamorphism

Destructive metamorphism can be a challenge for indoor snow halls (Clulow, 2006). This will result in snow crystals transforming into spheres which reduces the quality of the snow and its natural snow similarities. The snow will become gray and slow, and be less suitable for winter sports purposes.

To avoid this transformation a temperature gradient must exist across the snow base (Clulow, 2006). A floor cooling system will work as a thermal storage, which creates a temperature gradient in the snow base, as well as preventing the snow from melting. This will lead to a *constructive* metamorphism. When the floor is colder than the air surrounding the stored snow, water vapor from the air will be drawn into the snow due to the vapor pressure difference. The water vapor will begin to freeze and result in regrowth of the crystals in the snow.

Air cooling

The snowmaking system and the cooling system for an indoor snow center are interrelated (Clulow, 2006). The energy generated from the snow production will be transferred from the phase-changing water droplets to the air surrounding the snowmakers, and further to the air coolers. The temperature and dew-point conditions of the air that surrounds the snowmaking system will be of importance, since this air is being entrained into the plume of the snowmaker to absorb the latent heat of fusion, and to transfer it to the cold surfaces in the air coolers.

The air coolers used for dehumidification of the air inside skiing halls have fins with wide spacing (Clulow, 2006). This is to improve the efficiency of the dehumidification process, and obtain cold and dry air with lower relative humidity. High relative humidity and temperatures below 0 °C will lead to frost formation on the cold surfaces of the air coolers. This will result in increased frequency of defrosting periods for the evaporators, in order to remove the frost that reduces the effectiveness of the air coolers (Eikevik, 2015). Defrosting systems should be made for air coolers in a skiing hall as they operate at air temperatures below 0 °C.

A schematic section of a heat exchanger suited for indoor skiing halls is shown in Figure 3.4. The indoor air is being cooled by the coolant passing through the pipes (labeled as 25). The air flow is directed over the pipes, parallel to a series of fins (27A and 27B). The fins are connected to the pipes and contribute to the heat transfer between the coolant and the air.

Ice formation occurs on the fins when the air is cooled down. Since the fins will have a relative wide spacing between each other, typically 8 mm, the air will be unevenly cooled (Clulow and Winnett, 2006). The air close to the cold fins will be cooled to a temperature below the required temperature, while the air in the middle of two fins will not be effected by the cooling provided by the fins. The fan in Figure 3.4 (labeled as 28) does the necessary mixing of the air at the outlet, and ensures that the leaving air is below saturation. A fan with variable speed drive gives the possibility to regulate the indoor environment based on requirements for snow production, snow storage, and opening and closing hours. In addition to the fan for mixing of the air, the fins are arranged so that the air passing close to the first fin will pass in the middle between the next fins and so on (see the different arrangement for 27A and 27B in Figure 3.4). This contributes to the mixing of the air leaving the heat exchanger with the desired temperature and humidity.

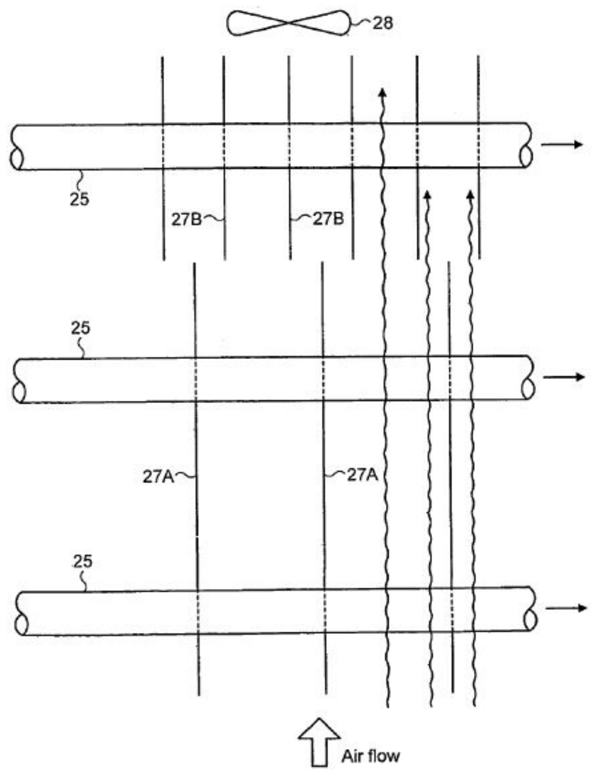

Figure 3.4: A schematic section of a heat exchanger in an indoor skiing hall (Clulow and Winnett, 2006). Pipes (25), fins (27A and 27B) and fan (28).

Chapter 4

Outdoor Snow Storage

4.1 Snowmelt

Snowmelt is driven by several physical processes and the snowmelt runoff can be a significant element of the hydrologic cycle (USDA, 2004). Calculation of snowmelt is important for hydropower purposes, flood prediction, avalanche protection and for research purposes regarding effects of climate change (Schuler, 2006). The energy balance per square meter for an uninsulated snowpack, ΔH [J/m^2], is the sum of heat fluxes that determines the change in the heat content of the snowpack (USDA, 2004). Equation 4.1 expresses the energy balance for a snowpack

$$\Delta H = H_{rs} + H_{rt} + H_{sh} + H_{lh} + H_g + H_p \tag{4.1}$$

where H_{rs} is the net solar radiation [J/m^2], H_{rt} is the net thermal radiation [J/m^2], H_{sh} is the sensible heat transfer from air [J/m^2], H_{lh} is the latent heat of vaporization from condensation or evaporation/sublimation [J/m^2], H_g is the conducted heat from underlying ground [J/m^2] and H_p is the advected heat from precipitation [J/m^2].

The solar radiation and the thermal radiation are the dominating terms in the energy balance, and constitute 60-90 % of ΔH (USDA, 2004). H_{rs} is the difference between the incoming solar radiation and the reflected solar radiation, related to the albedo of the surface. The albedo is the ability for a surface to reflect the incoming radiation, defined as a value between 0 and 1 (Store norske leksikon, 2013). Dark surfaces absorb more radiation than brighter surfaces, thus a lower albedo. This explains why dirty snow (albedo of 0.4) melts faster than new, fresh snow (albedo of 0.9). H_{rt} is the difference between the incoming radiation from the surrounding elements (atmosphere, clouds, vegetation etc.) and the outgoing radiation from the snowpack (USDA, 2004).

When the temperature of the snowpack and the air temperature differ, heat will be exchanged between the snowpack and the ambient air, causing sensible heat transfer (USDA, 2004). If the surrounding air is warmer than the snowpack temperature, heat will enter the snowpack (positive H_s). The latent heat of vaporization is energy being released or extracted as a result of phase change of water, condensation or evaporation/sublimation. The phase changes are related to the air humidity and the water vapor pressure gradient between the air and the surface of the snowpack. Windy weather conditions increase the contribution from H_s and H_l, which constitute 5-40 % of ΔH (USDA, 2004).

Temperature differences between the snowpack and the underlying ground causes conduction of heat, resulting in a positive H_g if the temperature of the snowpack is colder than the temperature of the ground. H_p is the heat content of precipitation with a positive value if the snowpack temperature is colder than the precipitation temperature. H_g and H_p will only have a relative importance of 0-5 % of ΔH (USDA, 2004).

4.2 Heat and Mass Transfer for an Insulated Snow Pile

Snow being stored during the summer will suffer from heat leakage and snowmelt due to air temperatures above freezing and stronger solar radiation. Covering the snow with a layer of insulation, such as sawdust, wood chips, etc., will have a protective effect. Weather conditions and the thermal properties of the insulating material will affect the convective heat and mass transfer through the insulation (Lintzén, 2012).

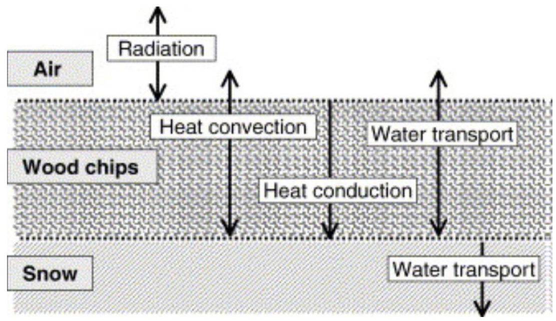

Figure 4.1: Heat and mass transfer through an insulating layer for snow storage (Skogsberg and Lundberg, 2005).

Figure 4.1 illustrates the principle of heat and mass transfer through an insulting layer covering snow (Skogsberg and Lundberg, 2005). Water will be transported downwards through the snow, but as a result of capillary forces and evaporation, a fraction of the water will be transported upwards through the layer of insulation (Lintzén, 2012). Energy is necessary for the evaporation to happen, and the insulating layer will therefore be cooled and the melting rate will decrease. Heat from both short-wave radiation and long-wave radiation will be exchanged at the surface of the insulation. Depending on the albedo of the insulation material some of the radiation will be reflected. The thermal conductivity of an insulating layer of wooden materials will be determined by the compaction, moisture content, the quality of the wood and the size and structure of the chips (Skogsberg and Lundberg, 2005).

4.3 Calculation of Snowmelt for Outdoor Snow Storage

This section describes the equations for calculating the snowmelt for an insulated snow pile stored outside during the summer. The snowmelt will be related to the following heat sources (Lintzén and Knutsson, 2016):

- Heat from the underlying ground.
- Heat from rain.
- Heat from the surroundings, including surrounding air and solar radiation.

Equation 4.2 sums up the contributions from every heat source, which constitute the total volume of melted snow, V_{total} [m^3], during the period of storage.

$$V_{total} = V_{ground} + V_{rain} + V_{surroundings} \tag{4.2}$$

Each term of Equation 4.2 will be described in the following sections.

4.3.1 Ground

The snow pile will cover a large area on the ground. The heat transfer between the pile and the ground area, q_g [W], can be determined using the equation below

$$q_g = k_g A_g \frac{\Delta T_g}{l} \tag{4.3}$$

where k_g is the thermal conductivity of the ground material [W/mK], A_g is the ground area covered by the pile [m^2], and ΔT_g is the temperature difference [°C] between the pile and the temperature at a distance l [m] down in the ground (Lintzén and Knutsson, 2016). The volume flow of melted snow due to heat from the ground, v_g [m^3/s], can then be calculated as

$$v_g = \frac{q_g}{h_{lf}\rho_{snow}} \tag{4.4}$$

where h_{lf} is the latent heat of fusion for the snow [J/kg] and ρ_{snow} is the density of the snow [kg/m^3].

Finally, the lost volume of snow caused by heat from the ground, V_{ground} [m^3], is

$$V_{ground} = v_g t \tag{4.5}$$

where t duration of the storage period [s].

4.3.2 Rain

Precipitation will also have an impact on the snow melting rate. For a period with P measured precipitation [m], the volume of melted snow, V_{rain} [m^3], is

$$V_{rain} = \frac{PA_s \rho_{water} c_{p,water} T_o}{h_{lf} \rho_{snow}} \tag{4.6}$$

where A_s is the surface area of the snow pile [m^2], ρ_{water} is the density of the water [kg/m^3], $c_{p,water}$ is the heat capacity of water [J/kgK] and T_o is the temperature of the surrounding air [°C] (Lintzén and Knutsson, 2016).

4.3.3 Surroundings

The surface melt is caused by the heat transfer from the surrounding air and the solar radiation to the snow storage.

Surrounding air

The wet-bulb temperature affects the heat transfer from the air, and depends on the air temperature, the relative humidity and the pressure. Equation 4.7 is an empirical expression for the wet-bulb temperature, T_{wb} [°C], as a function of the measured air temperature, T_o [°C] and the relative humidity, $RH\%$, at standard sea level pressure (101.325 kPa) (Stull, 2011). The arctan function uses argument values as if they are in radians.

$$\begin{aligned} T_{wb} = {} & T_o * arctan[0.151977 * (RH\% + 8.313659)^{1/2}] \\ & + arctan(T_o + RH\%) - arctan(RH\% - 1.676331) \\ & + 0.00391838 (RH\%)^{3/2} * arctan(0.023101 * RH\%) - 4.686035 \end{aligned} \tag{4.7}$$

Solar radiation

The total result of incoming short-wave radiation received by a surface horizontal to the ground, the global horizontal irradiation, q''_{GHI} [W/m^2], is given by

$$q''_{GHI} = q''_{DNI} cos\beta + q''_{DHI} \tag{4.8}$$

where q''_{DNI} is the direct normal irradiance [W/m^2], β is the solar zenith angle [°] and q''_{DHI} is the diffuse horizontal irradiance [W/m^2] (First Green Consulting, 2012). Figure 4.2 illustrates the different angles related to the position of the sun observed from the surface of the Earth.

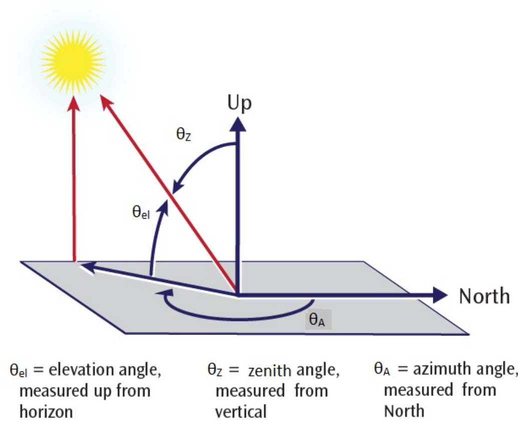

Figure 4.2: The position of the sun observed from the surface of the Earth (PVPMC, 2014)

The direct normal irradiance is the quantity of solar radiation per unit area, received by a surface normal to the direct path of the sun beams and its position on the sky (First Green Consulting, 2012). The received amount of direct normal irradiance will be maximized if the surface is held normal to the incoming radiation. The diffuse horizontal irrandiance is the quantity of solar radiation per unit area, where molecules and particles in the atmosphere have scattered the beams before they are received by the surface. In the case of scattered beams the radiation will be equal in all directions. Figure 4.3 shows how the direct and diffuse irradiation behave.

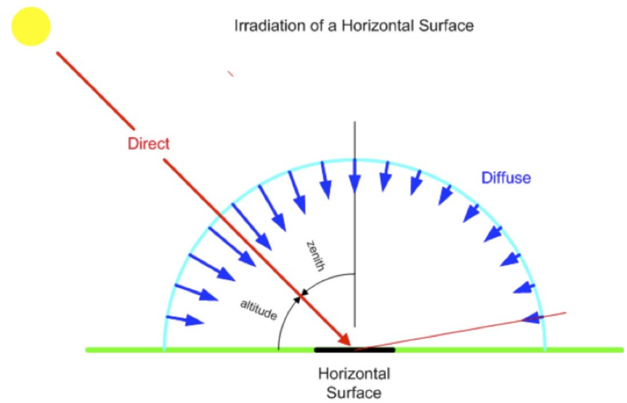

Figure 4.3: Incoming radiation (EcoSmart, 2017)

The amount of solar radiation absorbed by an outdoor snow pile, q''_{abs} [W/m^2], will be

$$q''_{abs} = q''_{GHI}a = q''_{GHI}(1-r) \tag{4.9}$$

where a is the absorptivity [-] and r is the solar radiation reflectivity, or albedo, of the surface material [-]. The surface is assumed to be opaque.

Since the sides of the snow pile will have different tilts and orientations relative to the sun, the solar radiation must be analyzed for each side of the pile. The solar radiation on a surface with a given tilt and orientation, $q_{surface}$ [W], is

$$q_{surface} = q_{abs}A_s[cos(\alpha)sin(\theta)cos(\psi - \phi) + sin(\alpha)cos(\theta)] \tag{4.10}$$

where A_s is the decomposed surface area [m^2], α is the elevation of the sun [°], θ is the tilt angle of the decomposed surface [°], ϕ is the solar azimuth angle [°] and ψ is the azimuth angle that the decomposed surface faces (clockwise from north) [°] (PV Education, 2017). For a surface that directly faces the sun ψ equals ϕ.

Sol-air temperature

The exterior surfaces of the insulated snow pile will be affected by the outdoor air temperature as well as the solar radiation. Depending on the properties of the covering material and the orientation of each side of the pile, relative to the sun, a certain amount of the radiation will be absorbed. This will result in a surface temperature of the insulating material which is higher than the temperature of the surrounding air, $T_s > T_o$ (Thomas, 2013).

The surface temperature, called sol-air temperature, T_s [°C], can be found from the following equation

$$T_s = T_o + \frac{q''_{surface}}{h_o} \tag{4.11}$$

where h_o is the outside surface conductance [W/m^{2}K]. $q''_{surface}$ can be found from Equation 4.10, which includes the absorbed solar radiation for a surface with a given reflectivity, as well as the solar elevation angle, the solar azimuth angle, the azimuth angle of the surface and the tilt angle of the surface. Since the snow pile will be exposed to wind, a value of 6 W/m^{2}K can be assumed for h_o (ASHRAE, 2010).

To determine the heat transfer between the insulated snow pile and its surroundings, q_{sur} [W], Equation 4.12 can be applied

$$q_{sur} = k_{avg} A_s \frac{T_s - T_{snow}}{\Delta z} \tag{4.12}$$

where k_{avg} is the average value of the thermal conductivity for water and the insulation material [W/mK], A_s is the surface area [m^2], T_{snow} is the temperature of the snow [°C] and Δz is the layer thickness of the insulation material [m] (Lintzén and Knutsson, 2016). k_{avg} takes into account that the insulating material will have a varying thermal conductivity depending on its moisture content (Skogsberg and Lundberg, 2005). Equation 4.13 and Equation 4.14 express the volume flow, v_{sur} [m^3/s], and the volume, $V_{surroundings}$ [m^3], of melted snow as a result of temperature differences between the snow pile and its surroundings.

$$v_{sur} = \frac{q_{sur}}{h_{lf} \rho_{snow}} \tag{4.13}$$

$$V_{surroundings} = v_{sur} t \tag{4.14}$$

4.4 Outdoor Snow Storage in Granåsen

This section includes a theoretical study of a 24 000 m^3 insulated snow pile in Granåsen, covered with sawdust and stored from the beginning of April to the end of September.

A model for snowmelt calculations is made in Excel. The model has the latitude, the longitude and the time zone for the location of the snow pile as input arguments, and calculates the the solar elevation angle and azimuth angle for every hour. By comparing the solar elevation angle to the horizon of the snow pile, it is possible to know when the snow pile will be exposed to solar radiation for each day. Together with weather statistic for Granåsen, including temperature, relative humidity, precipitation and global horizontal irradiance, the model calculates the melting of snow for every hour during the season, using the equations described in Section 4.3.

4.4.1 Assumptions

The snow pile will have the same location as the snow storage in Figure 3.2. Figure 4.4 shows where the snow storage will be placed relative to the cardinal directions. To simplify the calculations it is assumed that the pile will have the shape of an isosceles trapezoid prism, as illustrated in Figure 4.5. For the calculation of solar radiation, each of the five outer surfaces will be analyzed separately with respect to their orientations and tilts.

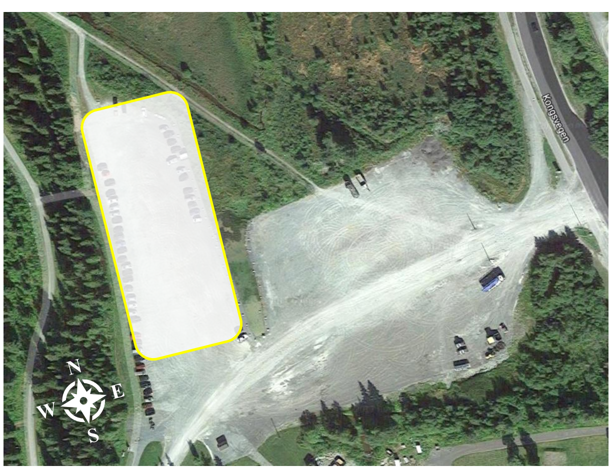

Figure 4.4: Ground area for snow pile.

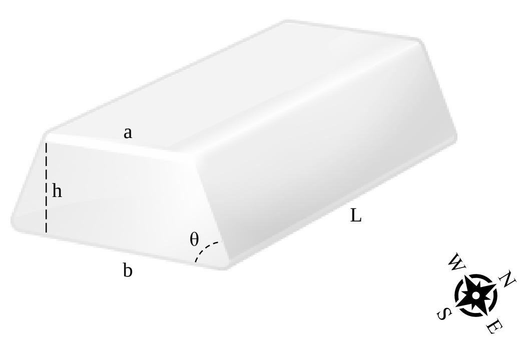

Figure 4.5: Snow pile geometry.

Horizon

The horizon of the snow pile has to be projected in order to compare the horizon of the pile to the elevation angle of the sun. This is done by using a topographic map, measuring the highest points around the snow pile for every 30°, as well as the distance from the pile to the corresponding point. The reference point for the pile is set at 170 masl. Since the hour angle of the sun is 15° per hour time, the horizon for every 15° is further obtained by calculating the mean value between each measurement.

The calculation of the solar elevation angle and the solar azimuth angle is based on equations from *Astronomical Algorithms* by Jean Meeus (National Oceanic & Atmospheric Administration, 2011). The equations are included in the snowmelt model, and corrects for latitude, longitude and time zone of the location. From this it can be found when the sun is above the horizon of the snow pile for every day during the storage season.

Figure 4.6 illustrates the solar elevation angle for the beginning (blue curve) and the end (dark green curve) of the storage season, as well as for summer solstice (June 21, light green curve), plotted against the snow pile horizon. Summer solstice represents the day when the sun reaches its highest point in the sky.

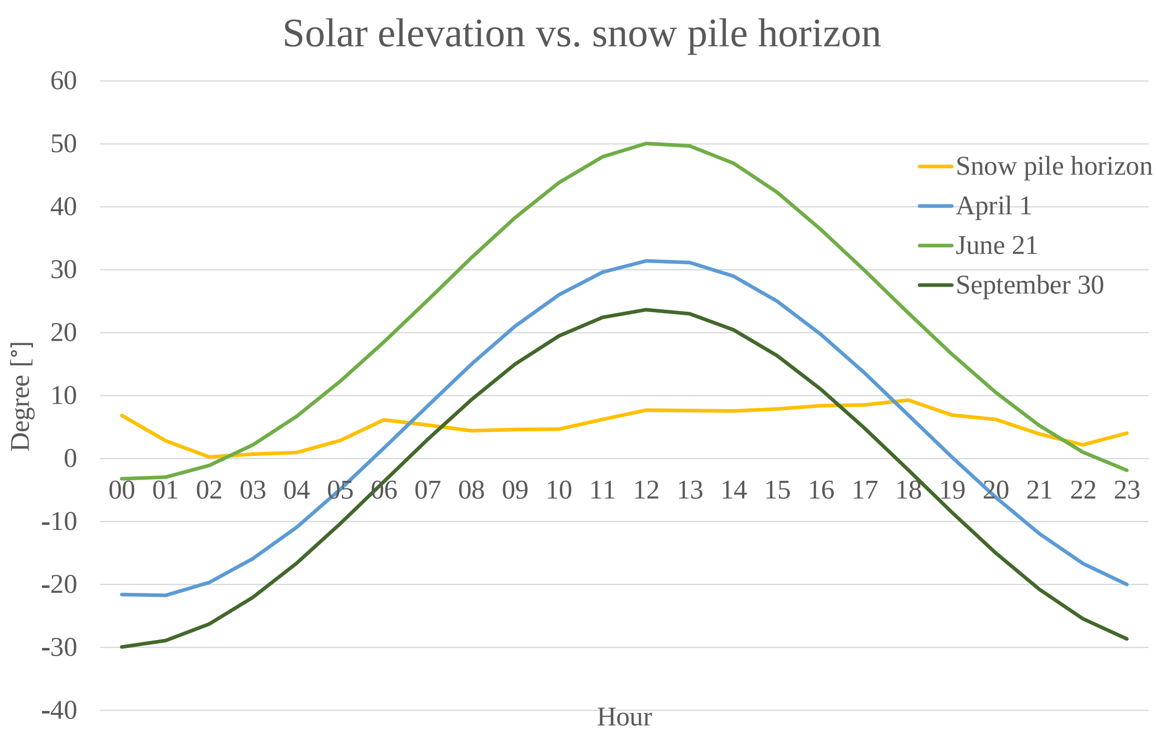

Figure 4.6: The solar elevation for three different days plotted against the horizon of the snow pile (yellow curve).

Weather statistics

Weather statistics for Granåsen are collected for eight years, 2009-2016. The statistics include values for air temperature, relative humidity, cloud cover, precipitation and global horizontal irradiance for every hour during the period from April 1 to September 30.

Albedo

The surface of the sawdust covering the snow pile will have a changing albedo depending on whether it is wet or dry. When it is raining or it has been raining during the last 12 hours, the albedo is assumed to have a value of 0.15. If the weather statistics have no registered precipitation the last 12 hours the albedo is set to 0.30. These values are based on another study on snow storage done by Ødegård (2013). When wet sawdust is exposed to solar radiation, the energy will be used to dry the sawdust before it will have an effect on the melting rate.

The amount of radiation being reflected by the sawdust will also depend on whether the sawdust is new or if it is reused. New and dry sawdust will have a lighter surface, thus a better ability to reflect the incoming solar radiation. The sawdust covering the snow storage in Granåsen is assumed to be new.

Specifications

Table 4.1 summarizes the specifications for the stored snow pile.

Table 4.1: Outdoor snow storage specifications

Period of storage	April 1 - Sept 30	Insulation material	Sawdust
Volume of stored snow	24 090 m^3	Δz	0.4 m
Ground area, A_g	4 400 m^2	k_{water}	0.58 W/mK
Length a	20 m	k_{avg}	0.33 W/mK
Length b	40 m	r (dry/wet)	0.3/0.15
Height h	7.3 m	Ground material	Gravel
Length L	110 m	k_g	0.7 W/mK
Θ	36°	ΔT_g	2 °C
Snow temperature	0 °C	l	2 m
ρ_{snow}	600 kg/m^3	$c_{p,water}$	4 180 J/kgK
ρ_{water}	1 000 kg/m^3	h_{lf}	334 000 J/kg

4.4.2 Results and Verification

Table 4.2 presents the theoretical melting losses for each year obtained from the snowmelt model. The last column states the average values of the eight years. In Table 4.2 the amount of measured precipitation for each season, P, is included in brackets.

Table 4.2: Theoretical snowmelt losses.

Source of melting	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**Average**
Ground [m^3]	243	243	243	243	243	243	243	243	243
Rain [m^3]	643	457	900	480	490	509	610	557	581
(P [mm])	*(617.3)*	*(470.9)*	*(787.4)*	*(555.3)*	*(459.7)*	*(482.2)*	*(608.5)*	*(526.2)*	*(563.4)*
Surr. [m^3]	4 210	3 755	4 111	3 552	4 044	4 469	3 777	3 978	3 987
Total melting loss [m^3]	5 096	4 455	5 253	4 276	4 777	5 221	4 630	4 778	4 811
Volume last day [m^3]	18 994	19 635	18 837	19 814	19 313	18 869	19 460	19 312	19 279
Loss in %	21	18	22	18	20	22	19	20	20

The percentage snowmelt contribution related to each heat source is shown in Table 4.3. The average values are included in the last column.

Table 4.3: Snowmelt contribution from each heat source.

Source of melting	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**Average**
Ground [%]	5	5	5	6	5	5	5	5	5
Rain [%]	13	10	17	11	10	10	13	12	12
Surroundings [%]	83	84	78	83	85	86	82	83	83

The presented results in Table 4.2 and Table 4.3 indicate that the surroundings (solar radiation and surrounding air temperature) have a remarkable impact on the snowmelt, and constitute more than 80 % of the total snowmelt.

Some practical examples of outdoor ground storage in Norway and Sweden are summarized in Table 4.4. The table includes storage location, the amount of stored snow, type of insulation material and the total snowmelt. Each of the examples had a storage season from late spring to October/November. By comparing the theoretical calculated melting losses from Table 4.2 to the melting losses in Table 4.4, it can be assumed that the calculated melting losses obtained from the snowmelt model are reasonable.

Table 4.4: Practical examples of outdoor ground storage (Vagle, 2017; Lintzén, 2016).

Location and year	**Volume of stored snow**	**Insulation material and thickness**	**Total snow melt**
Granåsen, Trondheim (Norway) - 2016	20 000 m^3	Sawdust, 40 cm	25 %
Östersund (Sweden) - 2006	20 000 m^3	Sawdust, 50 cm	20 %
Östersund (Sweden) - 2016	30 000 m^3	Sawdust, 40 cm	12 %
Lillehammer (Norway) - 2015	40 000 m^3	Wood chips, 30-50 cm	17 %

Considering Table 4.2 one can see that the seasons in 2011 and 2014 have the largest melting losses. The season of 2014 also has the highest amount of melting caused by the surroundings, which constitutes 86 % of the total melt. The highest amount of measured precipitation was in 2011, which results in a considerable part of melting due to heat from the rain.

The storage seasons in 2010 and 2012 have the smallest losses. These seasons also have rain melt below average. The ground melt is the same for each year as the temperature in the ground and the temperature of the snow pile are both assumed to be constant during the entire storage season. This is a reasonable assumption as the contribution from the ground heat is much smaller than the heat from rain and surroundings, as can be seen from Table 4.3.

4.4.3 Solutions for Snowmelt Reduction

To evaluate different solutions to reduce the snowmelt for the outdoor snow storage in Granåsen, the weather statistics for 2016 will be further used. Considering Table 4.2 and Table 4.3 the storage season of 2016 is a good representation of the average values. The following sections will study the effect of three solutions; solar shading, thicker layer of insulation and changes in snow pile geometry.

Solar shading

Figure 4.7 illustrates the average distribution of solar radiation per square meter on each side of the snow pile. The figure shows that the top surface and the side facing south are highly exposed to radiation from the sun.

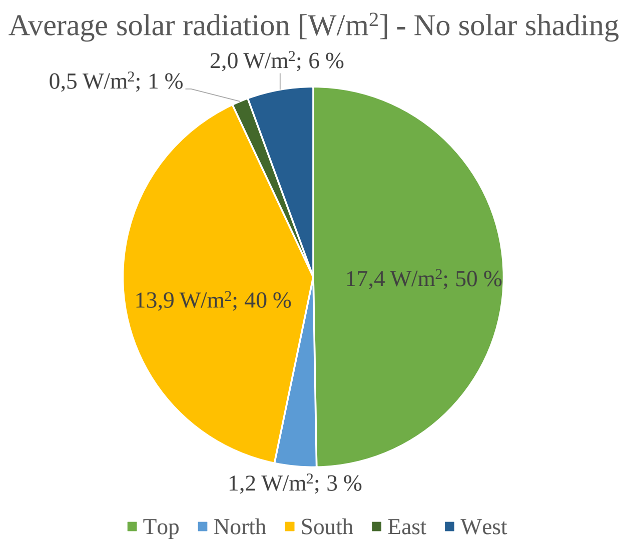

Figure 4.7: Average solar radiation on each side of the snow pile during storage season.

A wall for solar shading could be placed in front of the side facing south in order to reduce the impact of the solar radiation. If a 4 m high wall is placed 3 m from the side facing south, the horizon of the snow pile will be as the yellow curve in Figure 4.8. This means that the solar elevation angle must be higher than 53°, when the sun is in its southern positions, for the solar radiation to reach the surface. This reduces the number of hours where the snow pile is exposed to solar radiation. Figure 4.8 shows the solar elevation for three different days. The blue and the dark green curve represent the first and the last day of the storage period, while the light green curve represents the day when the sun reaches its highest point in the sky.

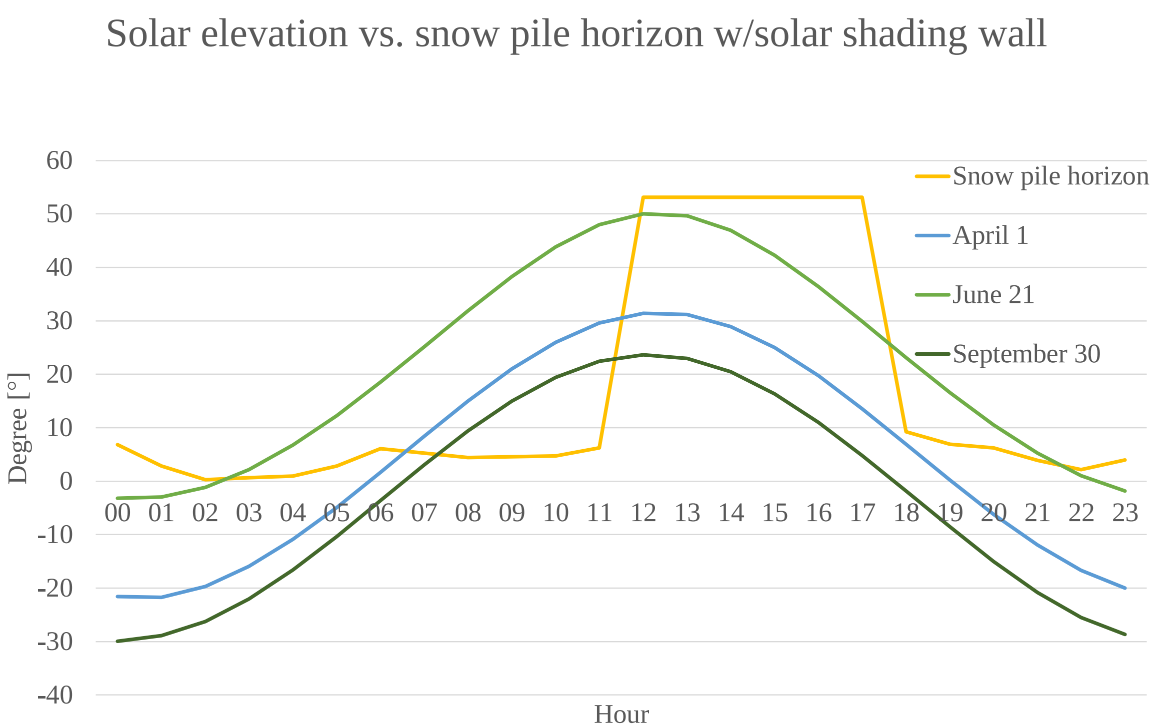

Figure 4.8: Solar elevation plotted against the snow pile horizon with solar shading wall.

By changing the horizon in the snowmelt model to include the solar shading wall, the model can be used to study the effect of the solar shading wall. The results are shown in Table 4.5.

Table 4.5: Result of snowmelt with and without solar shading wall.

Source of melting	**No wall**	**Wall**
Ground [m^3]	243	243
Rain [m^3]	557	562
Surroundings [m^3]	3 978	3 734
Total melting loss [m^3]	4 778	4 539
Volume last day [m^3]	19 312	19 551
Loss in %	20	19

From Table 4.5 one can see that the snowmelt has been slightly reduced, and that the rain melt is a bit higher for the case with the solar shading wall. The reason for that is probably related to the lowered snow melting rate, leading to a larger surface area being exposed to the rain. Figure 4.9 illustrates how the solar radiation is distributed on each side of the pile when a solar shading wall is used. The average solar radiation on the north, east and west side is almost the same as in Figure 4.7, but the average solar radiation on the top surface and south side is considerably reduced. However, a solar shading wall does not reduce the conductive heat transfer between the surrounding air and the snow pile, thus the total snowmelt reduction is small. It may provide shelter from the wind, but effects from wind has not been taken into consideration for the calculations.

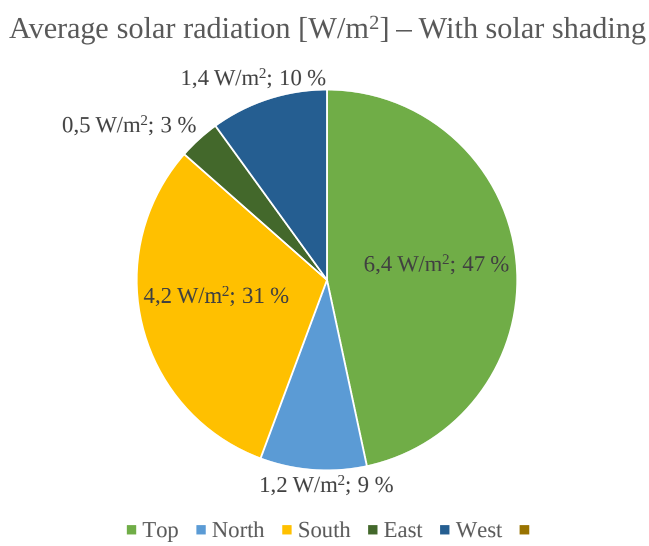

Figure 4.9: Distribution of solar radiation on each side with solar shading.

A solar shading wall of 40 m x 4 m will cost 99 200 NOK, for a given price of 620 NOK/m^2 (estimated price from different manufacturers). In addition the wall will require a solid framework for support against wind. The cost does not include the required amount of working hours to raise the wall.

Thicker layer of insulation

Equation 4.12 states that the heat transfer between the snow pile and the surroundings is inversely proportional to the thickness on the insulation material. This means that an increase in the thickness of the insulation layer will reduce the heat transfer.

By changing the insulation thickness in the snowmelt model, the effect of this can be studied. The results are shown in Table 4.6. From Table 4.6 one can easily observed the remarkable impact of a thicker layer of insulation, and that the snowmelt due to the surroundings is decreasing with increasing Δz. As for the case with the solar shading wall, the rain melt gets higher for higher values of Δz. The same explanation applies here; when the snow melting rate is reduced, a larger surface area of the snow pile is exposed to the rain. As indicated in Table 4.3, heat from the rain constitutes only 12 % of the total snowmelt. An increase in rain melt can therefore be accepted.

Table 4.6: Snowmelt result for different insulation thicknesses.

	Δz **[m]**					
Source of melting	**0.3**	**0.4**	**0.5**	**0.6**	**0.7**	**0.8**
Ground [m^3]	243	243	243	243	243	243
Rain [m^3]	536	557	570	579	585	590
Surroundings [m^3]	5 150	3 978	3 239	2 732	2 362	2 080
Total melting loss [m^3]	5 929	4 778	4 052	3 553	3 190	2 913
Volume last day [m^3]	18 161	19 312	20 038	20 537	20 900	21 177
Loss in %	25	20	17	15	13	12

Having a thicker layer of insulation is an option that requires more space. The sawdust must be stored and dried when it is not used. In the snow production guideline published by the Norwegian Ministry of Culture, it is recommended to use the sawdust every second year, and let it dry in between (Gjerland and Olsen, 2014). The guideline also advises to have a thickness of 0.3-0.5 m if an outdoor snow pile is to be covered with sawdust. A cost estimate is therefore done to compare whether it is cheaper to have a thicker layer of sawdust, or a thinner layer and compensate for the snow loss by buying the corresponding amount of snow. Choosing $\Delta z = 0.8$ m as reference case, 21 177 m^3 snow is needed at the end of the storage season. The result of the cost estimation is shown in Table 4.7.

Table 4.7: Cost estimation with respect to insulation thickness.

	Δz [m]					
	0.3	**0.4**	**0.5**	**0.6**	**0.7**	**0.8**
Sawdust needed [m^3]	1 609	2 145	2 681	3 217	3 753	4 289
Sawdust cost [NOK] (57 NOK/m^3)	91 713	122 265	152 817	183 369	213 921	244 473
Snow compensation [m^3]	3 016	1 865	1 139	641	277	0
Snow cost [NOK] (20 NOK/m^3)	60 320	37 300	22 780	12 820	5 540	0
Total cost [NOK]	152 033	159 565	175 597	196 189	219 461	244 473

The assumed prices of sawdust and snow are based on previous snow storage experiences from Granåsen and Beitostølen (Berg et al., 2016). The sawdust price includes transportation to the location, but the prices do not account for costs related to working hours. Table 4.7 states that the needed amount of sawdust is the major cost, and that the most expensive case is for Δz = 0.8 m without any snow needed to be bought. This supports the recommendation from Norwegian Ministry of Culture regarding insulation thickness.

Changing snow pile geometry

If the snow pile is assumed to have the shape as shown in Figure 4.5, one can easily see from Figure 4.7 that the top surface is exposed to the highest amount of solar radiation per square meter. This section investigates the effect of changing the snow pile geometry by reducing the top surface area and increasing the ground area, and still satisfy the snow volume requirement of 24 000 m^3. From Table 4.3 one can see that the heat from the ground make up for only 5 % of the total melt. The ground area of the snow pile can therefore be increased without leading to any significant raise in snowmelt. Since the ground area where the snow pile will be stored has the limitation of 112 m x 51 m, only the to parallel sides, a and b, will be changed. The length L and the height h will remain the same. The sum of a and b will also be the same in order to maintain the same cross-sectional area.

When a and b are changed, the two long sides of the pile (facing east and west) will change, as well as their tilt angle. By changing the geometry of the snow pile in the snowmelt model, the melting losses for the different geometries in Figure 4.10 can be found. The calculated melting loss for each geometry is shown in Table 4.8. For the case with the triangular prism the height is increased to obtain the same pile volume.

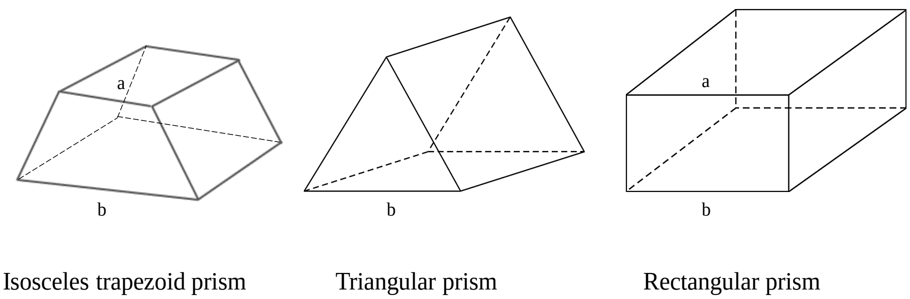

Figure 4.10: Different snow pile geometries.

Table 4.8: Snowmelt for different snow pile geometries.

Geometry	**Isosceles trapezoid prism**			**Triangular prism**	**Rectangular prism**
Properties	**a = 20 m b = 40 m**	**a = 15 m b = 45 m**	**a = 10 m b = 50 m**	**a = 0 m b = 50 m**	**a = b = 30 m**
Top surface area [m^2]	2 200	1 650	1 100	-	3 300
Ground surface area [m^2]	4 400	4 950	5 500	5 500	3 300
Total surface area [m^2]	5 362	5 758	6 222	6 266	5 344
SA:V [m^{-1}]	0.223	0.239	0.258	0.260	0.222
Source of melting					
Ground [m^3]	243	273	304	304	182
Rain [m^3]	557	595	638	647	551
Surroundings [m^3]	3 978	4 110	4 287	4 146	4 240
Total melting loss [m^3]	4 778	4 978	5 229	5 096	4 973
Volume last day [m^3]	19 312	19 112	18 861	18 999	19 117
Loss in %	19.83	20.66	21.71	21.15	20.64

A snow pile with the form of a triangular prism is the ideal geometry to minimize the top surface area parallel to the ground. However, Table 4.8 shows that this geometry will have a larger total surface area for the given volume requirement and ground surface restriction. The total snowmelt is therefore larger than for two of the trapezoid prisms and the rectangular prism.

The surface area of the snow pile should be as small as possible to reduce the exposure to solar radiation and surrounding air. The surface-area-to-volume ratio (SA:V) for the different geometries are included in Table 4.8. The lowest value for SA:V is found for the rectangular prism. However, the total melting loss for the rectangular prism is slightly larger than for the first trapezoid prisms. These two shapes have the same cross-sectional area, but the top surface area for the rectangular prism is larger. As previous stated, the top surface of the snow pile is the side which is exposed to the highest amount of solar radiation. This may explain why the rectangular prism does not have the smallest melting loss, despite its SA:V.

The ideal geometry to reduce the SA:V even further would be a hemisphere. For the required snow volume the SA:V would be 0.133, and the hemisphere would have a radius of 22.5 m. This geometry gives an unrealistic height for the snow pile, and is therefore not considered as an alternative.

Reducing the surface area will also reduce the amount of sawdust needed to cover the snow pile, as well as the costs related to the insulation. However, there will be challenging to form the snow pile into any desired shape as the snow storage is being produced. Limitation in maximum height, time, available vehicles and whether the areas around the storage are accessible by vehicles, are factors that have impact on the production and shape of the outdoor snow storage.

4.4.4 Discussion and Conclusion

The developed snowmelt model can be assumed to give reasonable snowmelt results, as the calculated snowmelt for each of the eight years is comparable to the snowmelt from other practical storage examples. The results also verify that the surface melt, due to solar radiation and surrounding air, constitutes the largest part of the total melt, as found by Skogsberg (2005). The model can be used for other snow storage facilities, as long as the latitude, longitude and horizon for the location are known, and weather statistics are available.

Figure 4.11 shows the decreasing snow pile volume during the season in 2016 for four different cases. The yellow curve illustrates the melting rate for the snow pile with the specifications given in

Table 4.1. Each one of the three other curves shows an investigated solution of snowmelt reduction.

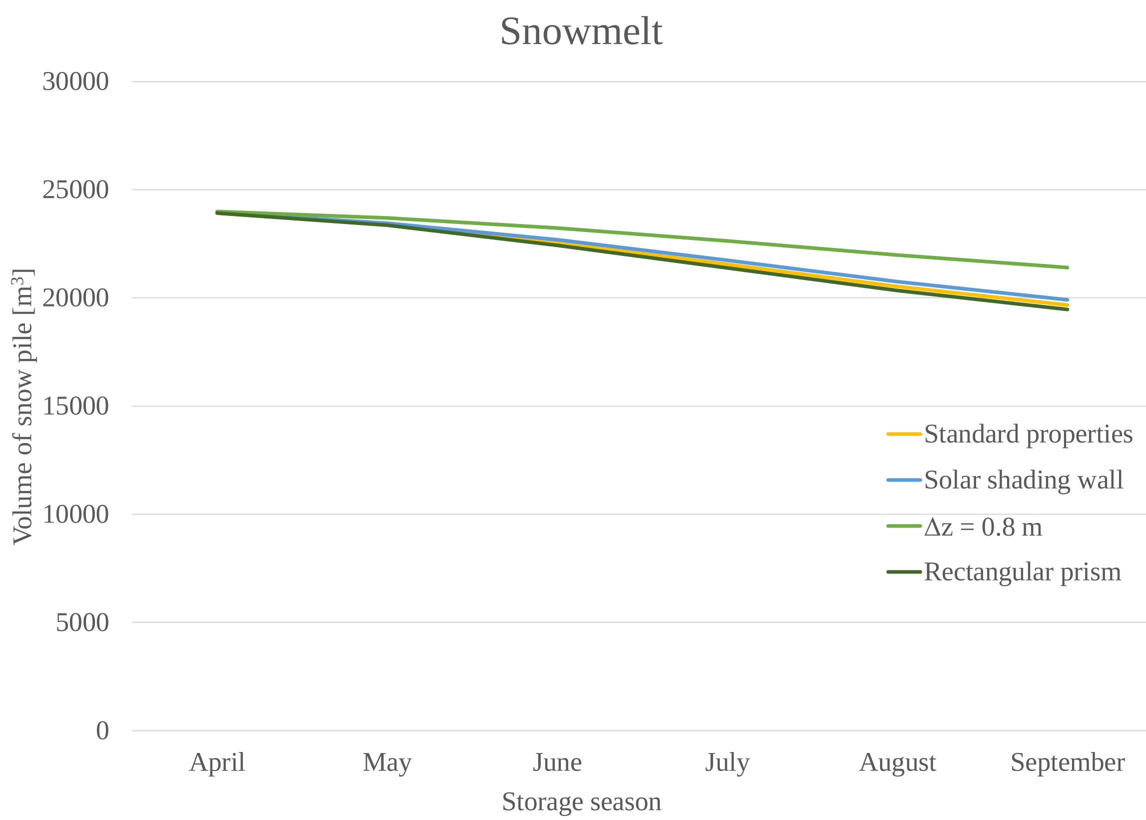

Figure 4.11: Decreasing of snow pile volume during the period of storage.

Only the increase in insulation thickness has a considerable reduction in melting rate, as can be seen from the light green curve in Figure 4.11. The same effect of insulation thickness was found in a laboratory experiment by Skogsberg and Lundberg (2005).

The cost estimation regrading insulation thickness has demonstrated that a thickness of 0.3-0.5 m sawdust, as recommended by Gjerland and Olsen (2014), can be accepted with respect to total snowmelt and insulation material costs. A solar shading wall cannot be regarded as an economical solution, as the reduction in snowmelt is minimal. Furthermore, the wall would permanently occupy space on the parking lot in Granåsen, when no snow is being stored. The results obtained by changing snow pile geometry, only demonstrated small variations in total snowmelt. The difference between the best and worst case of melting is only 451 m^3, which constitutes less than 2 % of the total snow pile volume. This indicates that the shaping of the snow pile when the snow storage is being produced, can be given less focus as long as the snow pile is kept compact. The main priority should therefore be given to efficient drying and maintenance of the sawdust.

Annual costs

Table 4.9 shows the an annual cost estimation for the outdoor snow storage with the specifications in Table 4.1. Assumptions regarding the calculations are listed below the table.

Table 4.9: Annual costs for the outdoor snow storage.

Annual costs	
Price of sawdust (57 NOK/m^3)	122 265 NOK
Sawdust covering (50 NOK/m^3)	107 250 NOK
Sawdust removal (50 NOK/m^3)	107 250 NOK
Buying extra snow (20 NOK/m^3)	100 000 NOK
Transportation of snow to trail (850 NOK/h)	510 000 NOK
Snow grooming (1 250 NOK/h)	40 000 NOK
Total	**986 765 NOK/year**

- The amount of sawdust needed to cover the pile is 2 145 m^3.
- Assuming that 5 m^3 snow must be bought to compensate for the melting loss.
- The time it takes to distribute the entire snow volume is assumed to be 600 hours.
- The snow grooming is assumed to take 32 hours in total.

The prices in Table 4.9 and the two last assumptions in the list above are based on previous snow storage experiences from Granåsen and Beitostølen (Berg et al., 2016; Ødegård, 2013).

The cost estimation in Table 4.9 does not include personnel expenses or fuel consumption. If the sawdust is dried between the seasons it is not necessary to buy new sawdust every year. The first cost in Table 4.9 will then be replaced by the cost related to the energy consumption for the drying process.

By comparing each cost in Table 4.9 one can see that the transportation of the snow to the trail constitutes 52 % of the total costs. It will therefore be profitable to locate the snow storage as close as possible to the trails.

Chapter 5

Indoor Snow Storage

5.1 Load Calculations for a Storage Hall

When snow is being produced and stored inside a refrigerated space, short term heat loads will be present. These heat gains can be categorized as the following list, where heat from the snowmaking has the largest impact (Eikevik, 2015; Clulow, 2006).

- **Transmission load** - heat through insulated walls, roof and floor.
- **Infiltration load** - heat from air infiltration through ventilation system, air penetration and opening and closing of doors.
- **Internal load** - heat from snow production, active and passive occupants, electrical equipment, ski lifts, lighting etc.
- **Equipment load** - heat from fans and defrosting of air coolers.

Sol-air temperature

When calculating the cooling load for a building and the heat gain through its external surfaces, the temperatures of the outside surfaces must be known. The outside surfaces of a building will be affected by the outdoor air temperature as well as the solar radiation. Depending on the material properties of the walls and roof, as well as the orientation of the surface relative to the sun, a certain amount of the radiation will be absorbed. This will result in an outside surface temperature which is higher than the outside air temperature, $T_s > T_o$ (Thomas, 2013). The heat transfer is illustrated in Figure 5.1.

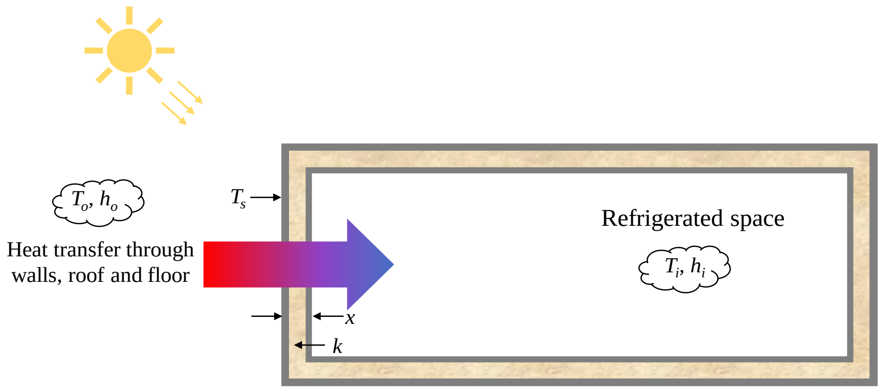

Figure 5.1: Refrigerated space with heat transfer through walls, roof and floor. The outside surface temperature, T_s, is higher than the outside air temperature, T_o, as a result of solar radiation. Adapted from Eikevik (2015).

The outside surface temperature, T_s [°C], can be calculated from the following equation

$$T_s = T_o + \frac{q''_{surface}}{h_o} \quad (5.1)$$

where h_o is the outside surface conductance [W/m^{2}K]. Since the outside surface will be exposed to wind a value of 6 W/m^{2}K can be assumed for h_o (ASHRAE, 2010). $q''_{surface}$ [W/m^2] can be found from Equation 4.10, which includes the absorbed solar radiation for a surface with a given reflectivity, as well as the solar elevation angle, the solar azimuth angle, the azimuth angle of the surface and the tilt angle of the surface. Each wall and the roof can then be treated separately.

5.1.1 Transmission Load

The transmission load, Q_{trans} [W], from heat through a wall can be found from the following equation

$$Q_{trans} = UA_s(T_s - T_i) \tag{5.2}$$

where U is the overall heat transfer coefficient [W/m^{2}K], A_s is the outside surface area of the wall [m^2] and T_i is the indoor air temperature [°C] (Eikevik, 2015).

The overall heat transfer coefficient depends on the thermal conductivity and the thickness of the wall, and can be calculated as

$$U = \frac{1}{1/h_i + x/k + 1/h_o} \tag{5.3}$$

where h_i is the inside surface conductance [W/m^{2}K], x is the thickness of the wall [m] and k is the thermal conductivity of the wall material [W/mK]. By assuming still air inside the refrigerated space h_i is set 1.6 W/m^{2}K (ASHRAE, 2010).

The same calculations apply for the other walls, the roof and the floor.

5.1.2 Infiltration Load

Unintentional air flow through cracks and openings in the building driven by wind, temperature differences and pressure differences causes natural infiltration (Spitler, 2010). The infiltration air must then be cooled down to the required air temperature for the refrigerated space. The heating load as a result of infiltration air, Q_{inf} [W], can be calculated from the following equation

$$Q_{inf} = C_s v_{leak}(T_o - T_i) \tag{5.4}$$

where C_s is the sensible heat factor [W/m^{3}Ks^{-1}] and v_{leak} is the flow rate of leaking air [m^3/s] (Spitler, 2010). A typical value of 2.7 W/m^{3}Ks^{-1} for the sensible heat factor will be used. The flow rate of leaking air depends on the pressure difference between the outside and the inside of the building, as well as the number, size and shape of cracks and gaps. This can be estimated by the following equation

$$v_{leak} = ACH\frac{V}{3600} \tag{5.5}$$

where ACH stands for the number of air changes per hour and V is the volume of the refrigerated space [m^3]. The value of ACH depends on type of building, construction and use (Spitler, 2010). A recommended value of ACH = 0.4 from the CoolPack software will be used.

5.1.3 Internal Load

Snow is produced by freezing of water, and a certain amount of heat has to be removed in order to freeze the incoming water. The internal load, Q_{int} [W], related to the snowmaking is then

$$Q_{int} = \dot{m}_{water}c_{p,water}(T_{water} - T_f) + \dot{m}_{water}h_{lf} + \dot{m}_{water}c_{p,ice}(T_f - T_{ice}) \tag{5.6}$$

where $\dot{m}_{water}$ is the mass flow of water [kg/s], $c_{p,water}$ is the specific heat capacity of water [J/kgK], T_{water} is the temperature of the incoming water [°C], T_f is the freezing temperature of water (0 °C), h_{lf} is the latent heat of fusion of ice [J/kg], $c_{p,ice}$ is the specific heat capacity of ice [J/kgK] and T_{ice} is the final temperature of the ice below freezing [°C] (ASHRAE, 2010).

5.1.4 Equipment Load

The refrigeration equipment will cause a certain heat gain during operation. This may includes heat from from fan motors, reheating for humidity control and defrosting of evaporators (ASHRAE, 2010).

The equipment load of significance for this case will be related to the heat gain from the air cooling fans. By using tabulated values of heat gain from typical electric motors (depending on power consumption per unit and location of the equipment), q_f [W], the heat gain from the fans, Q_{eq} [W], can be estimated as

$$Q_{eq} = q_f N \tag{5.7}$$

where N is the number of air cooler units. Tabulated values for q_f can be obtained from ASHRAE (2010).

5.1.5 Other Loads

Since there will be minimal activity and need of lighting in the hall used for snow production and storage, loads from lighting, people and door opening will be neglected.

5.1.6 Total Refrigeration Load

The total refrigeration load, Q_L [W], for the snow storage hall is then

$$Q_L = (Q_{trans} + Q_{inf} + Q_{int} + Q_{eq}) * 1.1 \tag{5.8}$$

The sum of each load is multiplied by 1.1 to add 10 % to correct for uncertainties in the calculations (Eikevik, 2015).

5.2 Heat Balance

The heat balance for the storage must be analyzed in order to determine the cooling load of the hall. The cooling load is the amount of heat that has to be removed from the hall in order to keep the indoor temperature constant (Spitler, 2010).

Assuming a building without any windows, the heat balance for the outside surfaces, in terms of heat fluxes [W/m^2], is

$$q''_{abs} + q''_{lwr} + q''_{conv} - q''_{cond} = 0 \tag{5.9}$$

where q''_{abs} is the absorbed solar radiation flux, q''_{lwr} is the long-wave radiation heat flux exchange with the surroundings, q''_{conv} is the convection heat flux exchange with the surrounding air and q''_{cond} is the conduction heat flux through the outer surfaces (Spitler, 2010).

The air heat balance for the indoor environment is

$$q_{conv} + q_{conv,int} + q_{inf} + q_{sys} = 0 \tag{5.10}$$

where q_{conv} is the convection heat transfer from the inside surfaces [W], $q_{conv,int}$ is the convection from internal loads [W], q_{inf} is the sensible load as a result of infiltration [W] and q_{sys} is the heat transfer to or from the heating/cooling system for the hall [W].

5.3 Indoor Snow Storage in Granåsen

This section is a theoretical study of a multipurpose hall in Granåsen as an indoor snow storage. 24 000 m^3 snow will be stored from the beginning of April to the end of September. The hall can be used for sports and arrangements during the winter.

5.3.1 Dimensions

If 24 000 m^3 snow is to be stored, a hall housing a football field of 48 m x 60 m with a height of 9 meter is large enough. A football field with these dimensions is suitable for nine players on each team. According to the rules given by the Norwegian Ministry of Culture and the Football Association of Norway, the football field must have a 3 m wide safety zone on each side (Norges Fotballforbund, 2018). This gives the hall a total ground area of 3 564 m^2 and a total volume of 32 000 m^3. Figure 5.2 shows the dimensions for a football field for 9 v 9 players recommended by the Football Association of Norway.

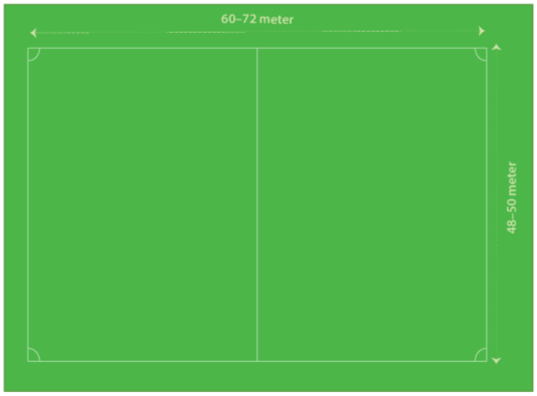

Figure 5.2: Standard football field dimensions for 9 v 9 (Norges Fotballforbund, 2018).

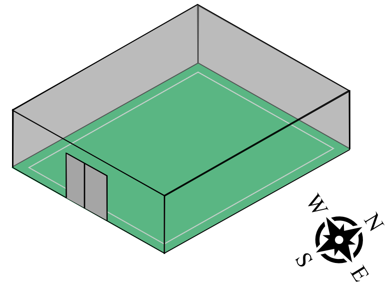

Figure 5.3: Multipurpose hall for sports and snow storage. The cardinal directions apply for the location of the storage in Granåsen.

Figure 5.3 illustrates a hall with artificial turf which can be used for both snow storage and sports. The cardinal directions in Figure 5.3 apply for the location where the hall is assumed to be placed in Granåsen. The location will be the same as for the outdoor snow storage discussed in Section 4.4. The hall must have a door which is large enough for vehicles when the snow is to be transported to the trails.

5.3.2 Construction of the Hall

The walls and ceiling can be made of mineral wool insulated panels with steel sheet facings, so-called sandwich panels (PAROC, 2018). Figure 5.4 shows an illustration of a sandwich panel from PAROC.

Figure 5.4: Sandwich panel from PAROC (PAROC, 2018).

Table 5.1 shows the technical performance for PAROC sandwich panels given by the manufacturer.

The U-value for the floor is assumed to be 0.1 W/m^{2}K.

Table 5.1: Technical performance of PAROC panels (PAROC, 2017).

Panel performance	Walls	Roof
Insulation material	Paroc AST L	Paroc AST E
Thickness [mm]	240	300
U-value [W/m^{2}K]	0.15	0.14
Color group	I	I
Absorption coefficient	0.1	0.1

5.3.3 Floor Cooling/Heating System

The snow will be stored on top of the football field made of artificial turf. To ensure that the surface carrying the snow always is below freezing, coolant pipes can be distributed over the surface. This will prevent the snow from changing and losing its quality. Pipes of polyethylene (PE) with glycol as coolant can be used for this purpose (Clulow, 2006). The pipes will be parallel to each other and covered in a thermally conductive material, such as activated alumina mixed with cement to form a concrete material (Clulow and Winnett, 2006).

The thermal resistance of PE pipes also makes them suitable for heating purposes. The pipes can be used at operating temperatures from -40 °C to 60 °C (Plastics Pipe Institute, 2008). Pipes made of PE hold a greater strength at increasing temperature than other thermoplastic materials, which allows for use in a wide variety of applications at a large temperature range.

Figure 5.5 illustrates a vertical section of the ground, including pipe system, insulation, gravel for drainage and bedrock. Typical thickness for each layer is included in the figure (Andersen, 2015).

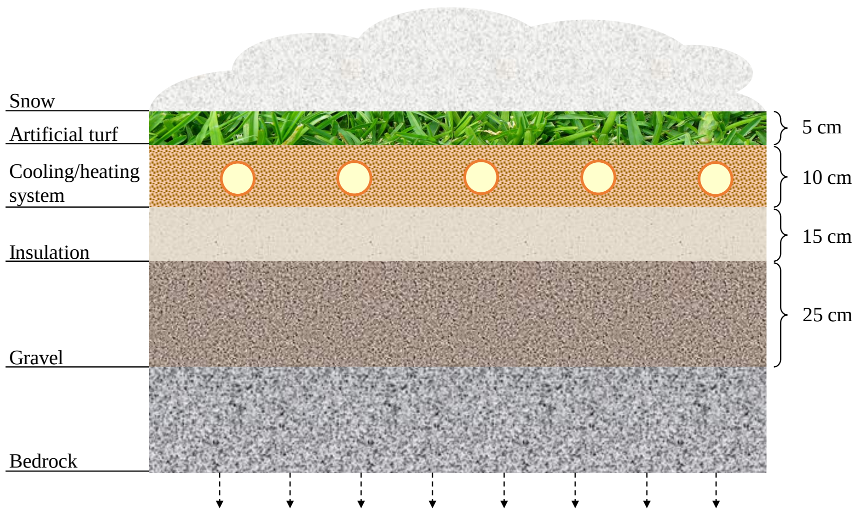

Figure 5.5: Vertical section of ground with pipe system for heating and cooling. Typical thicknesses are included.

5.3.4 Indoor Conditions

When the snow is being stored the indoor air temperature is set to -3 °C. At snow production the temperature should be reduced to temperatures around -10 °C.

According to the guideline for multipurpose halls published by the Norwegian Ministry of Culture, the indoor temperature should be 18 °C, with the possibility to be regulated between 15 °C and 21 °C, when the hall is used for sports purposes during the winter (Roa, 2016).

5.3.5 End of Storage Season

Before the snow can be transported from the storage to the trails, the ground beneath the snow must be thawed. Since the snow has been stored on top of the artificial turf, without any protective layer between, it is important to make sure that there is no frost in the artificial turf when the snow is being removed. If coolant pipes, as described in Section 5.3.3, are installed, they can also be used for thawing. When the bottom layer of the snow pile is melted, there will be no frost between the tuft and the snow. This will reduce the chance of harming the fibres in the turf, and avoid fibres and rubber granules being mixed with the snow. However, this heating procedure will lead to some melting loss. When the entire snow pile has been removed, the field must be sufficiently dried before it can be used for other activities.

5.3.6 Hour-by-hour Load Calculations

The same snowmelt model as used for the outdoor storage is applied for the indoor snow storage case. Since the outdoor storage and the indoor storage are assumed to have the same location in Granåsen, the horizon is the same. The geometry of the snow pile is further changed to the geometry and construction of the multipurpose hall, as described in Section 5.3.1 and Section 5.3.2. Obtained weather statistics for every hour from April 1 to September 30 will be used. The initial volume of the snow at first day of storage is 24 115 m^3, dimensioned as 65 m x 53 m x 7 m (L, W, H).

The indoor snow storage will be studied for the time of snow storage, assuming that the snow already has been produced. The heat input to the storage will then be related to transmission load and infiltration load. The magnitude of these loads will depend on the outdoor temperature and indoor air temperature. A larger temperature difference between the outside surface temperature and the indoor air temperature or between the outdoor air and the indoor air (see Equation 5.2 and Equation 5.4) will increase the heat load. These heat loads need to be balanced with the capacity of the refrigeration system (Eikevik, 2015). If this capacity is too low, the indoor air temperature will increase until there is a balance between the loads and the capacity.

The required indoor air temperature is set to -3 °C. Since the heat loads are depending on the weather conditions outside the storage, there will be great differences in need for refrigeration during one day or during the entire storage season. Weather statistics for the season of 2016 will be used to evaluate the loads.

Energy balance

Equation 5.9 and Equation 5.10 are simplified to the energy balance in Equation 5.11. This balance applies for the hall when the snow is being stored.

$$Q_{in} + Q_0 = Q_{air} + Q_{snow} \tag{5.11}$$

where

$$Q_{in} = Q_{trans} + Q_{inf} \tag{5.12}$$

Q_{trans} [W] and Q_{inf} [W] are found from Equation 5.2 and Equation 5.4 respectively. Each of the outer surfaces of the hall is treated separately. Q_0 is the constant refrigeration capacity of the system [W]. Q_{air} is the energy absorbed by the indoor air to raise the temperature [W] and Q_{snow} is the energy absorbed by the snow [W].

Q_{air} can be found from

$$Q_{air} = \dot{m}_{air} c_{p,air} \Delta T_{air} = \dot{m}_{air} c_{p,air} (T_{air,after} - T_{air}) \tag{5.13}$$

where $\dot{m}_{air}$ is the mass flow of the air [kg/s], $c_{p,air}$ is the heat capacity of the air, and ΔT is the temperature increase/decrease. If $T_{air,after} > T_{air}$ the energy of the system increases. The heat capacity of the air is set to 1 000 J/kgK.

As a simplification it will been assumed that the snow only melts on the surface. The temperature of the snow, T_{snow}, is set to 0 °C and the snow starts to melt if the air temperature, $T_{air,after}$, gets higher than 0 °C. The energy that will be absorbed by the snow is equal to the heat transfer between the air and the snow, expressed in the following equation

$$Q_{snow} = \dot{m}_{snow} * h_{lf} = UA_s (T_{air,after} - T_{snow}) \tag{5.14}$$

where $\dot{m}_{snow}$ is the mass flow of the snow [kg/s] and h_{lf} is the latent heat of fusion for snow, which is 334 000 J/kg (Bergman et al., 2011). U is the overall heat transfer coefficient set to 1.6 W/m^{2}K, assuming still air inside the storage and A_s is the surface area of the snow [m^2].

By evaluating the temperature distribution for the snow, the snow temperature can be found for every hour. This will be a transient conduction problem, and the dimensionless parameters *Bi* (Biot number) and *Fo* (Fourier number) must be determined from Equation 5.15 and Equation 5.16, respectively.

$$Bi = \frac{hL}{k} \tag{5.15}$$

where L is the characteristic dimension or thickness [m] and k is the thermal conductivity of the snow (Bergman et al., 2011). Compacted snow can be assumed to have a thermal conductivity of 0.33 W/mK, based on values from a study done by Côté et al. (2012). The heat transfer coefficient, h, is set to 1.6 W/m^2 assuming still air.

$$Fo = \frac{\alpha \tau}{L^2} \tag{5.16}$$

where α is the thermal diffusivity [m^2/s] and τ is time [s]. The thermal diffusivity can be expressed as

$$\alpha = \frac{k}{\rho c_p} \tag{5.17}$$

The specific heat capacity of snow/ice is 2 040 J/kgK (Bergman et al., 2011). The density of the snow is set to 600 kg/m^3.

For $0.1 \leq Bi \leq 100$ the average dimensionless temperature distribution for the snow, assuming a plane surface, is

$$\bar{\Theta} = \sum_{n=1}^{n \to \infty} \frac{2 sin^2 \mu_n}{\mu_n^2 + \mu_n sin \mu_n cos \mu_n} exp(-\mu_n^2 Fo) \tag{5.18}$$

and

$$\bar{\Theta} = \frac{T_\tau - T_{air,after}}{T_{\tau=0} - T_{air,after}} \tag{5.19}$$

where T_τ is the temperature of the snow at time τ and $T_{\tau=0}$ is the initial temperature of the snow (Eikevik, 2018). μ_n can be found from tables, see Table 5.2.

Table 5.2: Values for μ roots for selected Bi numbers. Extract from table by Eikevik (2018).

Bi	μ_1	μ_2	μ_3
30	1.5202	4.5615	7.6057
34	1.5251	4.5761	7.6293
40	1.5325	4.5979	7.6647

Snowmelt calculation

The Solver in Excel is used to find the temperature of the air, $T_{air,after}$, that balances Equation 5.11 with respect to the hour-by-hour load calculations. If $T_{air,after} > 0$ °C, the estimated amount of melted snow during one hour, m_{snow} [kg], is found by solving Equation 5.14 for $\dot{m}_{snow}$, which gives

$$m_{snow} = \frac{Q_{snow}}{h_{lf}} * 3600s = \frac{UA_s(T_{air,after} - T_{snow})}{h_{lf}} * 3600s \tag{5.20}$$

The volume of the melted snow during one hour, V_{snow} [m^3], is then,

$$V_{snow} = \frac{m_{snow}}{\rho_{snow}} \tag{5.21}$$

5.3.7 Design of Refrigeration System

Due to the variable cell limitation for the Solver (maximum 200 variable cells), it is not possible to use the Solver for the entire storage period in one operation. It is therefore decided to solve the energy balance for two different weeks, separately. The number of variable cells is then 168, which corresponds the number of hours in one week. Since there will be big differences in heat load during the storage season, the system is evaluated for a week with average temperatures and for the week with the highest temperatures. The amount of snowmelt during the average week and the warmest week will then be calculated at different refrigeration capacities for the system, Q_0.

The refrigeration system is assumed to have a water cooled condenser. The evaporation temperature, T_0, is set to -15 °C and the condensation temperature, T_c, is set to 20 °C. R290 (propane) is chosen as an appropriate refrigerant. Figure 5.6 shows the cooling cycle for the indoor storage. The isentropic efficiency is set to 0.7.

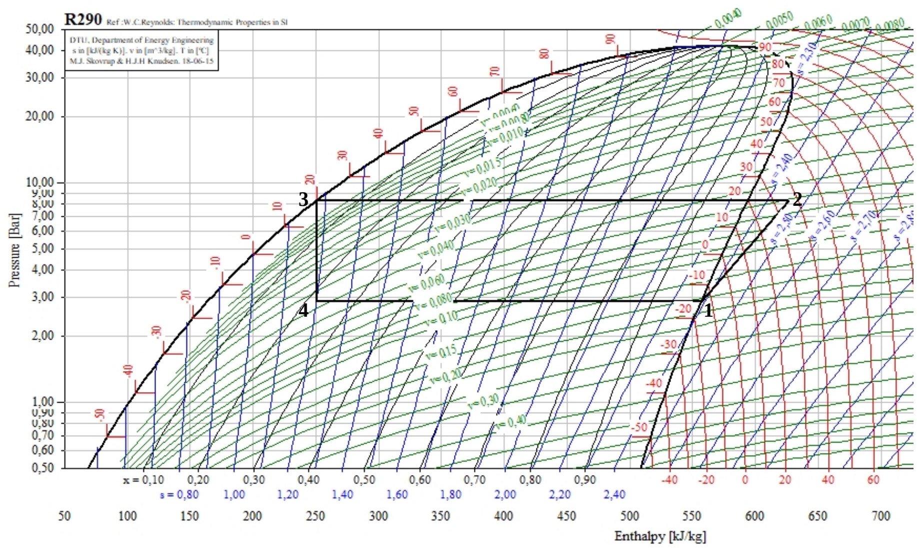

Figure 5.6: Log p-h diagram of the cooling cycle for the indoor snow storage. The isentropic efficiency is set to 0.7.

Data for the cooling cycle in Figure 5.6 is given in Table 5.3. In the next sections a short description of R290 as working fluid is provided, followed by the calculations for the two different weeks.

Table 5.3: Data for the cooling cycle in Figure 5.6.

Point	Temperature, T [°C]	Pressure, p [bar]	Enthalpy, h [kJ/kg]
1	-15	2.892	556.921
2	20	8.322	626.901
3	20	8.322	250.548
4	-15	2.892	250.548

R290 as working fluid

R290, also know as propane, is a common refrigerant used in commercial and industrial refrigeration systems. This refrigerant has A3 as safety group classification, which meas that it is highly flammable and non-toxic (The Linde Group, 2018). R290 has a low environmental impact with ODP (Ozone Depletion Potential) equal 0 and GWP (Global Warming Potential) equal 3.

The working fluid charge will be restricted according to class and type of occupancy. Assuming that the refrigeration system will be placed in a machinery room outside the storage hall, only authorized persons will have access. This is equivalent to occupancy category 3 according to the NS-EN 378-1:2008+A2:2012 standard. The standard states the maximum charge of A3 refrigerants to 1 kg below ground floor, and 25 kg above ground floor level. This must be taken into account for the system design.

The warmest week

The warmest week during the storage period in 2016 is July 21 - July 27. The average temperature for this week is 19.1 °C and the highest measured temperature is 29.8 °C. Figure 5.7 shows how the indoor air temperature for the storage will vary at different refrigeration capacities for the system.

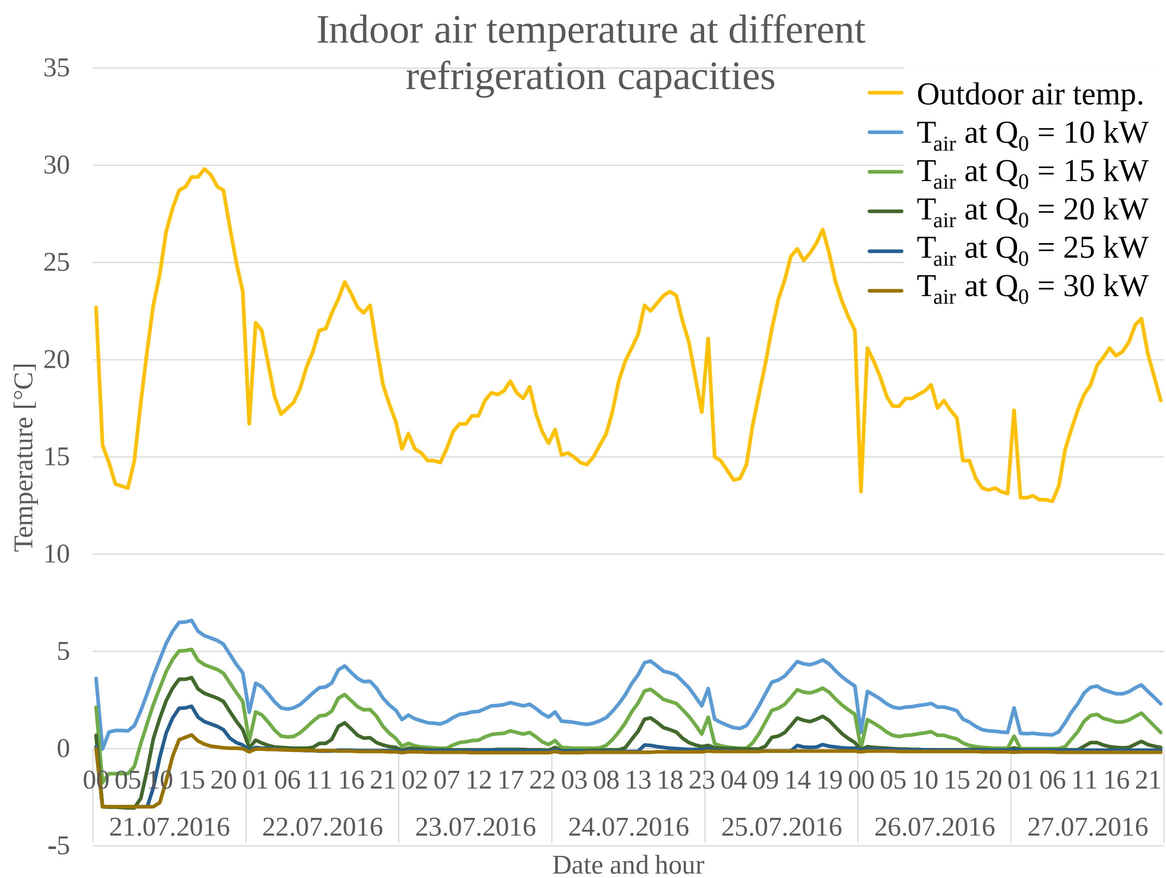

Figure 5.7: Indoor air temperature variation for the warmest week (July 21 - July 27, 2016) at different refrigeration capacities. The yellow curve shows the outdoor air temperature.

The increase in indoor air temperature will affect the snowmelt. From Figure 5.7 one can see that for the cases with lower refrigeration capacity the indoor air temperature raises above 0 °C. This means that the system needs a higher refrigeration capacity to avoid the air temperature from increasing with increasing outdoor temperatures, and to avoid the snow from melting. For Q_0 = 25 kW or 30 kW the increase in temperature is small, so is the snowmelt. The calculated snowmelt at different refrigeration capacities during the warmest week is shown in Table 5.4.

Table 5.4: Snowmelt and melting rate for the warmest week (July 21 - July 27) at different refrigeration capacities.

Cooling capacity, Q_0 [kW]	**Snowmelt [m^3]**	**Melting rate [m^3/h]**
10	64.30	0.383
15	30.74	0.183
20	10.56	0.063
25	2.57	0.015
30	0.38	0.002

From Table 5.4 one can see that the amount of melted snow is highly reduced at increased refrigeration capacity when the heat load to the storage is high. The snowmelt is reduced by 99.4 % when Q_0 is changed from 10 kW to 30 kW.

The average week

The average outdoor temperature for the storage season in 2016 is 11.1 °C. A week (May 5 - May 11) with the same average temperature is therefore studied. Figure 5.8 shows how the indoor air temperature for the storage will vary at different refrigeration capacities for the system.

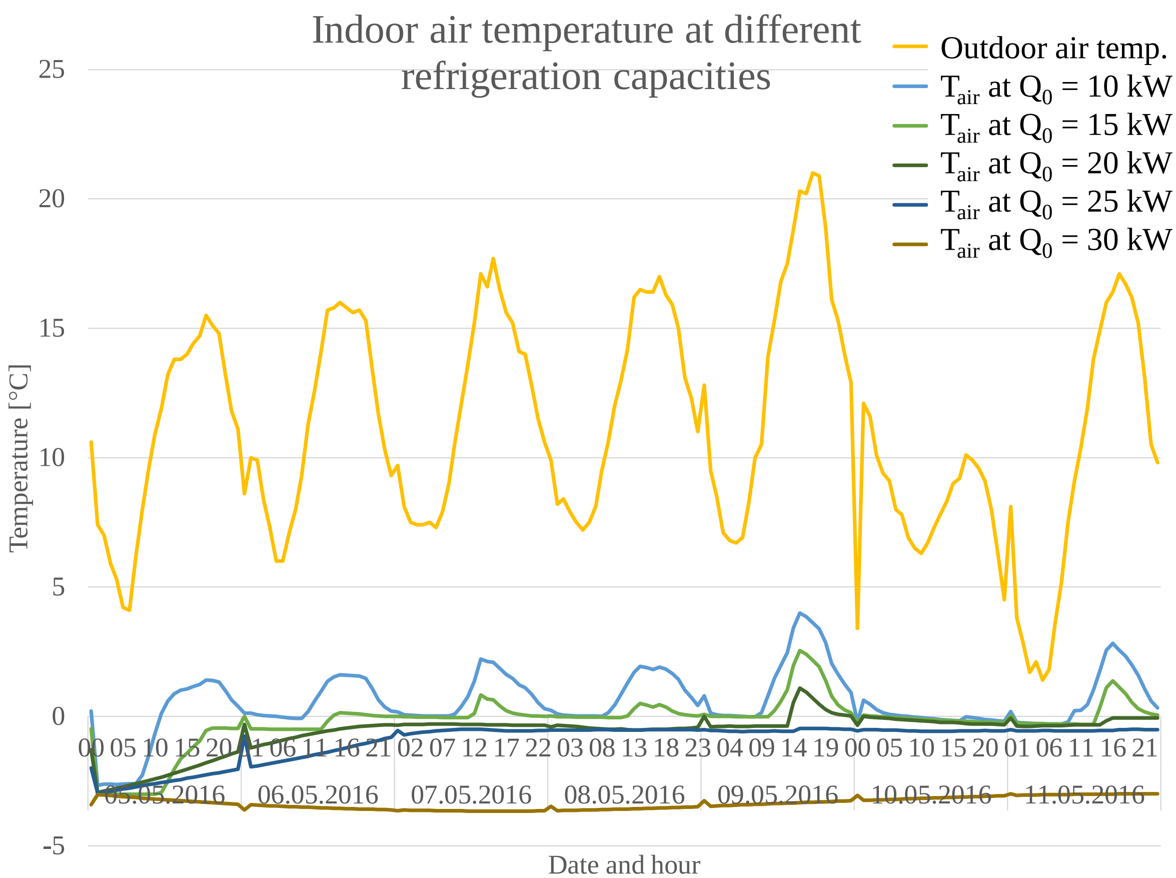

Figure 5.8: Indoor air temperature variation for the average week (May 5 - May 11, 2016) at different refrigeration capacities. The yellow curve shows the outdoor air temperature.

Figure 5.8 shows that the indoor air temperature will never raise above 0 °C if the refrigeration capacity for the system is 25 kW or 30 kW. This means that the heat load to the storage is smaller than Q_0 or not big enough to raise the indoor temperature that much.

The calculated snowmelt for the average week is shown in Table 5.5. Comparing Table 5.5 to Table 5.4 shows that the amount of melted snow for the lower capacities is less for the average week than for the warmest week.

Table 5.5: Snowmelt and melting rate for the average week (May 5 - May 11) at different refrigeration capacities.

Cooling capacity, Q_0 [kW]	Snowmelt [m^3]	Melting rate [m^3/h]
10	17.77	0.106
15	4.16	0.025
20	0.62	0.004
25	0.00	0.000
30	0.00	0.000

By looking at Figure 5.7 and Figure 5.8 one can easily see how the outdoor air temperature affects the indoor environment when the refrigeration capacity is low.

Evaluation of cooling system

Using the data for the cooling cycle given in Table 5.3 the refrigerant mass flow, m_r [kg/s], can be found from

$$\dot{m}_r = \frac{Q_0}{h_1 - h_4} \tag{5.22}$$

The work input to the compressor, W [W], is

$$W = \dot{m}_r(h_2 - h_1) \tag{5.23}$$

The coefficient of performance (COP) for the system can then be calculated from the following equations

$$COP = \frac{Q_0}{W} \tag{5.24}$$

or

$$COP = \frac{Q_{in}}{W} \tag{5.25}$$

where Equation 5.24 should be used if $Q_0 < Q_{in}$ and Equation 5.25 if $Q_0 > Q_{in}$.

The seasonal performance factor (SPF) will then be the average COP of the system over the full storage season.

$$SPF = \frac{\sum_{n=1}^{N=4392} COP_n}{N} \tag{5.26}$$

Since the calculations are based on hour-by-hour measurements, N = 4392 is the number of hours during the entire period (from April 1 to September 30).

The refrigeration capacity is further set to 20 kW for the single stage cooling cycle in Figure 5.6. The calculated SPF for each of the two weeks is shown in Table 5.6. The refrigerant mass flow and the compressor work are the same for both weeks as the cooling cycle is the same. The COP will vary with the heat input to the storage, leading to different values for SPF. This shows that the COP for the system will decrease if the input temperatures decrease. The charge of mass flow is acceptable according to the NS-EN 378-1:2008+A2:2012 standard.

Table 5.6: SPF for warm and average week.

	Q_0 **[kW]**	$\dot{m}_r$ **[kg/s]**	W **[kW]**	**SPF (**N **= 168)**
Warmest week	20	0.065	4.568	3.86
Average week	20	0.065	4.568	2.60

If it is assumed that the average week is a good representation of the entire storage season, the total amount of melted snow will be 18 m^3 for Q_0 = 20 kW. This is only 0.07 % of the initial snow volume. Figure 5.9 presents how much of the heat input which will be covered if Q_0 = 20 kW for the two different weeks. From Figure 5.9 it can be observed that almost everything will be covered for the average week.

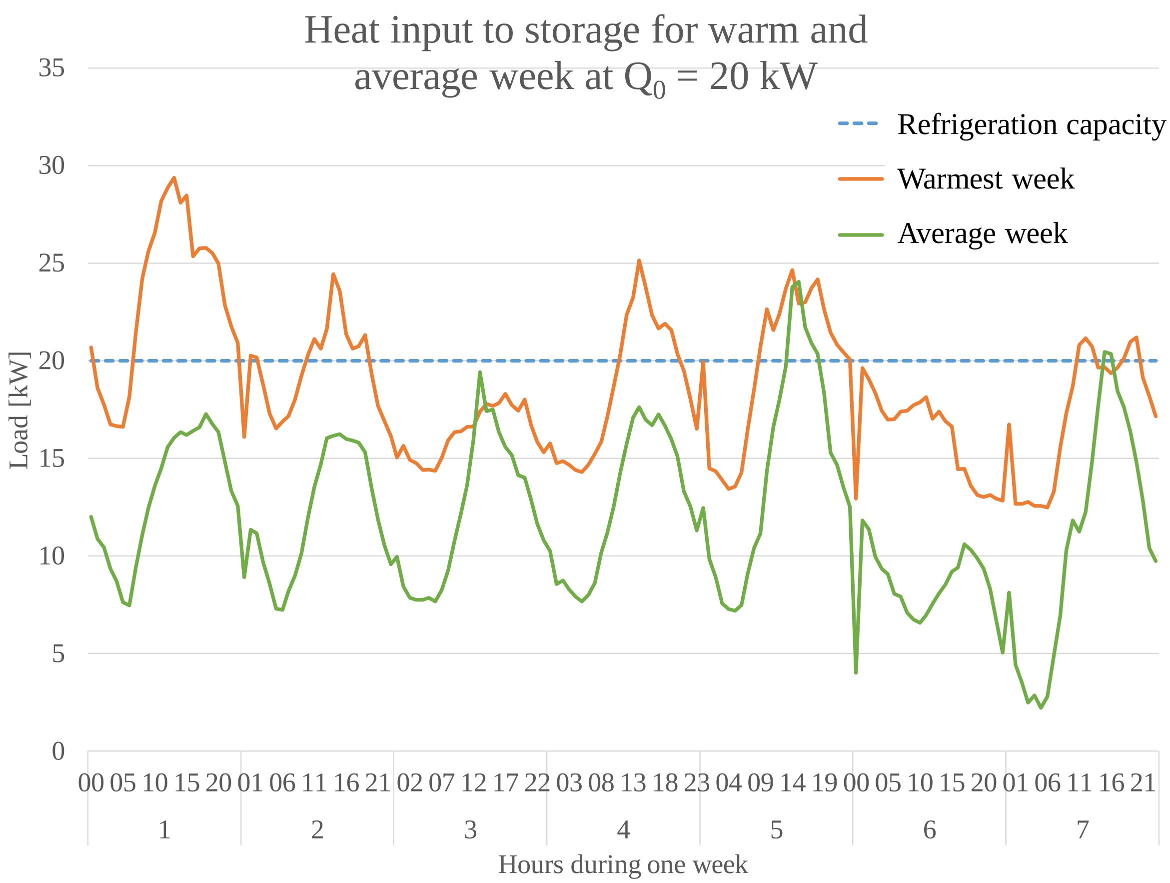

Figure 5.9: Heat input to the storage for the warmest week and the average week when the refrigeration capacity is 20 kW.

Assuming that the indoor air temperature of the storage is kept constant at -3 °C (T_i is constant in Equation 5.2 and Equation 5.4), there will be 564 hours out of 4392 hours in total, where Q_{in} is higher than 20 kW. If the warmest week is set as reference for the hours with $Q_{in} > 20$ kW, the melting rate can be set to 0.063 m^3/h (see Table 5.4). The amount of melted snow will then be 36 m^3. For the remaining 3828 hours the melting rate is set to 0.004 m^3/h (from Table 5.5), and the amount of melted snow will be 15 m^3. The sum of melted snow is then 51 m^3, which represents 0.21 % of the initial pile volume.

5.3.8 Discussion and Conclusion

The melting loss calculations show that the snowmelt for an indoor snow storage will be very low. This is as expected since the snow pile is not being exposed to rain, solar radiation or high surrounding air temperatures. By choosing construction materials with low absorption coefficients and low U-values, the heat transfer from the outside is reduced. Please note that the snowmelt calculations does not include loss related to infiltration by opening of doors when the snow is being transported from the storage.

The snowmelt results show that the melting loss for Q_0 = 20 kW is quite low for both weeks. These losses are acceptable and the cooling system for the hall can therefore be designed for a refrigeration capacity of 20 kW when the snow is being stored.

If the desired indoor air temperature is set to a higher temperature, still below 0 °C, for instance -1 °C, the compressor work would be reduced. However, T_i set to -3 °C will work as a buffer, and it would take longer time to raise the indoor air temperature above 0 °C, when the heat load is higher than the refrigeration capacity of the system.

It will be necessary to install temperature sensors in the hall to control the indoor environment. Since the volume of air inside the storage will be quite large, and since the solar radiation will not be the same for each outer surface of the hall, there might be variations in air temperature within the hall. Figure 4.7 shows that the top surface and the side facing south of the outdoor snow storage are much more exposed to solar radiation than the other sides. Since the indoor storage will have the same location, it can be assumed that the roof and the side wall facing south are critical surfaces considering absorption of solar radiation.

Costs and incomes

The total cost of building a multipurpose hall with the given specifications in Section 5.3.1 and Section 5.3.2, will be approximately 53.5 MNOK, assuming 15 000 NOK/m^2. This is based on the total costs for similar halls in Norway with steel and sandwich element construction. These are simplified hall concepts without wardrobes, secondary rooms, grandstands and such, with a total price estimate of 12 000-20 000 NOK/m^2, including engineering and construction work (Kilskar et al., 2011; Hallmaker Gruppen AS, 2018; Drammen Eiendom KF, 2018).

If the time to dry the football field after the snow is being removed is set to seven days, and so the time for preparation before the snow storage season begins, the hall can be rented out for 24 weeks. Assuming opening hours from 7 am to 11 pm, and that the price for renting the hall is 960 NOK/hour, the total rental income will be 2.6 MNOK per year. The payback period for the multipurpose hall is then approximately 21 years.

Table 5.7 presents an overview of the estimated costs for the indoor snow storage. Assumptions related to the calculations are listed below the table.

Table 5.7: Investment costs, income and annual costs for the indoor snow storage.

Investment costs	
Multipurpose hall	53.5 MNOK
Cooling system	50 000 NOK
Income	
Hall rental	2.6 MNOK/yr
Annual costs	
Power input (1 NOK/kWh)	21 960 NOK
Transportation of snow to trail (850 NOK/h)	510 000 NOK
Snow grooming (1 250 NOK/h)	40 000 NOK
Total	**571 960 NOK/year**

- The price for the cooling system is 2 000 NOK/kW x 20 kW + 25 % taxes (Vagle, 2016b).
- The work input to the compressor is 5 kW for 4392 hours.
- The time it takes to distribute the entire snow volume is assumed to be 600 hours.
- The snow grooming is assumed to take 32 hours in total.

The prices in Table 5.7 and the two last assumptions in the list above are based on previous snow storage experiences from Granåsen and Beitostølen (Berg et al., 2016; Ødegård, 2013).

The costs related to transportation of the snow to the trail and the snow grooming will be the same as for the outdoor storage (see Table 4.9). The annual cost estimation in Table 5.7 does not include personnel expenses or fuel consumption.

Chapter 6

General Conclusions and Suggestions for Further Work

For an outdoor snow storage in Granåsen containing 24 000 m^3 snow, it is reasonable to assume that approximately 20 % of the volume will be lost during the storage season. For similar examples of outdoor snow storage in Scandinavia the total snow melt varies from 12 % to 25 %.

The calculations for the outdoor snow storage demonstrate that the heat from the surroundings (solar radiation and surrounding air) will have the greatest impact on the snowmelt for an insulated snow pile stored outside. The contribution from the surroundings is found to be 78-86 % of the total snowmelt. Increasing the thickness of the insulation layer is found to be the best solution to reduce the melting rate. Changing the insulation thickness from 0.4 m to 0.8 m reduces the snowmelt from 20 % to 12 %. However, the cost estimation shows that the expenses will be higher for increased amount of sawdust. Thus, a thickness of 0.3-0.5 m can be recommended.

Changing the snow pile geometry or use of a solar shading wall does not lead to any significant melt reduction. When the pile is changed from a trapezoid prism to a triangular prism or to a rectangular prism, the snowmelt is increased by approximately 1 %. The solar shading wall only reduces the melting loss by 1 %. For that reason it can be concluded that maintenance of the sawdust is the most important measure in order to reduce the snowmelt. This includes necessary drying to maintain the quality and the low thermal conductivity of the sawdust. The the cost related to buying new sawdust will then be reduced. However, the method applied to dry the sawdust should be energy efficient in order to reduce the total costs. Drying methods for sawdust have not been studied in this thesis, and will therefore be suggested as further work.

The results from the indoor snow storage show that the melting losses will be very small for snow stored inside a refrigerated hall. The snowmelt model demonstrates that there will be great variations in indoor air temperature at different refrigeration capacities (Q_0) for the cooling system. The cooling system for the hall can be designed for Q_0 = 20 kW when the snow is being stored, and the snowmelt will be less than 1 % of the initial snow volume.

The investment costs for a multipurpose hall to be used for snow storage and sports purposes, will be approximately 53.6 MNOK. This makes a multipurpose hall a much more expensive alternative for snow storage, compare to outdoor storage. Renting out the hall during the winter will give an annual income of 2.6 MNOK/year, but the payback period will be 21 years. The need for indoor training facilities should therefore be thorough analyzed before the decision to build a multipurpose hall is taken.

More than 50 % of the annual costs for snow storage will be related to distribution and transportation of snow to the trails. For the outdoor storage there will be an additional cost related to the work for covering and removal of sawdust. In order to reduce the transportation cost it will be of importance to have detailed strategies in advance, regarding the need for snow and how much snow which should be distributed during the winter. This is to avoid that too much snow is being distributed at the same time, which has to be taken back to the storage or may get lost due to melting.

Snow storage is a good alternative to guarantee for skiing facilities in Granåsen from the beginning of October. This makes it possible to provide skiing trails even if no natural snow has fallen, or the temperature is too high for traditional snowmaking. However, there is a chance that the distributed snow will melt fast due to high temperatures in October. A short skiing trail located to areas with less sunlight should be considered as an alternative in October.

It should be taken into account that the snowmelt model does not include the effect of wind, which might have an impact on the outdoor snow storage. Heat loads from snowmaking and from the equipment are not included in the heat balance for the indoor system. When the snow is being produced, a much higher cooling capacity will be required due to the heat that has to be removed from the water. The system for the hall has not been designed for its heating demand. Evaluation of a combined heating and cooling cycle for the multipurpose hall is therefore suggested for further work.

Suggestions for Further Work

Considering the presented results and aspects which have not been analyzed in this thesis, the following list proposes suggestions for further work:

- Study solutions for drying and storage of sawdust. What is the most energy efficient method to dry sawdust which requires little space?
- Evaluate a combined heating and cooling system for the multipurpose hall.
- Study different methods for indoor snow production with emphasis on water droplet size and pathway in circulation of air.
- Further develop the snowmelt model to be used for snowmelt calculations for skiing trails, so that critical areas with high amount of solar radiation can be avoided.

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Appendix A

Scientific Paper

SNOWMELT MODELLING AND SOLUTIONS FOR OUTDOOR SNOW STORAGE

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ABSTRACT

As a result of the increasing global temperatures, shorter periods of natural snow and warmer winter temperatures are threatening winter sports facilities close to the cities. Different solutions for outdoor snow storage in Granåsen is studied with the intention to reduce the melting loss. 24 000 m^3 snow covered by sawdust will be stored from the beginning of April to the end of September. A snowmelt model is developed for calculation of the snowmelt due to heat from the ground, precipitation, the surrounding air and solar radiation. The snowmelt during the season is found to be 20 %, and the heat from the surrounding air and solar radiation constitute more than 80 % of the total melt. Increasing the thickness of the sawdust layer proves to be the solution which reduces the snowmelt the most. However, a thicker layer of insulation increases the costs.

1. INTRODUCTION

A worrying trend is developing with shorter winter seasons and milder winter temperatures. The increasing global temperatures reduce the periods of natural snow, which is threatening winter sports facilities. The climate changes are making it more difficult and complicated to provide skiing conditions close to the cities. In order to face the climate changes and still being able to provide good skiing facilities, snow storage might be a solution to prolong the winter season. Storing snow for the next season gives a certain predictability and a guarantee for skiing arenas, users and winter games arrangers. It also reduces the economic risk of not having enough snow. Snow storage can make it possible to provide skiing facilities at temperatures too warm for traditional snowmaking equipment.

This article describes snowmelt calculations for outdoor ground storage of a thermal insulated snow pile in Granåsen.

Ground Storage

When a snow pile is being stored outside it requires thermal insulation to shelter the snow and reduce the snowmelt. Today both natural wooden materials, such as sawdust and wood chips, and fabricated materials, such as plastic sheets and geotextile, are used for outdoor snow storage applications.

Important parameters for the performance of the cover materials are radiative properties, thermal conductivity, permeability, tensile strength, surface roughness and thickness of the insulation material (Olefs and Fischer, 2008). These characteristics affect the components of the energy balance for the sheltered snow. The guideline published by the Norwegian Ministry of Culture, recommends a thickness of 0.3-0.5 cm sawdust for a snow pile stored outside (Gjerland and Olsen, 2014).

2. METHODS

This section describes the necessary theory and equations for the snowmelt model.

2.1 Heat and Mass Transfer for an Insulated Snow Pile

Snow being stored during the summer will suffer from heat leakage and snowmelt due to air temperatures above freezing and stronger solar radiation. Heat from precipitation, wind, radiation and humidity, together with the thermal properties of the insulating material, will affect the convective heat and mass transfer through the insulation.

Figure 1 illustrates the principle of heat and mass transfer through an insulting layer covering snow (Skogsberg and Lundberg, 2005). Water will be transported downwards through the snow, but because of capillary forces and evaporation, a fraction of the water will be transported upwards through the insulation layer (Lintzén, 2016). Energy is necessary for the evaporation to happen, and the insulating layer will therefore be cooled, and the melting rate will decrease. Heat from both short-wave radiation and long-wave radiation will be exchanged at the surface of the insulation. Depending on the albedo of the insulation material, some radiation will be reflected.

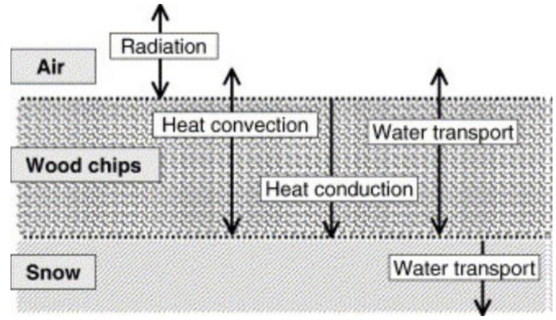

Figure 1. Heat and mass transfer for an insulating layer for snow storage (Skogsberg and Lundberg, 2005).

2.2 Snowmelt

When a snowpile is stored outside, snowmelt will occur in form of ground melt, rain melt and surface melt (Nordell and Skogsberg, 2007). The ground melt is caused by heat transfer from the ground beneath the storage, while heat transfer from the ambient air and radiation causes the surface melt. The rain melt occurs due to precipitation.

2.3 Snowmelt Calculation

This section describes the snowmelt model including the equations which simplifies the snowmelt to heat from the ground, heat from rain and heat from the surroundings. The total volume of melted snow during the storage period will then be the sum of the contribution form each heat source, expressed as

$$V_{total} = V_{ground} + V_{rain} + V_{surroundings} \tag{1}$$

Ground

The heat transfer between the pile and the ground area covered by the snow pile is

$$q_g = k_g A_g \frac{\Delta T_g}{l} \tag{2}$$

where q_g = heat transfer between ground and snow pile [W], k_g = thermal conductivity of ground material [W/mK], A_g = ground area covered by snow pile [m^2], ΔT_g = temperature difference [°C] between the snow pile and the temperature at a distance l [m] down in the ground (Lintzén, 2016). The volume flow of melted snow due to heat from the ground is then

$$v_g = \frac{q_g}{h_{lf}\rho_{snow}} \tag{3}$$

where v_g = volume flow of melted snow due to heat from ground [m^3/s], h_{lf} = latent heat of fusion for ice [J/kg], ρ_{snow} = density of snow [kg/m^3]. The volume of snowmelt caused by ground heat is

$$V_{ground} = v_g t \tag{4}$$

where t = duration of storage period [s].

Rain

For a period with P measured precipitation [m], the volume of melted snow due to the rain is

$$V_{rain} = \frac{P A_s \rho_{water} c_{p,water} T_{sa}}{h_{lf}\rho_{snow}} \tag{5}$$

where A_s = surface area of snow pile [m^2], ρ_{water} = density of water [kg/m^3], $c_{p,water}$ = heat capacity of water [J/kgK], T_{sa} = temperature of surrounding air [°C] (Lintzén, 2016).

Surroundings

The surface melt is caused by the heat transfer from the surrounding air and solar radiation, to the snow pile. The solar radiation absorbed by a surface is

$$q''_{abs} = q''_{GHI}a = q''_{GHI}(1-r) \tag{6}$$

where q''_{abs} = absorbed radiation [W/m^2], q''_{GHI} = measured global horizontal irradiation [W/m^2], a = absorptivity of surface, r = reflectivity/albedo of surface.

Since the sides of the snow pile will have different tilts and orientations relative to the sun, the solar radiation must be decomposed for each side. The solar radiation on a surface with a given tilt and orientation is then

$$q_{surface} = q_{abs}A_s[\cos(\alpha)\sin(\theta)\cos(\psi-\varphi)+\sin(\alpha)\cos(\theta)] \tag{7}$$

where $q_{surface}$ = solar radiation on decomposed side, A_s = surface area of decomposed side [m^2], α = elevation angle of the sun [°], θ = tilt angle of surface [°], φ = solar azimuth angle [°], ψ = azimuth angle that the surface faces (clockwise from north) [°] (PV Education, 2017).

The exterior surfaces of the insulated snow pile will be affected by the outdoor air temperature as well as the solar radiation. Depending on the properties of the covering material and the orientation of each surface relative to the sun, a certain amount of the radiation will be absorbed on the surface of the insulation. This will result in an insulation surface temperature which is higher than the temperature of the surrounding air. The surface temperature can be found from the following equation

$$T_s = T_o + \frac{q''_{surface}}{h_o} \tag{8}$$

where T_s = surface temperature [°C], T_o = outdoor air temperature [°C], h_o = outside surface conductance [W/m^{2}K] (Spitler, 2010). Since the snow pile will be exposed to wind, h_o can be set to 6 W/m^{2}K (ASHRAE, 2010). The heat transfer between the insulated pile and its surroundings is then

$$q_{sur} = k_{avg}A_s\frac{T_s-T_{snow}}{\Delta z} \tag{9}$$

where q_{sur} = heat transfer between insulated pile and surroundings, k_{avg} = average value of the thermal conductivity for water and the insulation material [W/mK], T_{snow} = temperature of the snow [°C], Δz = layer thickness of insulation material [m] (Lintzén, 2016). k_{avg} takes into account that the insulating material will have a varying thermal conductivity depending on its moisture content (Skogsberg and Lundberg, 2005). The volume flow and the total volume of melted snow can then be determined from the Equation (10) and Equation (11).

$$v_{sur} = \frac{q_{sur}}{h_{lf}\rho_{snow}} \tag{10}$$

$$V_{surroundings} = v_{sur}t \tag{11}$$

2.4 Outdoor Snow Storage in Granåsen

Table 1 summarizes the specifications for the stored snow pile. The snow pile is assumed to have the shape of an isosceles trapezoid prism, as illustrated in Figure 2.

Table 1. Snow storage specifications.

Period of storage	April 1 - Sept 30	Insulation material	Sawdust
Volume of stored snow	24 090 m^3	Δz	0.4 m
Ground area, A_g	4 400 m^2	k_{water}	0.58 W/mK
Length a	20 m	k_{avg}	0.33 W/mK
Length b	40 m	r (dry/wet)	0.3/0.15
Height h	7.3 m	Ground material	Gravel
Length L	110 m	k_g	0.7 W/mK
Θ	36°	ρ_{water}	1 000 kg/m^3
Snow temperature	0 °C	h_{lf}	334 kJ/kg
ρ_{snow}	600 kg/m^3	$c_{p,water}$	4.18 kJ/kgK

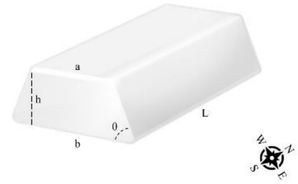

Figure 2. Snow pile geometry and cardinal directions for location in Granåsen.

Some assumptions and approaches for the snowmelt calculations are listed below.

- Weather statistics for Granåsen is obtained for eight years, 2009-2016, which includes measured values for air temperature, relative humidity, cloud cover, precipitation and global horizontal irradiance for every hour during the storage period.
- When it is raining, or it has been raining during the last 12 hours, the albedo is set to 0.15. If no precipitation is registered the last 12 hours, the albedo is set to 0.30. These values are taken from another study regarding snow storage done by Ødegård (2013).
- For calculation of snowmelt due to the surroundings, the five outer surfaces of the pile will be treated separately.
- The horizon of the snow pile in Granåsen is projected for every 15° using a topographic map.
- From the latitude, longitude and time zone for the location of the storage, the snowmelt model calculates the solar elevation angle and the solar azimuth angle for every hour. By comparing the solar elevation angle to the horizon of the pile, it is possible to know when the snow storage will be exposed to solar radiation for each day. Figure 3 shows the solar elevation angle for three different days plotted against the horizon of the snow storage (yellow curve). The figure illustrates the variations in hours with solar radiation during the season. The blue curve and the dark green curve show the solar elevation for the first and last day respectively. The light green curve illustrates the solar elevation for the day when the sun reaches its highest point in the sky.

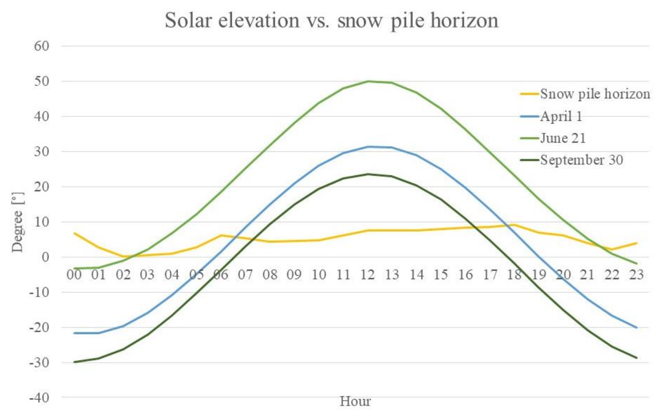

Figure 3. The solar elevation for three different days plotted against the horizon of the snow storage.

3. RESULTS

Table 2 presents the theoretical melting losses for each year obtained from the snowmelt model. The last column states the average values. The amount of measured precipitation during each season is included in brackets.

Table 2. Theoretical snowmelt losses.

Source of melting	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**Average**
Ground [m^3]	243	243	243	243	243	243	243	243	243
Rain [m^3]	643	457	900	480	490	509	610	557	581
(Precipitation [mm])	(617.3)	(470.9)	(787.4)	(555.3)	(459.7)	(482.2)	(608.5)	(526.2)	(563.4)
Surroundings [m^3]	4 210	3 755	4 111	3 552	4 044	4 469	3 777	3 978	3 987
Total melting loss [m^3]	5 096	4 455	5 253	4 276	4 777	5 221	4 630	4 778	4 811
Volume last day [m^3]	18 994	19 635	18 837	19 814	19 313	18 869	19 460	19 312	19 279
Loss in %	21	18	22	18	20	22	19	20	20

The percentage snowmelt contribution related to each heat source is shown in Table 3. The average values are included in the last column.

Table 3. Snowmelt contribution from each heat source.

Source of melting	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**Average**
Ground [%]	5	5	5	6	5	5	5	5	5
Rain [%]	13	10	17	11	10	10	13	12	12
Surrounding [%]	83	84	78	83	85	86	82	83	83

The results presented in Table 2 and Table 3 indicate that the surroundings (solar radiation and surrounding air temperature) have a remarkable impact on the snowmelt and constitute more than 80 % of the total snowmelt. By comparing the results to other practical examples of outdoor ground storage in Scandinavia (Lintzén, 2016), 20 % melting loss during the season can be assumed to be a reasonable result.

Considering Table 2 one can see that the seasons in 2011 and 2014 have the largest melting losses. The season of 2014 also has the highest amount of melting caused by the surroundings, which constitutes 86 % of the total melt. The highest amount of measured precipitation was in 2011, which results in a considerable part of melting due to heat from the rain. The storage seasons in 2010 and 2012 have the smallest losses. These seasons also have rain melt below average. The ground melt is the same for each year as the temperature in the ground and the temperature of the snow pile are both assumed to be constant during the entire storage season. This is a reasonable assumption as the contribution from the ground heat is much smaller than the heat from rain and surroundings, as stated in Table 3.

3.1 Solutions for Snowmelt Reduction

To evaluate different solutions to reduce the snowmelt for the outdoor snow storage in Granåsen, the weather statistics for 2016 will be further used. Considering Table 2 and Table 3 the storage season of 2016 is a good representation of the average values. This section studies the effect of three solutions; solar shading, thicker layer of insulation and changes in snow pile geometry.

Solar shading

Figure 4 illustrates the average distribution of solar radiation per square meter on each side of the snow pile. The figure shows that the top surface and the side facing south are highly exposed to the radiation from the sun.

A wall for solar shading could be placed in front of the side facing south to reduce the impact of the solar radiation. A 4 m high wall placed 3 m from the side facing south, is therefore included to the horizon in the snowmelt model. The effect of a solar shading wall is shown in Table 4.

Table 4. Snowmelt with and without solar shading wall.

Source of melting	No wall	Wall
Ground [m^3]	243	243
Rain [m^3]	557	562
Surroundings [m^3]	3 978	3 734
Total melting loss [m^3]	4 778	4 539
Volume last day [m^3]	19 312	19 551
Loss in %	20	19

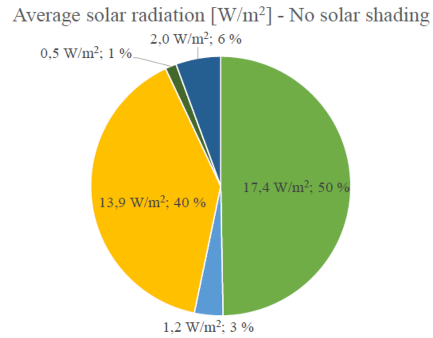

Figure 4. Average solar radiation on each side of the snow pile during storage season.

From Table 4 one can see that the snowmelt has been slightly reduced, and that the rain melt is a bit higher for the case with the solar shading wall. The reason for that is probably related to the lowered snow melting rate, leading to a larger surface area being exposed to the rain. However, a solar shading wall does not reduce the conductive heat transfer between the surrounding air and the snow pile, thus the total snowmelt reduction is small. It may provide shelter from the wind, but effects from wind has not been taken into consideration for the calculations.

Thicker layer of insulation

Equation (9) states that the heat transfer between the snow pile and the surroundings is inversely proportional to the thickness on the insulation material. This means that an increase in the thickness of the insulation layer will reduce the heat transfer. By changing the insulation thickness in the snowmelt model, the effect of this can be studied. The results are shown in Table 5. From Table 5 one can easily observed the remarkable impact of a thicker layer of insulation, and that the snowmelt due to the surroundings is decreasing with increasing Δz. As for the case with the solar shading wall, the rain melt gets higher for higher values of Δz. The same explanation applies here; when the snow melting rate is reduced, a larger surface area of the snow pile is exposed to the rain.

Table 5. Snowmelt result for different insulation thicknesses.

Source of melting	Δz = 0.3 m	Δz = 0.4 m	Δz = 0.5 m	Δz = 0.6 m	Δz = 0.7 m	Δz = 0.8 m
Ground [m^3]	243	243	243	243	243	243
Rain [m^3]	536	557	570	579	585	590
Surroundings [m^3]	5 150	3 978	3 239	2 732	2 362	2 080
Total melting loss [m^3]	5 929	4 778	4 052	3 553	3 190	2 913
Volume last day [m^3]	18 161	19 312	20 038	20 537	20 900	21 177
Loss in %	25	20	17	15	13	12
Total cost [NOK]	152 033	159 565	175 597	196 189	219 461	244 473

Having a thicker layer of insulation is an option that requires more space. The sawdust must be stored and dried when it is not used. A cost estimate is therefore done to compare whether it is cheaper to have a thicker layer of sawdust, or a thinner layer and compensate for the snow loss by buying the corresponding amount of snow. Choosing Δz = 0.8 m as reference case, it implies that 21 177 m^3 snow is needed at the end of each storage season. The price for sawdust and snow is set to 57 NOK/m^3 and 20 NOK/m^3 respectively (Ødegård, 2013; Berg et al., 2016). The estimated cost is shown in the last row of Table 5 and states that the needed amount of sawdust is the major cost. This supports the recommended insulation thickness of 0.3-0.5 m, given by the Norwegian Ministry of Culture.

Changing snow pile geometry

From Figure 4 one can easily see that the top surface is exposed to the highest amount of solar radiation per square meter. Different geometries are implemented in the snowmelt model. The geometries must still satisfy the volume requirement of 24 000 m^3 and a ground area limitation of 112 m x 51 m. Figure 5 illustrates the different geometries. The calculated snowmelt losses are presented in Table 6.

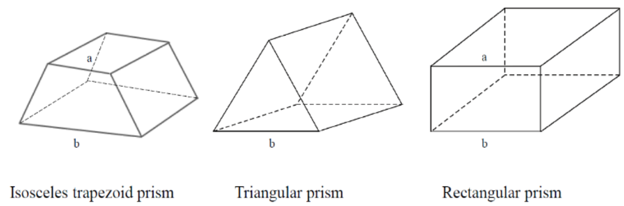

Figure 5. Different snow pile geometries.

Table 6. Snowmelt result for different snow pile geometries.

	Isosceles trapezoid prism			**Rectangular pyramid**	**Rectangular prism**
Properties	**a = 20 m; b = 40 m**	**a = 15 m; b = 45 m**	**a = 10 m; b = 50 m**	**b = 50 m**	**a = b = 30 m**
Top surface area [m^2]	2 200	1 650	1 100	-	3 300
Ground surface area [m^2]	4 400	4 950	5 500	5 500	3 300
Total surface area [m^2]	5 362	5 758	6 222	6 266	5 344
SA:V [m^{-1}]	0.223	0.239	0.258	0.260	0.222
Source of melting					
Ground [m^3]	243	273	304	304	182
Rain [m^3]	557	595	638	647	551
Surroundings [m^3]	3 978	4 110	4 287	4 146	4 240
Total melting loss [m^3]	4 778	4 978	5 229	5 096	4 973
Volume last day [m^3]	19 312	19 112	18 861	18 999	19 117
Loss in %	19.83	20.66	21.71	21.15	20.64

A snow pile with the form of a triangular prism is the ideal geometry to minimize the top surface area parallel to the ground. However, Table 6 shows that this geometry will have a larger total surface area, and the total snowmelt is larger than for two of the trapezoid prisms and the rectangular prism.

The surface area of the snow pile should be as small as possible to reduce the exposure to solar radiation and surrounding air. The surface-area-to-volume ratio (SA:V) for the different geometries are included in Table 6. The lowest value for SA:V is found for the rectangular prism. However, the total melting loss for the rectangular prism is slightly larger than for the first of the three trapezoid prisms. These two shapes have the same cross-sectional area, but the top surface area for the rectangular prism is larger. As previous stated, the top surface of the snow pile is the side which is exposed to the highest amount of solar radiation. This may explain why the rectangular prism does not have the smallest melting loss, despite its SA:V.

Reducing the surface area will also reduce the amount of sawdust needed to cover the snow pile, as well as the costs related to the insulation. However, there will be challenging to form the snow pile into any desired shape as the snow storage is being produced. Limitation in maximum height, time, available vehicles and whether the areas around the storage is accessible by vehicles, are factors that have impact on the production and shape of the outdoor snow storage.

4. DISCUSSION

The developed snowmelt model can be assumed to give reasonable snowmelt results for an outdoor snow storage, as the calculated results match the snowmelt from other practical snow storage examples. The results also verify that the surface melt, due to solar radiation and surrounding air, constitutes the largest part of the total melt, as found by Skogsberg (2005). The model can be used for other snow storage facilities, as long as the latitude, longitude and horizon for the location is known, and weather statistics is available.

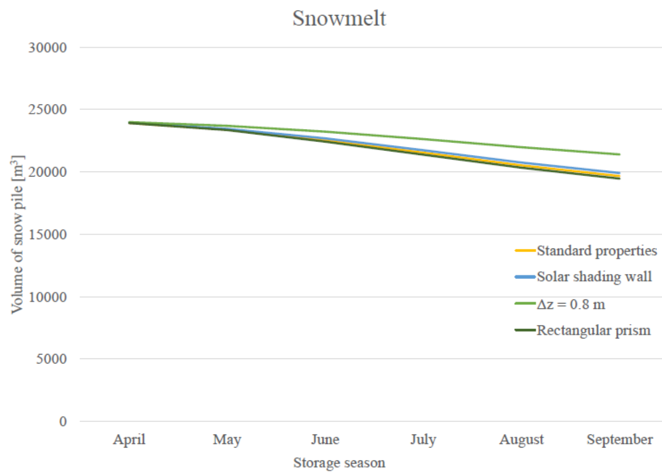

Figure 6. Decreasing of snow pile volume during the period of storage.

Figure 6 shows the decreasing snow pile volume during the season in 2016 for four different cases. The yellow curve illustrates the melting rate for the snow pile with the specifications given in Table 1. Each one of the three other curves shows an investigated solution for snowmelt reduction. Only the increase in insulation thickness has a considerable reduction in melting rate, as can be seen from the light green curve in Figure 6. The same effect of insulation thickness was found in a laboratory experiment by Skogsberg and Lundberg (2005).

The cost estimation regrading insulation thickness has demonstrated that a thickness of 0.3-0.5 m sawdust can be recommended, with respect to total snowmelt and insulation material costs. A solar shading wall cannot be regarded as a useful solution, as the reduction in snowmelt is minimal. Furthermore, the wall would permanently occupy space on the parking lot in Granåsen, when no snow is being stored. The results obtained by changing snow pile geometry, demonstrate only small variations in total snowmelt. The difference between the best and worst case of melting is only 451 m^3, which constitutes less than 2 % of the initial snow pile volume. This indicates that the shaping of the snow pile when the snow storage is being produced, can be given less focus, as long as the snow pile is kept compact. The main priority should therefore be given to efficient drying and maintenance of the insulation material.

5. CONCLUSION

When 24 000 m^3 snow is stored outdoor in Granåsen, it can be assumed that approximately 20 % of the insulated snow pile will melt during the season. The snowmelt calculations have demonstrated that heat from the surroundings (solar radiation and surrounding air) will have the greatest impact on the snowmelt. The contribution from the surroundings is found to be 78-86 % of the total snowmelt. Increasing the thickness of the insulation layer is further found to be the best solution to reduce the melting rate. Changing the insulation thickness from 0.4 m to 0.8 m reduces the snowmelt from 20 % to 12 %. However, increasing the insulation thickness gives higher expenses. Thus, a thickness of 0.3-0.5 m can be recommended.

Changing the snow pile geometry or use of a solar shading wall does not lead to any significant melt reduction. For that reason, it can be concluded that maintenance of the sawdust is the most important measure to reduce the snowmelt. This includes necessary drying to maintain the quality and the low thermal conductivity of the sawdust, which will reduce the cost related to buying new sawdust. Drying methods for sawdust has not been studied in this article, and should therefore be suggested as further work.

Snow storage is a good alternative to guarantee for skiing facilities in Granåsen from the beginning of October. This makes it possible to provide skiing trails even if no natural snow has fallen, or the temperature is too high for traditional snowmakers. However, there is a chance that the distributed snow will melt fast due to high temperatures in October. A short skiing trail located to areas with less sunlight should be considered as an alternative in October.

NOMENCLATURE

Latin letters		**Greek letters**	
a	Absorptivity [-]	α	Solar elevation angle [°]
A	Area [m^2]	θ	Tilt angle of surface [°]
c_p	Heat capacity [J/kgK]	ρ	Density [kg/m^3]
h	Surface conductance [W/m^2K]	φ	Solar azimuth angle [°]
h_{lf}	Latent heat of fusion [J/kg]	ψ	Azimuth angle of surface [°]
k	Thermal conductivity [W/mK]	**Subscripts**	
l	Distance [m]	abs	Absorbed
P	Precipitation [m]	avg	Average
q	Heat transfer [W]	g	Ground
r	Reflectivity/albedo [-]	GHI	Global horizontal irradiation
SA:V	Surface-area-to-volume ratio [m^{-1}]	o	Outdoor
t	Time [s]	s	Surface
T	Temperature [°C]; [K]	sur	Surroundings
v	Volume flow [m^3/s]		
V	Volume [m^3]		
Δz	Insulation thickness [m]		

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Appendix B

Risk Assessment

NTNU	Hazardous activity identification process	Prepared by	Number	Date
		HSE section	HMSRV2601E	09.01.2013
		Approved by		Replaces
HSE		The Rector		01.12.2006

Unit: Department of Energy and Process Engineering **Date:** 08.02.2018

Line manager: Therese Lauvås

Participants in the identification process (including their function)**: -**

Short description of the main activity/main process: Master project for student Marianne Heimdal. Climate Independent Snow Production and Solutions for Snow Storage.

Is the project work purely theoretical? (YES/NO): YES *Answer "YES" implies that supervisor is assured that no activities requiring risk assessment are involved in the work. If YES, briefly describe the activities below. The risk assessment form need not be filled out.*

Signatures: *Responsible supervisor:* [signature] *Student:* Marianne Heimdal

ID nr.	Activity/process	Responsible person	Existing documentation	Existing safety measures	Laws, regulations etc.	Comment