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Analysis of resource consumption of methods for snow production to ski resorts

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MASTER THESIS

for

Student Ragnhild Ekerholt

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Analysis of resource consumption of methods for snow production to ski resorts

Analyse av ressursforbruk ved metoder for snøproduksjon til skianlegg

Background and objective

With increasing temperatures as a result of global warming, the access to natural snow decreases in areas vulnerable to climatic changes. Temperature increase leads to shorter winter seasons and limits the snowpack in lower altitudes.

In Nordic countries, we have long traditions linked to skiing and other snow related activities. Besides being a key activity in our everyday life, the reliability of snow access is important for the sports industry and snow security is a key factor to be able to hold sports events. To meet these expectations, we need to be able to produce snow, maybe even in temperatures above 0°C. This is an energy and resource consuming process, and it is therefore of interest to analyze different existing methods to optimize the process in terms of energy, water consumption, transport and labor intensity.

The object of this MSc thesis is to carry out a systematic study of the resource consumption characteristics of common and/or promising methods for snow production, as a basis to provide recommendations for strategies and solutions under chosen context situations, founded on quantitative analysis.

This master thesis work is carried out in collaboration with Senter for idrettsanlegg og teknologi (SIAT) at NTNU, with Bernhard Haver Vagle and Bjørn Aas as contact persons.

The following tasks are to be considered:

1) Carry out a literature study on different possible methods for production, preparation and storage of snow relevant to the objectives of this thesis.
2) Investigate, define and describe the technologies and operations of different options for snow production, preparation and storage, according to a set of defined context situations for ski resorts with Norwegian location. If appropriate, link your work to one or more chosen cases.
3) Develop a model and methods to analyse the different options and their performance (quantitative and qualitative) linked to a set of parameters chosen

4) Discuss main finding from your comparative study of options, and identify main contributions to resource consumption and performance. Discuss strengths and weaknesses of your methods, and the implications of your findings regarding preferred choices for different contexts.
5) Give suggestions for further work and conclusions from your own 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 analysed 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.

Pursuant to “Regulations concerning the supplementary provisions to the technology study program/Master of Science” at NTNU §20, the Department reserves the permission to utilize all the results and data for teaching and research purposes as well as in future publications.

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, 10. February 2017

H. Brattebø

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Professor Helge Brattebø
Academic Supervisor

Preface

This master thesis has been written at the Department of Energy and Process Engineering at The Norwegian University of Science and Technology (NTNU). It is developed in cooperation with SIAT, aiming to give an overview of the systems performance of three main alternatives for snow production in Granåsen in Trondheim.

As a skier, my favorite activity is directly affected by snowmelt resulting from temperature increase. With a heartfelt desire to protect the winters, this attempt to quantify environmental impacts from snow production has been truly interesting. To develop a quantified model of the real world is challenging and, at some times, frustrating. Nevertheless, with valuable help from existing reports on the field and first-hand information from experienced people, I have made an attempt to do so.

A big thanks goes to my supervisor Helge Brattebø, and my co-supervisor Bernhard Haver Vagle for helpful guidance and support through this semester. I would also like to thank Vidar Finnland and Heidi Arnesen in Trondheim Municipality for valuable help about the logistics in Granåsen. Last but not least, I want to thank my classmates for all the smiles and interesting discussions during the thesis work.

I hope Trondheim will get the chance to host the Nordic World Ski Championship in the near future and wish them all the best in further preparations.

Trondheim, June 2017

Ragnhild Stamer Ekerholt

Sammendrag

Denne masteroppgaven er et case studie av Granåsen skiarena i Trondheim. Den ser på de totale miljøpåvirkningene fra drift av en 5 km sløyfe gjennom en sesong fra 1. november til 30. april. Tre hovedalternativer, med noen variasjoner av disse, er analysert:

- Alternativ A: snøproduksjon gjennom sesong én samles i et snølager og lagres over sommeren til sesong to.
- Alternativ B: temperaturuavhengig isproduksjon produserer is kontinuerlig gjennom høsten for å kunne dekke løypene ved sesongstart.
- Alternativ C: en kombinasjon av snøproduksjon gjennom sesong én og høsting av resterende snø fra sesong én er samlet i et snølager over sommeren og distribuert i sesong to.

Alle tre alternativene inkluderer også vedlikehold av løypene gjennom sesong. Dette innebærer etterfylling og løypepreparering. Miljøpåvirkningene er målt i global warming potential (GWP) og andel NOx og svevestøv er evaluert med tanke på lokal luftforurensing. Strømforbruk er også vurdert i alle tre alternativer. Analysen er gjort ved bruk av LCA-metodikk og modellen bygger på innhentet informasjon fra driftsteamet i Granåsen og eksisterende litteratur på feltet.

Alternativ C står frem som det beste alternativet sett fra et miljøperspektiv, med totale utslipp på 24,9 ton CO2 ekvivalenter per år. Alternativ A og C er begge knyttet til lave utslipp, men miljøpåvirkningene er noe høyere i alternativer der høsting blir erstattet med mer energikrevende snøproduksjon. Alternativ C er også foretrukket med tanke på lokal luftforurensning. Høyest utslipp får vi fra alternativ B, på grunn av en svært energiintensiv isproduksjon. Årlige utslipp på hele 214,4 ton CO2 ekvivalenter er knyttet til dette alternativet.

Strømforbruk er parameteret med desidert høyest påvirkning på GWP og det er en sterk korrelasjon mellom disse. Energiintensive prosesser som reduserer arbeidstimer knyttet til logistikk er derfor knyttet til høyere utslipp. En vurdering av arbeidsbruk opp mot miljøpåvirkning vil derfor være basert på preferansene til beslutningstaker.

Abstract

This thesis is a case study of Granåsen ski arena in Trondheim. It considers the environmental impacts from operating a 5 km track from November 1st to April 30th, analyzing three different alternatives and a few variations of these. The three main alternatives are:

- Alternative A: snow is produced in season one, stored over summer, and distributed into the tracks at the beginning of season two.
- Alternative B: temperature independent ice production is running from August to season opening, creating e.
- Alternative C: a combination of snow production in addition harvesting of snow from tracks at the end of season one is stored over summer and distributed into the tracks at the beginning of season two.

All alternatives do also include operation of tracks during the season, involving replenishment and grooming. The environmental impacts are considered with respect to global warming potential (GWP) and local air pollution, measured in NO_x and particulate matter. Electricity use is also considered in all alternatives. The study is conducted using LCA methodology, and the inventory is built on information from the operation team in Granåsen and literature study.

The most efficient alternative in terms of GWP is alternative C. In this alternative, 24,9 ton CO2-eq is emitted during the entire season. Environmental impacts from alternative A and C are similar, but slightly higher environmental impacts occur when harvesting is replaced with snow production. Regarding local air pollution, alternative C is also considered the best option. An alternative based on ice production leads to significantly higher emissions, with 214,4 ton CO2-eq at most.

Impacts on GWP is strongly correlated to electricity use, which is also the most influencing parameter studied. Energy intensive processes that reduces the amount of labor hours are therefore associated with higher emissions, in general. A valuation of labor use versus environmental impacts are therefore a matter of choice and should be done by decision makers.

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Terminology

CF_4	Fluorocarbon
CH_4	Methane
CO_2	Carbon dioxide
CO_2-eq	CO_2-equivalents
GWP	Global warming potential
IPCC	Intergovernmental panel on climate change
LCA	Life cycle analysis
LCI	Life cycle inventory
LCIA	Life cycle impact assessment
NO	Nitrous monoxide
NO_2	Nitrous dioxide
NO_x	Nitrous oxides
PM	Particulate matter
SF220	Snowfactory model 220 from TechnoAlpin
SPA	Structural path analysis
TDS	Temperature dependent snowmaking
TIS	Temperature independent snowmaking

1.INTRODUCTION

1.1 The importance of skiing in the Norwegian culture

As our national sport with deep cultural roots, skiing is highly valued among Norwegians. At the Nordic World Ski Championship in Oslo 2011, 50 000 people joined the opening ceremony in the Oslo city center. Almost 100 000 people attended the prize ceremony for the men's rely [1]. That equals to 20% of Oslo's total population.

"The Norwegian Sports Model" developed by The Norwegian Ministry of Culture states that a forward leaning national policy on sports management must facilitate the participation of the population in sports and physical activities at all levels [2]. Following from this, skiing is an important part of national culture, both as a cultural value, but also as a measure for promoting public health.

Snow related activities depend on access to snow and are vulnerable to temperature increase caused by climatic changes. We are already experiencing the consequences of global warming. Figure 1 shows the snow conditions at the World Cup event arranged in La Clusaz in December 2016. La Clusaz is located in the French Alps, at an elevation of about 1000 meters above sea level – a location and elevation that normally serves good skiing conditions during the winter season.

Figure 1 - La Cluzas

The World Cup in La Clusaz is one of several events that has experienced the challenges of snow scarcity. The annual national opening race at Beitostølen was cancelled in both 1998, 2005 and 2011[3] due to absence of snow, and the prestigious ski race Marcialonga had to shorten the distance in 2017 for the fourth time since the turn of the millennium because of snow scarcity [4].

In the report "Snøproduksjon og snøpreparering", The Norwegian Ministry of Culture provides a guideline to snow production – and maintenance. The report recommend "to produce snow on surrounding trees for an aesthetically impression of the area" [5]. Are we facing a new form of winter, based on artificial snow in green surroundings?

1.2 Granåsen

This case study consider Granåsen ski arena located in Trondheim, Norway. The ski tracks in Granåsen is both a training facility and an arena for recreational purposes. Elite athletes, a wide range of exercisers, schools and kindergartens use the arena on a daily basis during winter season. In addition to be an important arena for skiing activities at all levels, it is decided that the next Nordic World Ski Championship assigned to Norway will be arranged in Trondheim and Granåsen. Based on this, further decisions on new investments in Granåsen should be done based on the ability to provide good skiing conditions in a large scale, in addition to secure the possibility of skiing for recreational purposes. In this regard, a study of the environmental impacts from snow production is desired.

1.3 Climatic trends

Global surface temperature has increased since the end of the 19th century. Each of the three last decades has been successively warmer than any other decades measured, and the decade of the 2000's has been the warmest [6]. Measurements of the climatic trends in Trøndelag County done by the Meteorological Institute shows a steady increase in precipitation over the last century (Figure 2). Temperature is following the same trend, which leads to an increased precipitation in the form of rain. Looking at weather statistics from 1900 until today, with a focus on the 50 warmest measurements from each month, one third of the heat records has occurred after the millennium. In addition, the most significant results seem to occur in the late winter months from January to May [7].

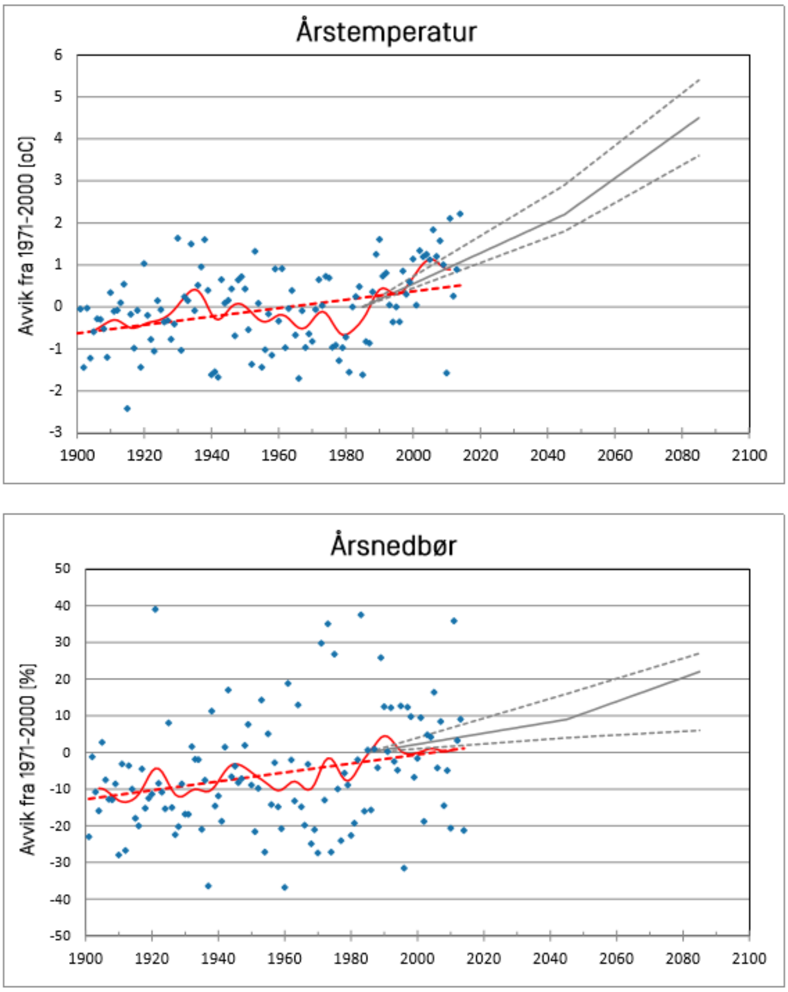


Figure 2 - Annual deviation in temperature and percipitation based on 1971-values [8]

The report “Klimatilpasning i Sør-Trøndelag” developed by Norwegian Climate Service Center as a cooperation between Meteorological Institute, The Norwegian Water Resources and Energy Department, Uni Research and Bjørknessenteret states that number of rainy days in Trøndelag will increase with around 20% by the end of this century. Within the same time frame, temperatures are assumed to increase with 4 degrees on average. Coastal areas will experience higher temperature increases than inland [8].

1.4 Why is this study of importance?

Snow is wanted not only for recreational reasons and to maintain cultural history. Snow reliability is important also for economic reasons. Ski resorts all over the globe attract visitors that want to try skiing for the first time, spend their winter holidays in the mountains or practice for the World Championships. Ski resorts at high altitudes with a cold inland climate would in general experience longer seasons, while resorts at lower altitudes and milder climate will have to utilize the few months they are able to provide ski slopes – or tracks. Climatic changes leading to shorter snow seasons requires technology that enables the resorts to take advantage of marginal periods where temperatures are just around zero.

There are comprehensive logistics linked to snow production. The process is energy intensive in form of machinery use, transportation and infrastructure development. Temperature increases will further increase the complexity of snow production. Consequently, the ability to adapt to climatic changes without creating new problems for the future will be of big importance. Knowing this, environmental impacts should be evaluated when deciding on new investments and strategies. Based on this, the following research questions are formed:

- What is the most efficient way to ensure good snow conditions in Granåsen throughout winter, seen from an environmental perspective?
- Knowing this – are the impacts of snow production itself big enough to be considered a threat to climate change?

This study investigates different methods for snow production and evaluates their performance with regard to environmental impacts from a life cycle perspective. All alternatives evaluated in the study represent different combinations and technologies to provide one season of snow for cross-country skiing. An overview of the case and alternatives considered follows.

1.5 Case presentation

This case study is looking at three alternatives for Granåsen to be able to guarantee a 5 km track for cross-country skiing during one season, lasting from November 1st to April 30th. To be able to guarantee snow through the entire season, these three options are considered the most relevant and realistic alternatives and will be further studied in this report:

A. Snow for season two is produced through season one and stored in an outdoor pile throughout summer
B. Snow for season two is produced the same autumn and/or harvested from surrounding areas that are more snow secure.

C. Snow for season two is a combination of harvesting from the tracks in season one and snow production in season one. The snow is stored in an outdoor pile throughout summer.

All three alternatives involve replenishment of artificial snow during the season. This happens directly into the slopes and the need for distribution will be negligible.

Alternative A requires an increased snow production during season one to be able to guarantee good snow conditions in the long run, which in this case is the next season. The snow storage needs to be of a size that allows for melting losses over summer, but still provides sufficient amounts of snow by the beginning of next season.

Alternative B excludes the need for summer storage and the melting problem following from it. The need for transport will vary largely depending on the mix of snow – and ice production on site and harvesting from surrounding areas. The higher share of total snow requirement produced on site, the less transportation is needed.

The last alternative, C, is most similar to how they operate in Granåsen today. By harvesting snow from the tracks at the end of the season, this method takes advantage of snow that is already produced. This snow, in combination with production directly into the pile, ensure a sufficient size on the snow storage prior to the upcoming season.

2. BACKGROUND

The Report “Klima i Norge 2100”, compiled by The Norwegian Environment Agency, forms a basis for decision making in the process of climate adaption. Based on IPCC’s report on climate change it concludes that predicted climate change for the next century will require a faster and more extensive adaption to climatic changes than what we have experienced over the previous decades [9]. These changes will have large effects on infrastructure and weather conditions, and milder winters combined with increased precipitation will lead to less intense spring floods, but more frequent cloud bursts year round [8].

For the winter sports industry, these changes require solid methods for snow production to be able to secure good snow conditions at marginal temperatures. The industry is extremely vulnerable to climatic changes and adaptions to these are vital to be able to survive, seen from an economic perspective. Actors would benefit from being less dependent on meteorological conditions, both in a short and a long term perspective [10]. Methods to provide secure snow conditions could involve snow production in temperatures above 0 degrees, snow storage or harvesting of snow. Technologies linked to these methods will be further explained in this chapter.

2.1 Snow production basics

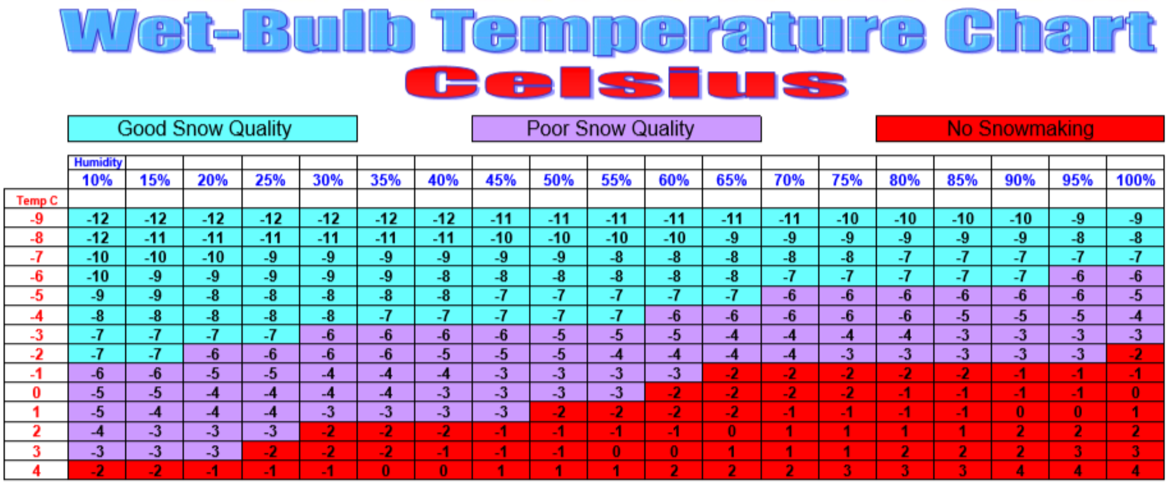
Natural snow is formed when water vapor freezes from its core to create small ice crystals. Depending on air temperature and humidity, these crystals form different shapes. High humidity often lead to more complex crystal formations because of higher agglomeration on its way down to the earth surface [10]. After reaching the ground, the snow is constantly changing. Self-weight stress, weather and winds will grind the edges of the snow crystals, leaving them round and compact, so-called destructive metamorphism [10]. Because of the initial crystal shape, natural snow contains more air in the snow layers than what is the case for artificial snow, which freezes from the outside to the core. This makes natural snow fluffy, but also more exposed to warmer temperatures because of rapid melting.

Artificial snow is made when water and air at high pressures are mixed and spread through a nozzle. The droplets ability to freeze depends on air temperature and distance from the nozzle to earth. For the droplets to freeze, thermal balance is required. This is achieved with a certain relationship between wet-bulb temperature and water volume that allows the core in the water droplets to freeze [5]. Because of its compact structure, artificial snow is more durable and withstands higher temperatures to a larger extent.

Snow density will vary depending on temperature and wind conditions, but generally, artificial snow has a higher density. According to the report by The Norwegian Ministry of Culture, 10 cm of artificial snow equals, on average, as much as 40 cm natural fallen snow, meaning artificial snow is four times more efficient [5].

2.1.1 Wet-bulb temperature

Beside air temperature and distance from nozzle to earth, snow production is in general dependent on one third crucial factor: relative humidity. The relationship between relative humidity and air temperature is called the wet-bulb temperature, which is a relationship that tells us whether we are able to produce snow. Air temperature is often designated as the dry-bulb temperature. Wet-bulb temperature is a value considering the relative humidity of the air in addition to the temperature we read on the thermometer and is therefore commonly used in the context of snow production. A relative humidity equal to 100% means the air has reached the limit of how much water it can possibly absorb. This is also known as the dew point temperature because at this point, the air starts to condensate water. When water evaporates, energy in form of heat is released, and we are left with a lower temperature because of the heat loss. This explains the fact that with a hundred percent humidity, the dry-bulb temperature equals the wet-bulb temperature. Different wet-bulb temperatures as mixes of humidity and temperature is shown in Figure 3.



Wet-Bulb Temperature Chart
Celsius

Good Snow Quality | Poor Snow Quality | No Snowmaking

Temp C \ Humidity	10%	15%	20%	25%	30%	35%	40%	45%	50%	55%	60%	65%	70%	75%	80%	85%	90%	95%	100%
-9	-12	-12	-12	-12	-12	-12	-12	-11	-11	-11	-11	-11	-11	-10	-10	-10	-10	-9	-9
-8	-12	-11	-11	-11	-11	-11	-11	-10	-10	-10	-10	-9	-9	-9	-9	-9	-9	-8	-8
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0	-5	-5	-4	-4	-4	-4	-3	-3	-3	-3	-2	-2	-2	-2	-1	-1	-1	-1	0
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3	-3	-3	-3	-2	-2	-2	-1	-1	-1	0	0	1	1	1	2	2	2	3	3
4	-2	-2	-1	-1	-1	0	0	1	1	1	2	2	2	3	3	3	4	4	4

Figure 3 - Wet-bulb temperature chart [11]

As the figure shows, wet-bulb temperature is always lower than the air temperature, unless the humidity is 100%. This makes us able to produce snow at higher temperatures with decreasing humidity. Hence, the trends in relative air humidity at the snow providing location is of big importance when it comes to the production potential.

2.1.2 Water in snow production

It takes large amounts of water to produce snow, and surrounding lakes or dams are normally used as water sources. To avoid high costs and infrastructure development linked to establishing penstocks, the water source should not be too far away. Height difference from water source to point of withdrawal is preferred to limit the need for pumping stations leading the water stream to where snow is produced.

Natural water sources are preferred because of their high content of particles. Water freezes around these particles and do therefore allow the water to freeze at higher temperatures than purified water, which contains fewer particles. Distilled water requires a temperature of -40 degrees to freeze, a temperature that is not achievable without help from energy intensive heat exchangers in the production phase [5]. To streamline the freezing process, natural proteins can be added in the water. Snomax has the highest nucleation temperature we know of, working at temperatures up to -0,6 degrees celcius [12]. Thanks to proteins such as Snomax, each droplet finds a core, allowing more water to become snow and less to evaporate. It is not detected any negative effects of adding such proteins. Improved efficiency in production as a result of this additive may, on the other hand, lead to positive indirect effects from reduced electricity use from higher productivity [5].

However, there are some limitations linked to water withdrawal from natural lakes or dams. Lakes play an important role in an ecosystem and should therefore be used responsibly. The water directive conducted by European Union came into force in 2000 and is considered EU's most comprehensive environment directive [13]. It aims to secure a sustainable use of fresh water, ground water and coastal waters all over Europe. The water directive focuses on a comprehensive management of water and watercourses. Even though water withdrawal at one point in a river do not cause negative impacts locally, it might affect the ecosystem largely downstream. That means the whole water stream needs to be taken into consideration when concessions for water depletion are given to a certain area [13]. Water withdrawal does not necessarily cause negative effects in terms of emissions or damages directly. However, withdrawal may lead to fish mortality and other indirect damages because of drought. A minimum water requirement is therefore often demanded when licensing water withdrawal [14].

2.2 Production methods

As early as in 1934, the Toronto Ski Club met climatic difficulties when trying to arrange a ski jump competition. The lack of snow that winter made it impossible to rely on natural snow. The solution ended up being transport of shaved ice with trucks to the arena where they managed to cover the absolutely necessary part of the hill with the long travelled snow [15]. Since then, more improved technologies have been developed to help such events in lack of natural fallen snow. In short lines, we have two possibilities for snow production. In this report, we divide between snow – and ice production, which main difference is that they produce snow in cold and warm temperatures, respectively. Snow production is also known as temperature dependent snowmaking (TDS) because a low wet-bulb temperature is required in order to use the technology. Ice production is also known as temperature independent snowmaking (TIS) because of the technology's ability to produce snow even in temperatures above zero. A closer explanation of the two technologies follows.

2.2.1 Snow production

Snow production, or TDS, is dependent on the air temperature. With this technology, snow is created by spreading finely divided water particles in the air and allowing them to freeze on their way to earth. Today, we have two real alternatives on the market when it comes to TDS's: fan guns and lances. Generally, lances consume less energy per m^3 of snow compared to fan guns. If instead capacity is compared, fan guns produces more snow per hour compared to lances [16]. Both methods are summarized in Table 1.

Table 1 - Comparison of fan guns and lances

	FAN GUNS	LANCES
Production capacity (m3/h)	95-105	55-65
Water use (l/sec)	11-44	25-30
Optimal reach (meters)	60	20
Adjustments	Adjustments according to weather to improve snow quality is possible	No adjustments
Mobility	Mobile, but heavier than lances. Makes them harder to transport	Lower weight make them easier to move
Source of power	Electricity	A compressor serves the lance with high pressure air

2.2.1.1 Lances

Lances are light weight aluminum "showers" that create artificial snow by spreading water particles from a nozzle placed on a tall aluminum stick. The height is of importance to allow the particles to freeze on its way down to the ground. A lance itself does not require any electricity, but has to be connected to a compressor leading high-pressure air through the lance. They are normally connected to a comprehensive piping system transporting high-pressure water from the centralized pump stations. Lances are connected to junction points along the pipeline and can be moved in a certain radius from these points. Preferably, the piping system should be below the frost line, to prevent the water from freezing. The advantage of this snow technology is that the physics and mobility makes it easy to produce snow directly into the slopes, allowing the grooming process to start immediately. However, lances are more vulnerable to wind because of its distance from nozzle to earth and is therefore a more fragile snow production method in windy areas [17].

Figure 4 – Lance [18]

2.2.1.2 Fan guns

Fan guns uses a fan to blow ambient air through a barrel. Water and small amounts of compressed air are added to the airflow, making the fan gun able to produce snow up to a 60 meters range [19]. Unlike lances, that are connected to centralized compressors, compressed air is made directly on the fan gun by a small piston compressor [17]. At optimal conditions, a fan gun is able to produce more than 100 m^3/hour [19]. Fan guns has up to 100% higher production capacity than lances. However, their direct connection to a power outlet make them less mobile. Because of their productivity, but less mobility, fan guns are typically located where they can produce snow in a pile, for further transport into the slopes.

Figure 5 - Fan gun [20]

2.2.2 Ice production

It do also exist technology that is able to produce snow even in temperatures above zero. In this report, the technology is referred to as ice production or temperature independent snowmaking. The technology of ice production is independent of air temperature and cools the water to freezing point through a heat exchanger. The final product has a temperature down to -5 degrees Celsius, which make it very resistant to melting. The market for temperature independent snow production methods has increased in recent years, and it exists several providers of the technology. Ice production was, among others, used during the 2014 Olympic Winter Games in Sochi [21].

Ice production is very energy intensive compared to conventional snow production, and requires a power supply of between 20-30 kWh/m^3, depending on the model [21]. Because of the energy intensity, ice production is not recommended as a complete substitute to snow production, but rather as a complement during winters with lack of snow and prior to big events. Although snow storage provides snow security towards next season, temperature independent snow production is the only technology that make us able to guarantee good snow conditions at any given time, as other technologies will always have uncertainties regarding melting rate. Note that summer storage will give the same snow guarantee, but depends on long-term planning.

2.3 Storage

In recent times, snow storage has become of greater interest both as an alternative and to complement snow production [10]. To fulfill expectations of good skiing conditions in the early season, storage of snow from last season is an alternative to ice production during autumn. This is an efficient method to fully exploit the cold periods during winter. Among the arenas that have used snow storage successfully the last years is Beitostølen [3]. As the host of the first national cross-country skiing event of the season, they need to be able to serve good skiing conditions by mid-November [22]. Snow is then stored in large piles over summer for re-use the next season. There are significant melting losses associated with this alternative, which more or less can be reduced by using methods that limits these. Snow can be stored indoor, underground, in ground and on ground, where the two latter alternatives imply use of an insulating top layer [23].

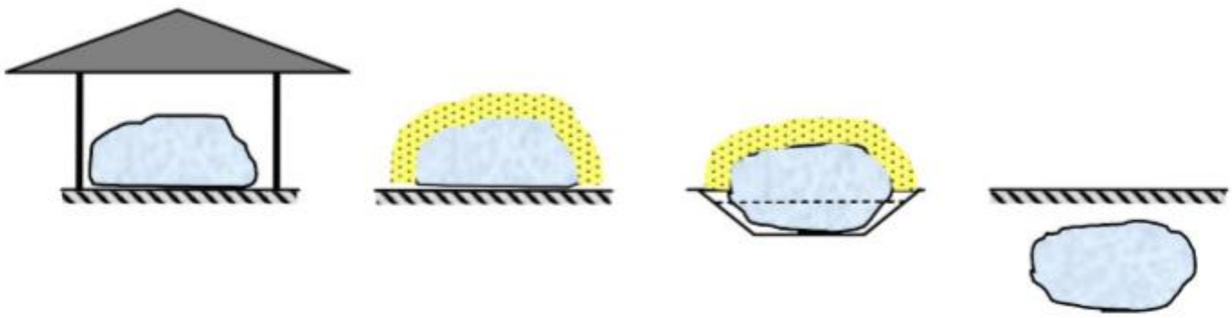

Figure 6 - Methods for snow storage [23]

2.3.1 Cover material

Use of geotextile or wood chips are the most common methods for insulating a snow storage, having different properties. Here, the term wood chips do include sawdust, wood powder, cutter shavings and larger wood chips [10]. The use of wood chips for isolation is an old technique that was used in the ancient Greece, where ice blocks was used as refrigerators. Sawdust was used to prevent the ice from melting [24].

Melting is here divided in two categories; forced and natural melting. Forced melting describes the melting that comes from re-circulation of the energy carrier (indirect melting) and natural melting can be divided into surface melt, rain melt and ground melt (direct melting) [24]. Surface melt is responsible for as much as 80% of the natural melt [10]. Most of the surface melt from a snow storage percolates downwards through the snow, but a fraction of the melt water evaporates through the insulation to air. As evaporation requires energy, this process releases heat, which will give a positive cooling effect on remaining snow. Latent heat of vaporization is measured to be as much as 7,5 times as the latent heat of fusion. Evaporation will therefore cause a significant reduction in melting rate even at a low rate [25].

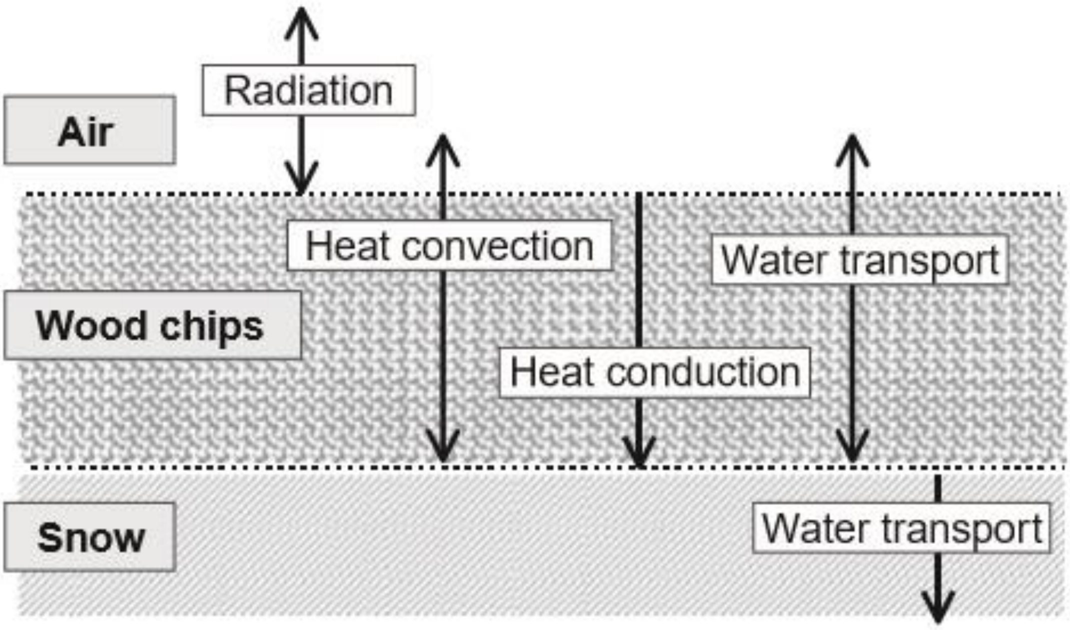

Figure 7 – The insulating effect from wood chips as top layer [24]

In a study done by Skogsberg & Lundberg (2005), thermal resistance of wood chips, bark and geotextile was analyzed. They found that two snow piles, one with a 0,1 m layer of cutter shavings and the other with 0,2 m of sawdust, had the same insulating effect. The properties of cutter shavings as insulating material is explained by its large surface and airy structure. They also found that wet cutter shavings led to lower melting rates because larger thermal conductivity counteracts by increased evaporation [24].

Because of its dark color, and thus decreased albedo and poor water transporting qualities, bark is assumed a poorer insulating material. Geotextile clothing reduces the heat conductivity largely, but do also prevent the effect from evaporate cooling. The net effect from geotextile clothing, however, needs to be studied further [24].

Lintzén (2016) collected the melting loss from different insulating methods found in a series of studies. Results are presented in Table 2.

Table 2 - Performance overview of different cover methods for snow storage [10]

Place	Volume [m^3]	Cover material	Estimated total snow melt [%]
Vuokatti, Finland	20 000 - 25 000	Tarpaulin and sawdust, 30-40 cm	20
Östersund, Sweden, 2006	2 piles á 10 000	Sawdust, 70-80 cm	30
Östersund, Sweden	20 000	Sawdust, 50 cm	20
Östersund, Sweden, 2015	30 000	Sawdust, 40 cm	12
Orsa, Sweden	5000	Bark, 40-50 cm	-
Högbo Bruk, Sweden	8000	Sawdust	-
Piteå, Sweden (2012)	2400	Geotextile and 50-60 cm of bark	29
Piteå, Sweden (2013)	3400	Geotextile and 50-60 cm of bark	29
Arjeplog, Sweden (2013)	1600	Geotextile and 40-50 cm of bark	61
Birkebeiner Ski Stadium, Norway	40 000	Wood chips, 30-50 cm	17
Sochi, Russia (2013)	800 000 (several piles)	Geotextile in several layers, foamed plastics, aluminum folio	20-50

2.4 Salting

Adding salt (NaCl) to wet snow causes a chemical reaction that releases heat energy, leaving the remaining snow colder and harder. Salting can therefore be a quick method to improve snow quality. For optimal effect, the top layer needs to be soft and water content in the snow should be between 35-50 %. Because of salts impact on the ecosystem and because it is a short-term solution causing even worse snow conditions in long term, this method is mainly used in situations that require good conditions fast, such as in front of a world cup event [5].

2.5 Managing a system

Managing a manual snow production system requires thorough experience from the operations team. The water-air relationship is dependent on the wet-bulb temperature and need continuous adjustments – low wet-bulb temperature allows a higher water share than a higher wet-bulb temperature. A high water share at high temperatures gives wet snow leading to icy skiing conditions, which is not preferred. However, a higher water ratio gives the possibility of higher production capacity and can be a good option if the snow is produced in a pile for future activities. In that case, the snow will have time to drain and achieve a good quality before used in the tracks. Wet snow is also preferable as a sole towards the ground and a dryer top layer, because it resist melting better than dry snow [5].

Figure 8 - Desired relationship between sole and top layer [5]

An arena for Nordic skiing can have different methods for snow production. Fixed facilities can be installed along the tracks so that snow is produced more or less where it is needed or snow production can be more centralized so that large quantities are produced at one place and further transported to the tracks [5]. Most arenas for cross-country skiing is a combination of these two, with storage in big piles and replenishment from fan guns and/or lances along the tracks. Groomers with a front shovel can be used to transport snow for short distances.

2.6 Pumping methods

Even with a sufficient height difference from water source to where water is required for snow production, there will be a need to distribute water on site. To make sure this is happening, water pumps should be installed. Powered by electrical motors, they are able to pump water through pipes to the snow making unit. Suction pumps can be used at the outlet of the water source, while screw pumps are well suited at the arena to distribute water throughout the system. Depending on the flow rate from the water source, screw pumps at the stadium should be dimensioned to handle these quantities [26].

3. METHODOLOGY

This report consists of a literature study of relevant background knowledge and a quantitative part including a life cycle analysis (LCA). The literature study provides an overview of existing methods for snow production and considers important factors related to snow production management. The quantitative study is analyzing the three main snow production alternatives already introduced, including a few variations of these. All alternatives are entirely based on the use of artificial snow [27]. All methodology and alternatives are explained in detail in this chapter.

3.1 Literature study (background)

After what I know, no studies has been done to quantify the environmental footprints from snow production in a lifecycle perspective. From this, there has been somewhat limited existing studies with the same approach to base this report on. However, it exists a number of studies that considers energy use, economy – and ecological impacts from snow production using other methodological frameworks. This has been important in the process of trying to clarify the existing technologies and methods in the literature chapter. Alongside this, first hand experiences from the operation team in Granåsen has been highly valuable in the attempt to provide an authentic picture of the case studied.

3.2 Life Cycle Analysis (LCA)

To investigate the environmental footprint of snow production, a life cycle analysis has been conducted. An LCA calculates the environmental footprints of a product or a process by aggregating fractions of the input needed for each functional unit of the final output. By providing a holistic overview of the system unveiling bottlenecks and inefficient joint processes, an LCA is a well suited decision making tool for further improvements [28]. The three main steps when conducting an LCA is shown in Figure 9 and explained here.

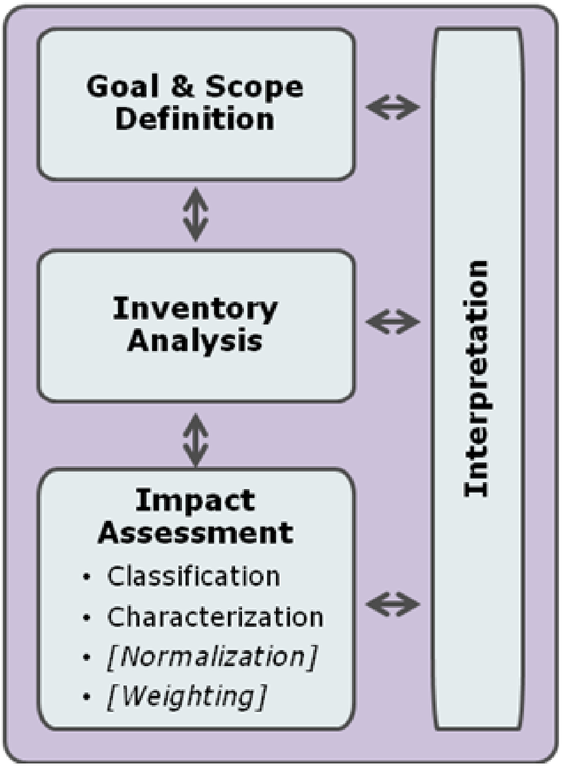

Figure 9 – LCA main steps [29]

3.2.1 Goal and scope definition

To investigate impacts related to a given case, the system boundaries need to be clearly defined. These sets the premises for what to be included in the study. A clear understanding of the system boundaries limits the probability of problem shifting. Problem shifting occur when a problem is ignored – either by leaving it outside the system boundaries or by creating a problem while solving another. Problem shifting can typically arise when the contractor of the LCA has economic interests in the results, or it can result from lack of knowledge. Defining the scope does also include a specification of the environmental impacts to be addressed [28]. The functional unit form the basis for comparison, and should be of relevant size according to the study. In the case of snow production, the functional unit could be defined as per skier, per snow day, per m^3 snow or per snow season. The latter is used in this study.

3.2.2 Inventory analysis

After defining goal and scope, the life cycle inventory (LCI) is constructed. A flowchart illustrating all the processes considered in the study, and the connection between these, provides an overview of the system [28]. Second, all technologies linked to each process, and the input requirement for each of these, needs further investigation. Inputs from material extraction, use phase, transport, recycling process and demolition can be included, depending on where the system boundary is set. Normally, all inputs are collected in the background system, while the foreground system allow us to modify these inputs according to the functional unit.

In this study, the EcoInvent database is used to build and modify the background inventory. Arda software from NTNU is used to run the model and process the results.

3.2.3 Impact categories

The last step links the inventory to well-developed impact categories. This is an indicator on how the system perform according to environmental interventions. Global warming potential (GWP) is one of several impact categories, and is the default metric used as characterization factor in life cycle impact assessment (LCIA) [28]. A structural path analysis (SPA) allows us to get an overview of the performance related to different production chains in the system. This makes us able to go deeper into the understanding of each process by tracking the joints and find where emissions occur.

LCA methodology divide between midpoint – and endpoint levels, where impact categories belongs to the midpoint level. Here, the environmental impact is given in different quantitative units, depending on which impact category we are studying. Endpoint categories, or "areas of protection" is made as a continuation of these impact categories, aiming to serve a better tool for comparison with more merged units.

3.3 Parameters studied

Electricity and fuel consumption are assumed the biggest contributors to environmental impact because of energy demanding processes and comprehensive operation logistics involving use of heavy-duty vehicles. Based on this, indirect emissions from extraction, production and use of these inputs will probably be responsible for the most significant impacts linked to operation of the ski arena in Granåsen. Knowing this, an environmental analysis on a series of impact factors will to some extent end up being a study of impacts from electricity and fuel production, which is somewhat outside the scope of this report. Global warming potential will therefore be the main parameter considered in this report. GWP considers the impact from the four most influencing greenhouse gases and does therefore provide insight in how the system perform with respect to climate change. An overview of the electricity use linked to each alternative will also be provided.

When conducting the LCA, all alternatives are analyzed with both Nordic – and European electricity mix. The difference between these is the energy source; a Nordic mix is based on a higher share of renewables, such as hydropower, while the European mix involve a higher share of fossils, such as coal. A Nordic el-mix is most representative for this case. However, the European mix is included for two reasons:

1. To provide an overview of the system performance if the same strategies for snow production is adopted to areas outside Scandinavia
2. As a sensitivity analysis, showing the impacts on overall performance from changing the assumed most influential parameter

Leirsjøen provides water to the system in Granåsen. Because of its large size, water consumption is not considered a limiting factor in this case – neither for the system, nor for the ecosystem in and around the lake. Environmental impacts from water use is therefore not considered in this report. Note that this has to be considered in each respective case and that water use in general can lead to large environmental impacts on surrounding ecosystems if regulations on minimum water requirement are not followed.

In addition to GWP and electricity use it is of interest to look at the local emissions to which the population is exposed. The most hazardous stressors to local environment is particulate matter (PM) and Nitrous Oxides (NOx). These parameters are studied in all alternatives, and will be referred to as local air pollutants. A closer explanation of GWP, NOx and PM follows.

3.3.1 Global warming potential

GWP addresses the effect of increased temperature in the lower atmosphere. A part of the solar radiation reflects back from the atmosphere by the earth's surface, but an increased content of greenhouse gases in the atmosphere weakens this reflection process, causing temperature increase. This impact category is thus a measurement on global warming and considers greenhouse gases like carbon dioxide (CO_2) methane (CH_4), nitrous oxides (NO_x) and chlorofluorocarbons [30], shown in Table 3. GWP is measured in kg CO_2 equivalents. Although NO_x is already considered in the GWP impact factor, it is of interest to take a closer look at this gas because of its direct local effect on human health.

Table 3 - Overview of stressors considered in GWP impact category [30]

Impact category (midpoint)	Stressors	Unit
GLOBAL WARMING POTENTIAL (GWP)	Carbon dioxide (CO2) Methane (CH4) Fluorcarbon (CF4) Nitrous oxide (NOx)	kg CO2-eq

3.3.2 Nitrous oxides (NO_x)

Nitrous oxides includes the two greenhouse gasses Nitrous dioxide (NO_2) and Nitrous monoxide (NO). They have an acidifying effect on the atmosphere and a high concentrations of these gases may lead to respiratory diseases. This include cardiovascular and carcinogenic diseases. In Norway, most NO_x emissions stems from the oil – and gas industry, but as much as 22% is linked to road transport [31]. NO_x is therefore one of the biggest direct threats to human health through air, together with particulate matter.

3.3.3 Particulate matter (PM)

Particulate matter is a mixture of different compounds creating particles that spreads through air. We divide between fine and coarse particles, denoted as PM2,5 and PM10. The numbers represent the diameter of the particle in micrometers. Road traffic is a huge contributor to PM, mainly through road – and tire wear. Particulate matter cause the same impacts to health as NO_x, but can have cause more direct impacts on human health, such as pneumonia, cough and asthma [31].

3.4 Study area (case)

Granåsen is the main arena for ski jumping, cross-country skiing and Nordic combined in Trondheim. It is located between Byåsen and Heimdal, south-west of Trondheim city center. The arena lies at an elevation of around 182 meters above sea level. There are, however, quite large elevation differences within the tracks linked to the arena, and the highest point is at about 222 meters above sea level. This implies an elevation difference of 40 meters, which causes significant differences in air temperature. A 5 km track is expected to serve good snow conditions throughout the skiing season. The track varies in size, but an average width of 6 meters is assumed. A depth of 0,5 meters of snow layer is also used when calculating the required snow load.

As the main arena for winter sports in the Trondheim area, it is expected that Granåsen is able to provide proper snow conditions throughout the season. It is important for Granåsen to be able to provide good skiing conditions in early season for recreational reasons and for athletes depending on the ability to do season preparations on snow as early as possible [27]. Season length is therefore defined from the beginning of November until the end of April, equal to 181 days. There are, however, complex logistics linked to providing snow of high quality throughout a winter season and a combination of different methods are required for optimal results.

Today, Granåsen is based on manual technology, which means all operations have to be managed by experienced personnel being able to operate the machinery at short notice because of rapid weather changes in the area. This implies unfavorable working hours and comprehensive logistics linked to managing and moving the snow machinery – including fan guns, lances and water pumps. In addition to the desire for a more or less automated facility, Trondheim bydrift has also promoted desire for more efficient logistics – this will mainly involve less transport between storage and tracks [27]. A possible solution would be to limit the transport to be from storage to tracks and not both ways, which is the current situation.

3.4.1 Present logistics

A snow storage is placed on the parking lot nearby the stadium, marked by the red circle in Figure 10. During winter, two fan guns are stationed by the snow storage to produce snow for the next season. The snow can also serve as a buffer during the present winter in case of longer periods with rapid melting causing a need for replenishment. Snow is transported to the tracks by the use of heavy-duty vehicles, including excavators and lorries. The distance from storage to the nearest point on the stadium is 350 meters. In early season, snow is transported directly into the tracks, and wheel loaders and tractors are used to transport the snow to narrow and steep places that are harder to access. A road is running beside the tracks, which makes it possible for lorries to transport some of the snow to a point in the other end of the track system.

Figure 10 - Map showing the snow storage in Granåsen [32]

During season, lances are continuously producing snow directly into the tracks when the weather conditions allows it. Lances can produce snow with a reach of approximately 20 meters in good wind conditions [33]. When the pile is reaching the preferred size, they are rotated manually to be able to spread the snow over a bigger area. This is labor intensive work as it require frequent inspection. In good snow making conditions, lances have to be moved every 1 to 2 hours to avoid increased melting of the piles [27]. Snowmobiles are used to move the lances within the system to where it is appropriate. Turns and bridges are typical exposed areas because of skidding and plowing and do therefore require more replenishment than straight stretches. Normally, the bridges in the tracks do also need a more comprehensive replenishment during winter. Depending on the season, this needs to be done between 1-3 times. While doing this, tracks will be closed and heavier machinery will be required to add snow in larger piles, which can be further transported into the tracks by use of groomers and snowmobiles.

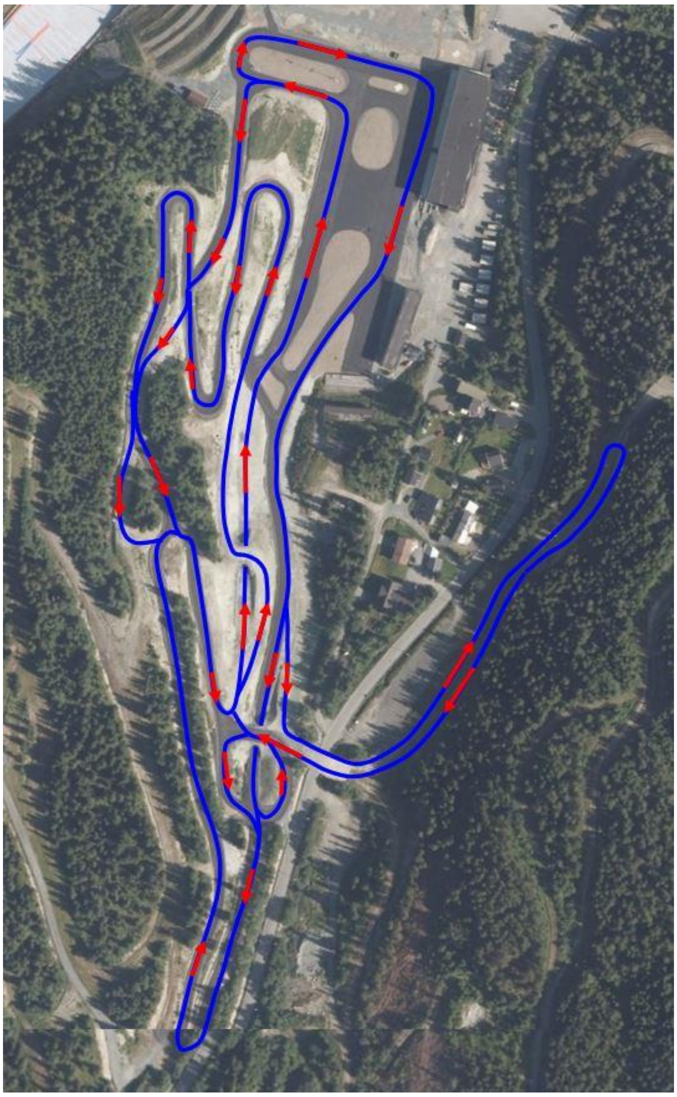

Figure 11 - Map showing the 5 km tracks in Granåsen [34]

3.4.2 Present machinery

The machinery required to operate the ski tracks is comprehensive and involve a significant amount of labor hours. Table 4 provides an overview of the working hours linked to the respective machinery.

Table 4 - Overview of working hours, harvesting and distribution [21]

EQUIPMENT USED FOR HARVESTING AND DISTRIBUTION, 2015/2016		
Equipment	working hours	
	harvesting	distribution
groomer	76	54
lorry (15-18 m3)	92	91
wheel loader	115	43
tractor with trailer	70	142
excavator (8 tons)	70	0
excavator (30 tons)	30	43
Wille	43	0
Aibi	29	0
TOTAL	525	373

Beside the machinery that depend on production method, a comprehensive underground pipeline system is installed at the arena. A pipeline system is also connected to Leirsjøen, which provides the system with water. Distance from the water source is estimated to be around 1 km. Water is transported in two pipelines for 250 meters in east direction before merging and led through one pirpeline the remaining distance to the ski arena. A suction pump is installed at Tjønna in Granåsen [35]. This pump has the capacity to transport 280 m^3/h. To equalize this, three screw pumps are installed at the arena. All together, they have the capacity to pump 300 m^3/h through the pipeline system at Granåsen. All pumps are powered by electric motors [26].

The existing snow producing machinery linked to the cross-country tracks consists of 8 fan guns and 25 lances, providing snow for both cross country and ski jump [27]. No temperature independent machinery is used.

Lances, modelled TG Track, are from the Swedish company JL Toppteknik. They are manually driven and have a production capacity of around 15 m^3 snow/hour when temperature is around -5 degrees Celsius and good wind conditions are present. The production capacity increases with decreasing temperature, and the size of the nozzle can be regulated based on temperature and water consumption. In temperatures around -10 degrees Celsius, the production rate is about three times larger. The total weight of one lance with stand is 42 kg [18]. Lances are connected to a pipeline system leading compressed air (40 m^3/min) from a centralized compressor with a power consumption of 128 kW [18]. The pipeline system has junction points every 50 meters, making the lances mobile in the radius of 25 meters from the junction point [27].

Fan guns are from Lenko and have a maximum capacity of 72 m^3 snow/hour. Power consumption is 22 kW. Adjustment options at the nozzles makes it possible to increase or decrease the size of the outlet dependent on the production conditions [36].

3.5 Modelling a system

Because Granåsen is planning to invest in improved methods for snow production the next few years, there was at some point early in the process discussed if this study should be done based on existing technology or if it was more constructive to base it on improved technology that we know is on the market. To be able to find the most important areas of improvement, it was decided that a study based on existing technology was preferred. This study is therefore studying the performance of a manually driven system.

3.5.1 Inventory

Based on experiences made by Trondheim bydrift and existing technology – and production methods, a model of the system has been conducted. The model consists of seven processes, and the inputs required for each process forms the inventory. The model includes all processes that are directly contributing to the functional unit: one snow season, defined as 181 days. Note that all processes in the model do involve several background processes which include material use, fuel and electricity use and that all footprints are linked to these background processes – not the foreground process itself. Inputs linked to the respective processes are calculated in a more comprehensive Excel-sheet that can be found in *Appendix A-F*. Here, all values and calculations with information about where they are retrieved can be found. Some values are based on assumptions because theoretical information about these are missing. Note also that the inventory in the database do not reflect the current machinery perfectly. That means numbers needs to be adjusted to fit the inventory. E.g. if it exists a complete inventory of a 30 ton lorry in the database and the lorry used for transport in this system is measured to be 15 tons, the value is adjusted to 0,5 of the original unit. However, this customization is, in some cases, also adjusted in terms of working hours, assuming the impact from a 30 ton lorry working 10 hours equals the impact from a 15 ton lorry working 20 hours. Amount of working hours and machinery size do therefore deviate slightly from the technical data provided.

The system boundaries are set around the direct requirements for providing one snow season, meaning all existing infrastructure such as pipelines, lighting and leveling of tracks are excluded. Maintenance is also excluded in this analysis. A qualitative explanation of each process and assumptions linked to these follows.

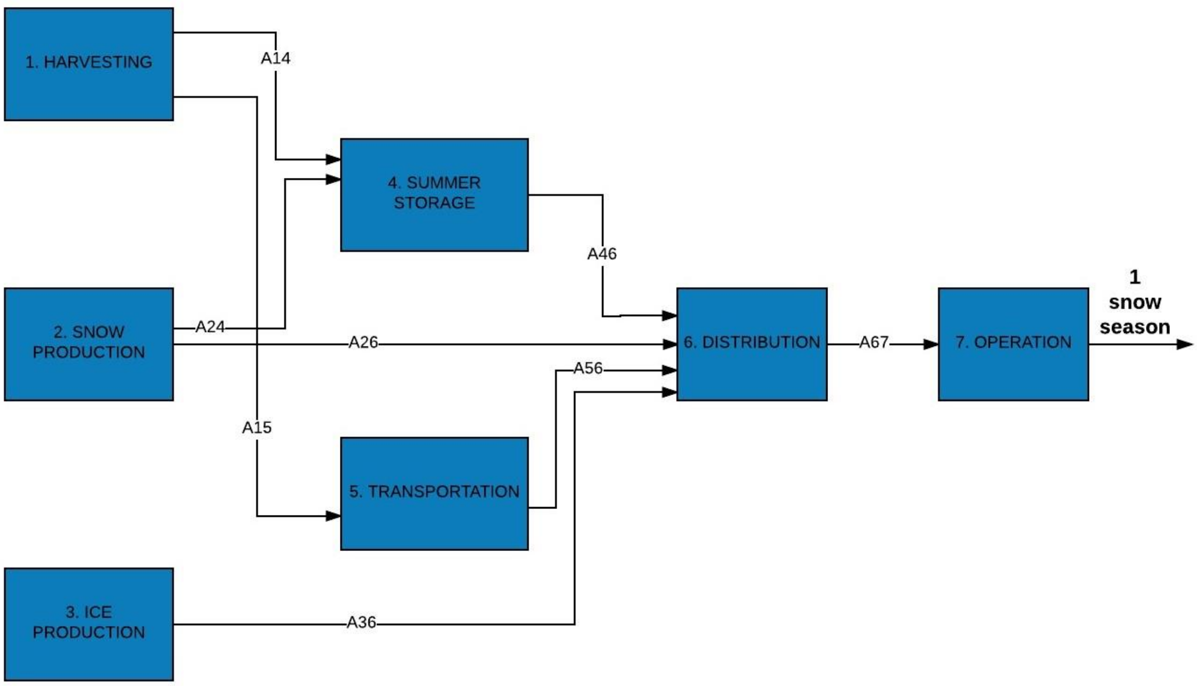

Figure 12 - System flowchart, showing all the processes and connecting flows

3.5.2 Harvesting

A method to secure a sufficient amount of snow for proper skiing conditions in early season is snow harvesting. This study is considering the following options:

1. Harvesting the remaining snow from last season
2. Harvesting from surrounding areas with a higher snow security

We assume that methods for harvesting are identical in these two cases, and include use of lorry, excavator, wheel loader, tractor with trailer and groomer [21]. The harvesting process is defined in seasonal unit. That means one unit of harvesting contains all inputs required for harvesting of all the snow that can be harvested after one season, in this study assumed 10.000 m^3, which equals two thirds of a full snow load at the arena. Working hours as a factor of predicted lifetime of each machinery is used to find the impacts linked to material use for the machinery. Impacts related to the use phase is measured in kilograms of fuel use and depends on amount of effective working hours, fuel consumption and estimated speed. Some machinery do not have a built inventory in the database. For these, the inventory for a similar product with same technology is used as a basis, and adjusted based on weight and engine power to reflect the studied machinery in a best possible way. The distance of 350 meters from storage to the nearest point at stadium is used when calculating fuel consumption for the heavy-duty vehicles transporting the snow.

3.5.3 Snow production

Snow production is defined as production of artificial snow in temperatures below zero, and can include use of both fan guns and lances. In the modelled system, however, this process considers intensive snow production in large quantities. Therefore, only fan guns are considered in this process. Lances do also play an important role in the system, but snow production from lances are further considered in process 7 – Operation. Material use per season is calculated from share of lifetime as a factor of unit output. Electricity use is calculated based on total amount of working hours for the fan guns and water pumps. The fan guns used in Granåsen has a max snow making capacity of 72 m^3/h [37]. The model assumes a capacity of 60 m^3/h, considering the fact that conditions are not always optimal. In the model, snow production is measured in seasonal units in the background. If we are considering an alternative that e.g.

assumes a combination of snow production and harvesting, the amount of summer storage should be a size between 0 and 1 in the foreground system.

3.5.4 Ice production

Ice production is defined as production of artificial snow in temperatures above zero degrees and is measured in cubic meters in this model, meaning it needs to be scaled in the foreground system. There are a few providers of this technology on the market, and this report is based on the use of Snowfactory (SF220) by TechnoAlpin. The most vital part of the SF220 is the heat exchanger. As there are no existing inventory of any ice producing machinery in the database, the material composition of Snowfactory is assumed limited to a heat exchanger and steel [19]. These two inputs are adjusted to the right weight and power capacity provided by the machine studied. Impact calculation includes electricity use for snow production and water pumps, inventory of a heat exchanger and steel.

3.5.5 Summer storage

Being able to provide good skiing conditions in early season requires good preparatory work. Saving snow from last season is one method to secure proper snow conditions as early as late autumn. This process includes production and transportation of cover material for the snow storage. Notice that this does not include transportation of snow from the tracks at the end of the season, neither the snow production itself nor distribution of snow into the tracks in the beginning of the season. These processes are linked to the harvesting – and distribution processes, respectively. This study uses sawdust as cover material for two reasons. First, experience shows that sawdust is the most efficient cover material in terms of melting rate. Second, this is the cover material that is already in use in Granåsen, and it is therefore of relevant interest to focus on this option.

This study assumes a requirement of 40 cm sawdust covering the snow pile. Assuming the pile is shaped like a hemisphere storing 18750 m^3 from the end of the previous season, accounting for a melting rate of 20%, 2492 m^3 of sawdust is required. With a loading capacity of 110 m^3 [38], 23 lorry deliveries are needed to transport the required amount of sawdust each spring.

Sawdust is anticipated to have a five-year lifetime and can therefore be re-used for several years if stored properly when not in use. In that case, one should account for 1/3 loss from one season to another stemming from transportation [27]. Despite this fact, we assume that Granåsen is provided with new sawdust every year. There are two reasons for this:

1. Granåsen does not have available space to store and dry these amounts of sawdust during wintertime [27].
2. In winter 2017, an agreement was signed between Granåsen and Kjeldstad sawmill, that includes transportation of new sawdust annually. Alternatively, the sawdust would be sent to Sweden for burning [27]. One can therefore argue that the use as cover material, in this case, is better than the alternative.

Impact calculation is considering production of sawdust and lorry use – and transportation from Kjeldstad sawmill, where it is produced, to Granåsen [39]. The process is measured in seasonal units, meaning all impacts related to a summer storage is calculated in the background inventory and need no further modifications in the foreground.

3.5.6 Transportation

All transportation required to move snow between summer storage and the tracks are included in the harvesting – and distribution processes. Transport of sawdust is also included in the summer storage process. This process do therefore only include long distance transport related to harvesting. As mentioned in chapter 3.4.2, snow can be harvested from surrounding areas. Inventory is measured in cubic meters, meaning the transport volume needs to be modified in the foreground. Vassfjellet, a mountain area at a higher altitude and better snow security is considered the alternative harvesting area from Granåsen. The distance is 20 km, and the transport process do therefore involve transportation from Vassfjellet to Granåsen for the given number of truckloads required for the studied alternative.

3.5.7 Distribution

The distribution process deals with the machinery required to serve the tracks with stored snow, and is measured in seasonal unit because the process is assumed to be relatively independent of what kind of production methods that is used. It is similar to that of the harvesting process, and involve groomer, lorries, tractor with trailer, wheel loader and excavators. The distance of 350 meters from storage to the nearest point at stadium is used when calculating fuel consumption for the heavy duty vehicles transporting the snow.

3.5.8 Operation

This process is measured in seasonal unit, meaning all inventory is scaled to the amount required for one full snow season. It considers the maintenance of the tracks, which involve grooming on a daily basis throughout the season and refill of snow from lance production during season. The required amount of refill is assumed 3000 m^3 snow/year. It does also include the operation of the lances and the system as a whole, which require use of snowmobile on a daily basis. Snowmobiles are mainly used to redistribute operative lances when needed.

Groomers are assumed to have a reach of 4,5 meters width [40]. Following the assumption that the track has an average width of 6 meters, the total driving distance for groomers are 10 km a day.

The material use for water pumps are also included in this process because the material use linked to these are constant and independent of operation hours. Because we assume that the impact of material use from these are almost negligible, this is included here, rather than separated in its own process.

3.6 Alternatives of snow production

From communication with the operators in Granåsen, the following alternatives are formed and assumed relevant to study further. Note that alternative A, B and C are three independent alternatives, and modifications of these, such as B1, B2, B3, C1 and C2 represent these alternatives, with small adjustments. For some alternatives, snow production in one season is dependent on preparatory work through the previous season. This is denoted as season one and season two, where season one is the previous season and season two is the season studied. Alternative A and C are fully feasible with the existing machinery in Granåsen. Note, however, that alternative B include use of ice production, a machinery that is not available in Granåsen today. An implementation of this option will therefore require further investments.

3.6.1 Alternative A

3.6.1.1 A1

The first alternative is compiled based on preferences from Trondheim bydrift that seeks to reduce the amount of transport required to provide one snow season. This is done by removing the process that includes harvesting from tracks in early summer. To be able streamline this process and still provide the same quality, we need to take advantage of the cold periods in season one to produce snow that can be stored and used in season two. In the calculation, it is assumed that snow for season two is produced by three fan guns directly to the storage throughout season one. The total amount of snow required for storage, assuming a 20% melting loss over summer, is 18 750 m^3. The produced snow will consecutively be stored in a pile over summer and distributed to the tracks in the beginning of season two.

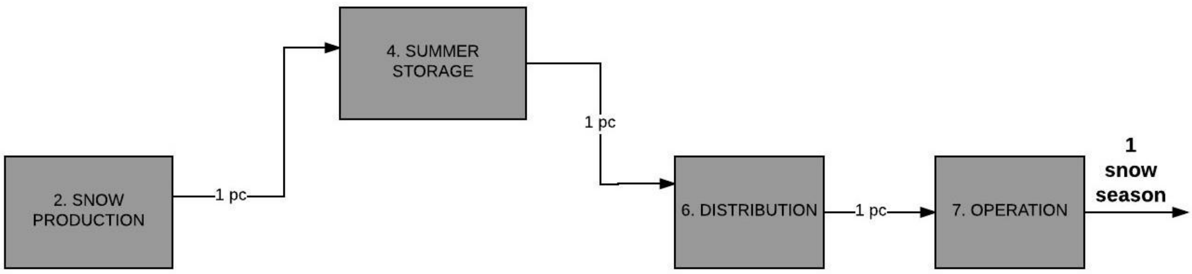

Figure 13 - Flowchart illustrating alternative A1

3.6.2 Alternative B

It may also be possible to cut the storage process. This alternative analyzes the possibility of snow production without being dependent on a summer storage. By doing this, we will eliminate the melting losses during summer, which in this case is assumed 20%, and cut the need for production and transport of sawdust from Kjeldstad sawmill. This solution require methods for snow production at warmer temperatures (ice production). It also considers harvesting from surrounding areas, which we assume has better snow conditions than that of Granåsen. Knowing that ice production and long distance transport is energy intensive in terms of both electricity and fuel consumption, the performance of this alternative depends on the emissions linked to these two factors relative to the gains from a negative melting loss and sawdust production – and transportation linked to summer storage.

3.6.2.1 Alt B1

Alternative B1 is an extreme scenario assuming that all snow required is produced with temperature independent technology. With an assumed melting rate of 5%, this will require 72 days of intensive production to be able to ski the whole track with full width by November 1st. with the assumed melting loss of 5%, a total production of 15 789 m^3 is required. With a efficiency of 220 m^3 snow/day, this means production needs to start in late august and run continuously until the beginning of the season.

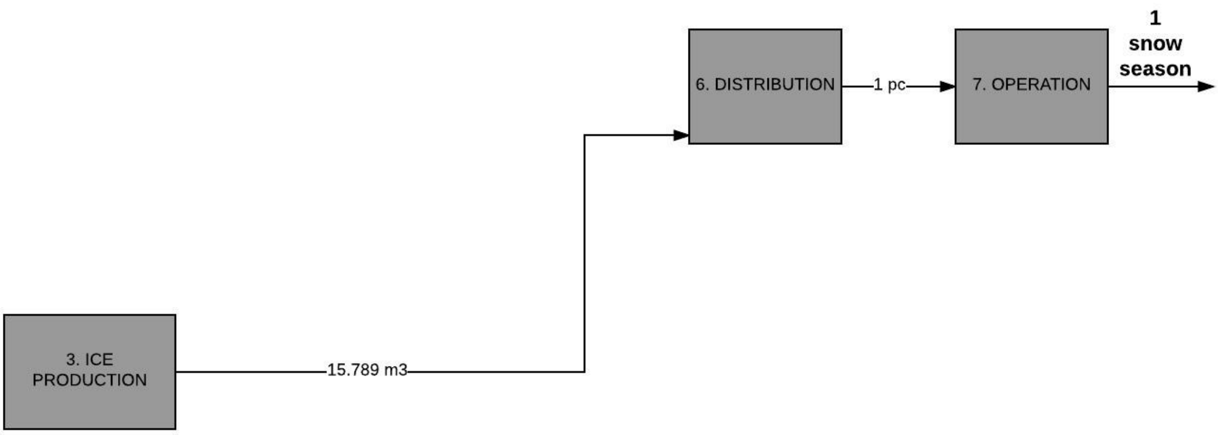

Figure 14 - Flowchart illustrating alternative B1

3.6.2.2 Alt B2

This is a modification of the previous alternative, changing one third of the ice production with long distance harvesting. This could be a good alternative if surrounding areas at higher altitudes, and thus better snow conditions, are accessible. For Trondheim, Vassfjellet is the closest area with relatively good snow guarantee and is therefore considered in this study. This is a vulnerable alternative compared to that of snow storage and ice production because it depends largely on climatic conditions and season variations. The high vulnerability of long distance harvesting as an alternative source of snow is the reason why a share of only one third of the initial ice production is changed. Because of predicted temperature increase in the future, this alternative may be irrelevant in a long term perspective.

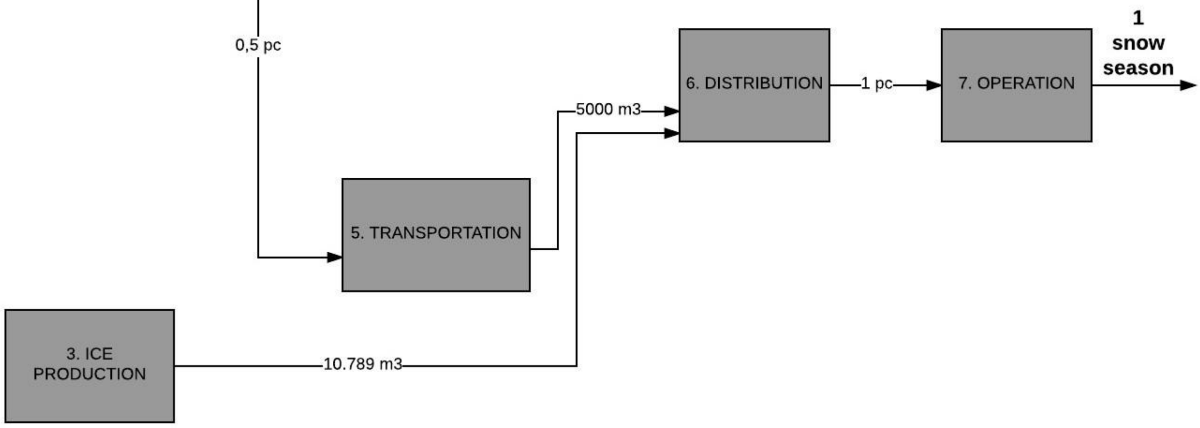

Figure 15 - Flowchart illustrating alternative B2

3.6.2.3 Alt B3

Like B2, this is also a modification of alternative B1. However, this alternative includes a 1/3 share of temperature dependent snow production replacing ice production instead of snow harvesting that was considered in B2. This limits the need for long distance transport. Note that like B2, this alternative is dependent on low temperatures during autumn because it involve snow production as a part of the preparation for early season skiing.

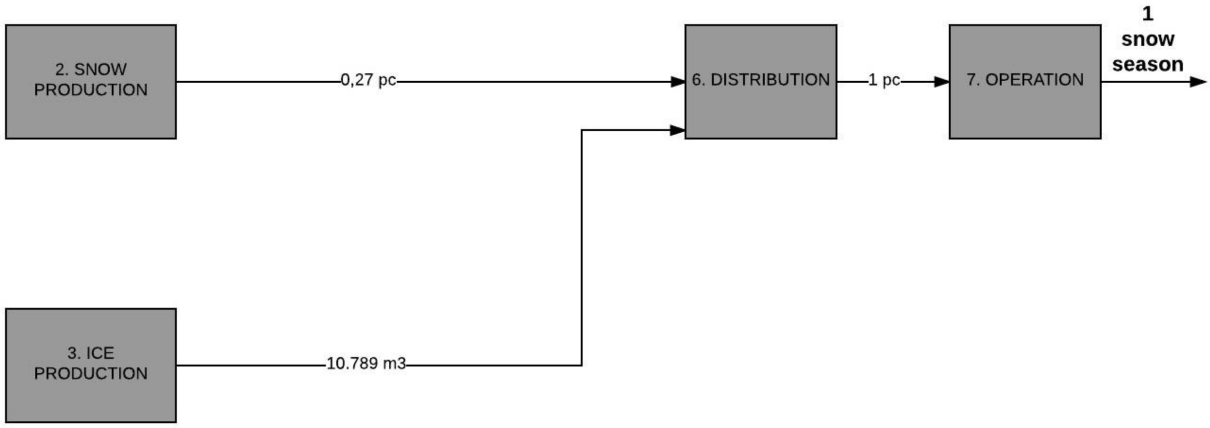

Figure 16 - Flowchart illustrating B3

3.6.3 Aternative C

Alternative C is most similar to the production method used in Granåsen today. It involve snow production during season one and harvesting of remaining snow in the tracks for summer storage towards season two.

3.6.3.1 Alt C1

50% of the remaining snow from tracks in Granåsen is harvested in this alternative. The remaining snow is assumed 2/3 of the total amount distributed in the tracks in the beginning of season, equaling around 10 000 m^3. That means this alternative assumes around 5 000 m^3 harvested, the rest being produced by fan guns during season one is represented in this alternative. It do also include summer storage.

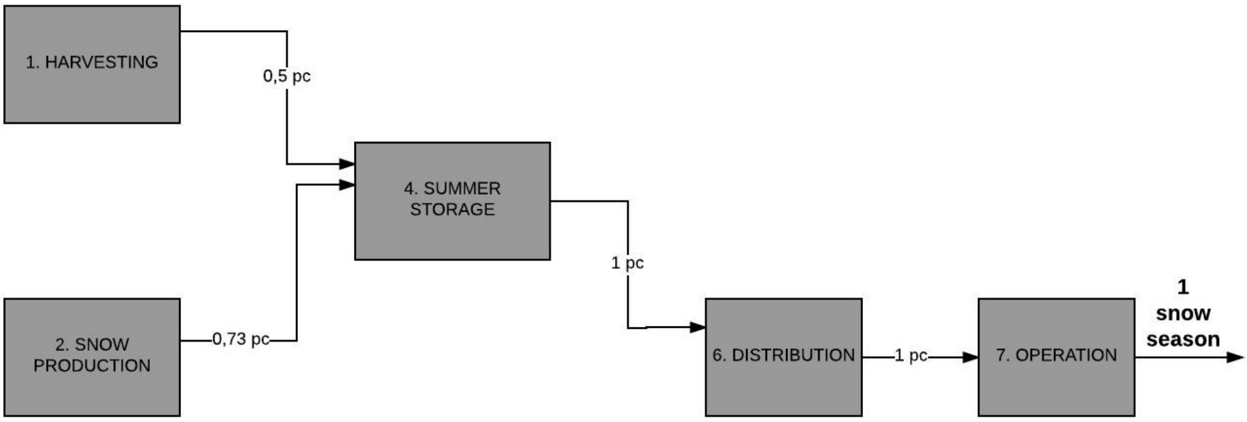

Figure 17 - Flowchart illustrating alternative C1

3.6.3.2 Alt C2

Like C1, this alternative represent a combination of harvesting and snowproduction for summer storage. However, this alternative assumes harvesting of all the remaining snow from tracks in April. This requires less snow production.

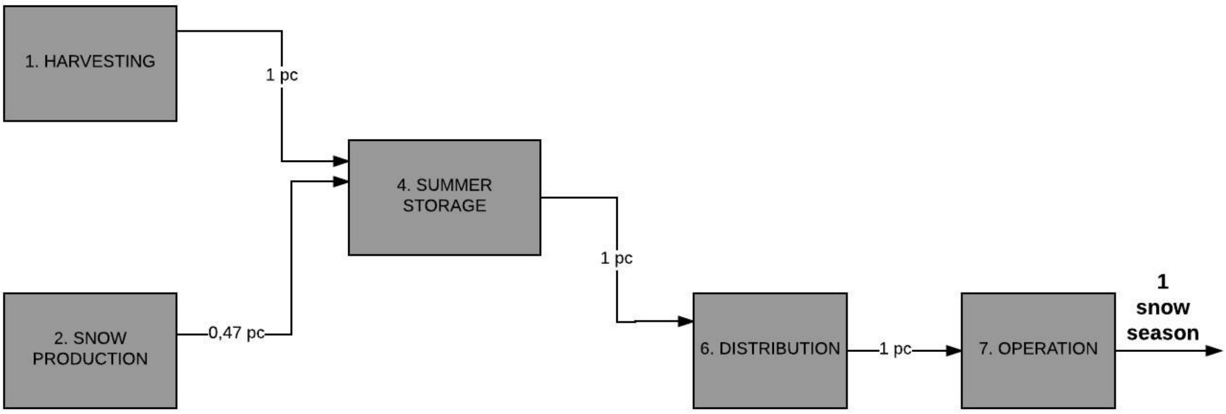

Figure 18 - Flowchart illustrating alternative C2

3.7 Limitations

A quantification of a system with comprehensive logistics and processes is a challenging task. Partly because it can be difficult to find the correct technical information about the different machinery or how they are operated, and partly because some things cannot be quantified in numbers. This model is no exception. *Appendix A-F* shows the calculations done in the attempt to quantify the system in Granåsen, and provides information about where the numbers are found. Some of these assumptions are associated with significant uncertainties. An explanation of these follows.

- In the case of ice production between August to November, a melting loss of 5% is assumed. Because no top cover material is used in this case and the ice is fully exposed to wind and high temperatures, this share is highly uncertain and a higher melting rate may be more realistic. A higher melting rate will lead to increased production, which will further increase the total impact from alternative B
- Assumption is also done regarding working rate for the required machinery used for harvesting and distribution. The working rate is varying from 0,5 to 0,8 where machines constantly working within the slopes has been allocated a higher working rate than for example lorries, that is assumed to have a lower working rate because of time used for reloading. The reason for these modifications are related to the assumptions of inefficiency. The working rates may in reality be both smaller and larger, and influence the results accordingly.
- The machinery is quantified based on existing inventory in the EcoInvent database. The modification is done based on weight or energy capacity and is not, in any situation, a perfect reflection of reality. Like for the working rate, real values may be both smaller and larger and influencing the results accordingly.

- Vassfjellet is used as the alternative place to harvest snow, located at a higher altitude and therefore associated with a higher snow security. However, the ski resort located at Vassfjellet makes harvesting from this place less realistic in a real situation because relying on harvesting may open up for a conflict of interest about who should get access to the snow.

4. RESULTS

This section aims to give an overview of the results. GWP is presented in detail for each alternative, while NO_x and PM will be presented together in the end of the chapter. All results provides the system performance using both Nordic and European electricity mixes. However, the Nordic mix is used as a basis for comparison and further discussions. To get a better understanding of the respective performances, some comparisons are done when presenting the results. However, further discussions are provided in the next chapter. Because the distribution process is identical in all three alternatives A, B and C, this process can be used as a basis for comparison to see the size of impact in all alternatives analyzed.

4.1 Alternative A

4.1.1 A1

Table 5 - Overall performance of A1 with respect to GWP, using Nordic and European el-mix

A1 [ton CO2-eq]	**NORDIC**	**EUROPEAN**
Harvesting	0,0	0,0
Snow prod	8,0	13,5
Ice prod	0,0	0,0
Summer storage	6,8	6,8
Transportation	0,0	0,0
Distribution	3,0	3,0
Operation	9,0	17,7
TOTAL	**26,8**	**41,0**

A solution including snow production during season one, summer storage with following distribution – and operation in season two has a total GWP of 26,8 ton CO_2-eq when using a Nordic electricity mix and 41 ton CO_2-eq when using a European mix. From this, we can see that electricity is a significant contributor to the final GWP, leading to a 53% increase in total impacts. Snow production and operation are the two processes affected by this, using electricity to operate fan guns, water pumps and lances.

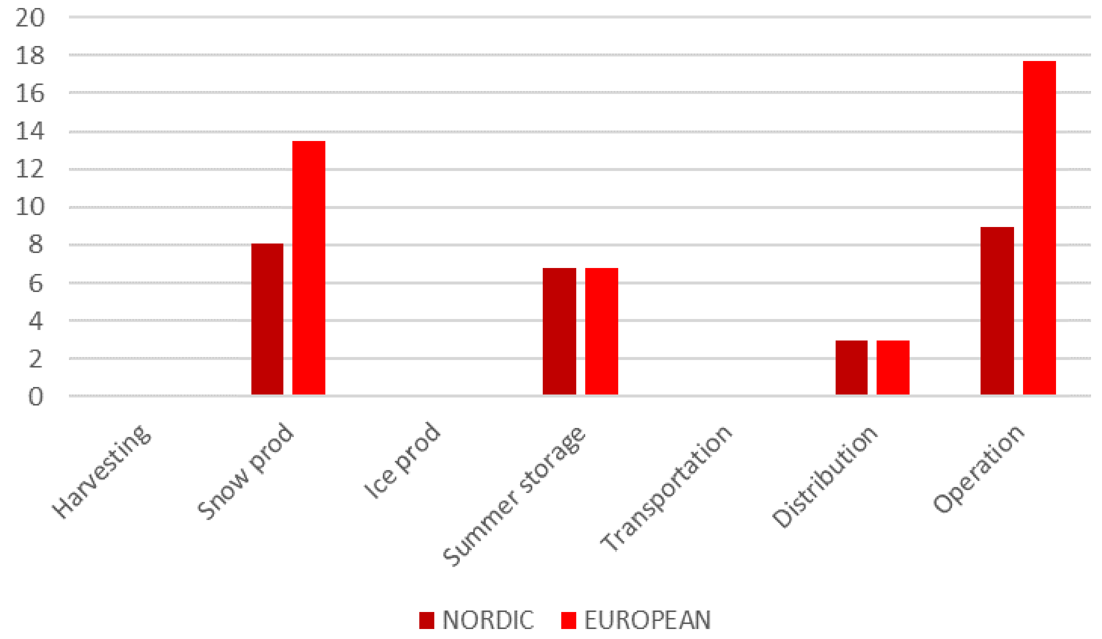

Figure 19 - GWP from alternative A1 in ton CO_2-eq/yr, using Nordic and European electricity mixes

4.2 Alternative B

4.2.1 B1

Table 6 - Overall performance of B1 with respect to GWP, using Nordic and European el-mix

B1 [ton CO2-eq]	**NORDIC**	**EUROPEAN**
Harvesting	0,0	0,0
Snow prod	0,0	0,0
Ice prod	202,6	593,9
Summer storage	0,0	0,0
Transportation	0,0	0,0
Distribution	3,0	3,0
Operation	8,9	17,6
TOTAL	**214,4**	**614,5**

In this alternative, ice production is a huge contributor to global warming potential, as expected. The distribution process, which stands for a significant contribution to total GWP in alternative A1, is a small share of total impact because of the energy intensive ice production. With a total GWP of 214,4 ton CO_2-eq when using Nordic electricity mix and 614,5 ton using a European mix, this alternative is 8 and 15 times higher than alternative A, respectively. Ice production is an extremely energy intensive process. Note that this alternative was constructed as a reference scenario where no snow, nor any low temperatures allowing snow production are present.

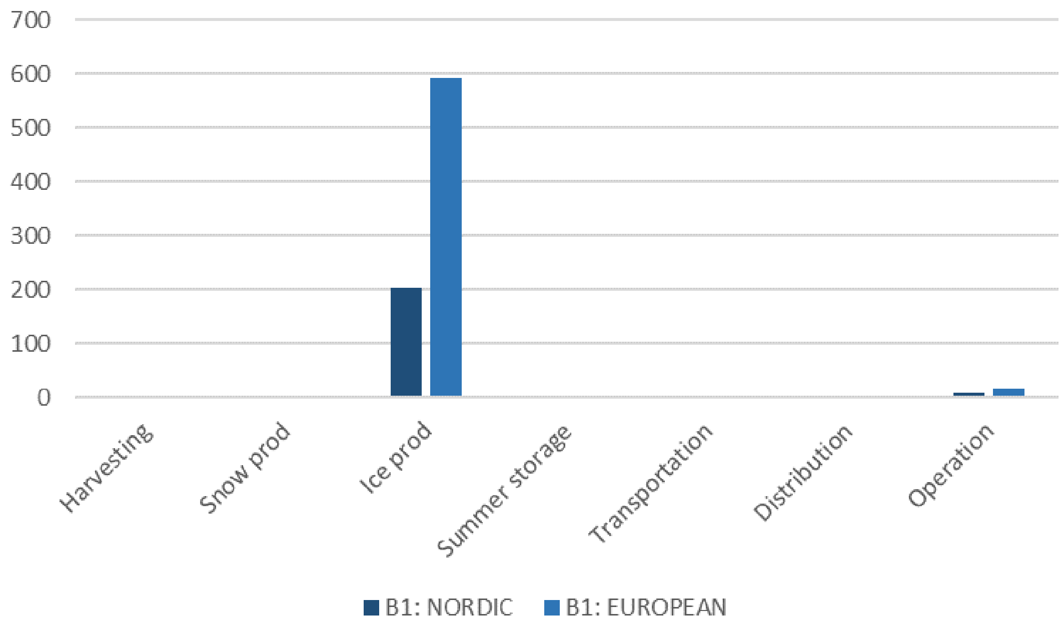

Figure 20 - GWP from alternative B1 in ton CO_2-eq/yr, using Nordic and European electricity mixes

4.2.2 B2

Table 7 - Overall performance of B2 with respect to GWP, using Nordic and European el-mix

B2 [ton CO2-eq]	**NORDIC**	**EUROPEAN**
Harvesting	1,4	1,4
Snow prod	0,0	0,0
Ice prod	138,4	405,8
Summer storage	0,0	0,0
Transportation	0,5	0,5
Distribution	3,0	3,0
Operation	9,0	17,7
TOTAL	**152,3**	**428,4**

We find that total GWP is reduced to 152,2 ton CO_2-eq (Nordic mix) and 428,4 ton (European mix) when changing one third of the ice production with long distance harvesting from Vassfjellet. When comparing impacts from the harvesting – and transport process linked to long distance harvesting with impacts from ice production of the same amount of snow, we find that ice production is from 35 to 100 times more impact than that from long distance harvesting. However, we know that long distance harvesting has some disadvantages that will be further discussed in the next chapter.

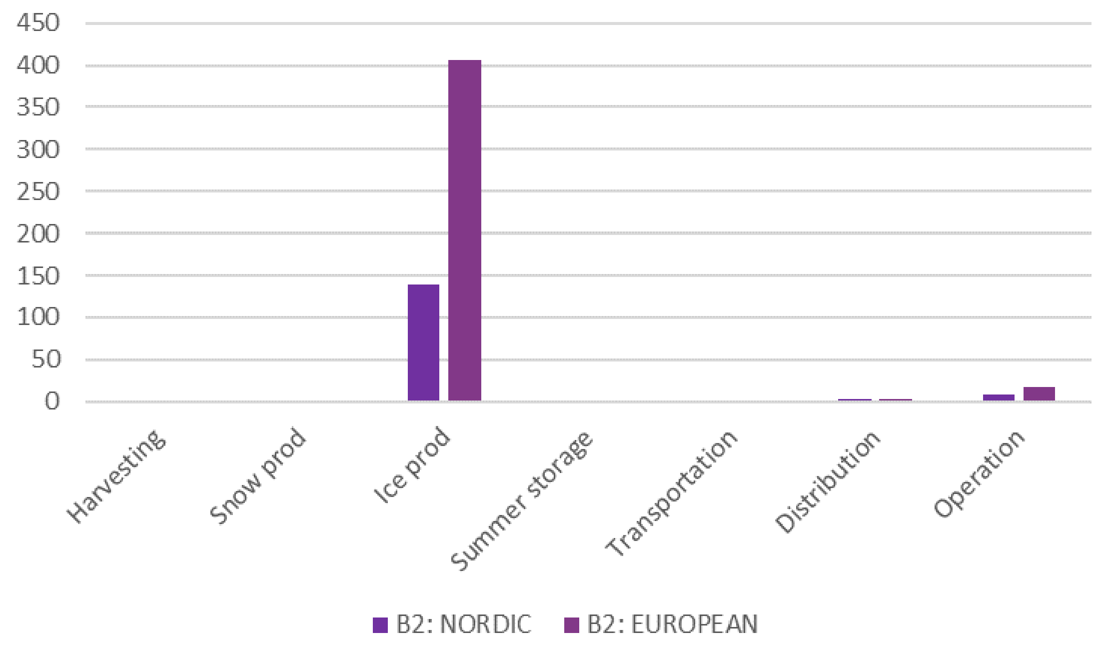

Figure 21 - GWP from alternative B2 in ton CO_2-eq/yr, using Nordic and European electricity mixes

4.2.3 B3

Table 8 - Overall performance of B3 with respect to GWP, using Nordic and European el-mix

B3 [ton CO2-eq]	**NORDIC**	**EUROPEAN**
Harvesting	0,0	0,0
Snow prod	2,1	3,6
Ice prod	138,4	405,8
Summer storage	0,0	0,0
Transportation	0,0	0,0
Distribution	3,0	3,0
Operation	9,0	17,7
TOTAL	**152,5**	**430,2**

Similar to B2, B3 is based on the reference alternative with 100% ice production. However, this alternative changes one third of the ice production with snow production from fan guns. Total GWP in CO_2-eq for this alternative is 152,5 ton with Nordic – and 430,2 ton with European electricity mix. These results are very similar to B2, telling us that the difference in climatic impacts from long distance harvesting and snow production is negligible in the big perspective. Like in the case of long distance harvesting, there are some limitations related to snow production in this alternative, as it relay on low temperatures during late autumn to allow snow production to happen. These are further discussed in the next chapter.

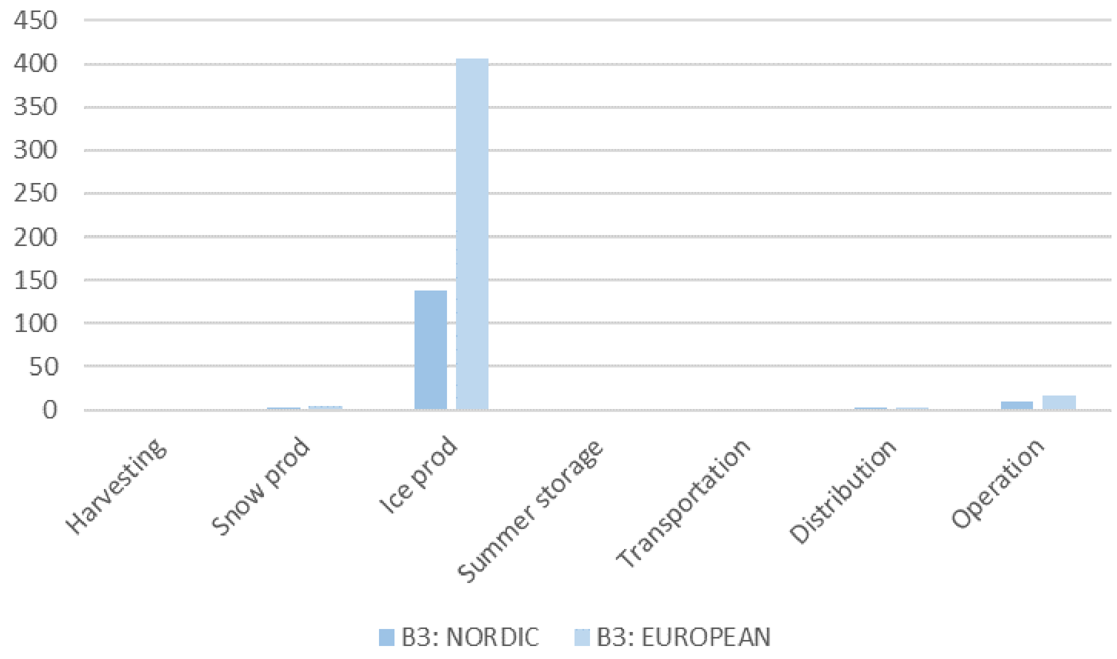

Figure 22 - GWP from alternative B3 in ton CO_2-eq/yr, using Nordic and European electricity mixes

4.3 Alternative C

4.3.1 C1

Table 9 - Overall performance of C1 with respect to GWP, using Nordic and European el-mix

C1 [ton CO2-eq]	**NORDIC**	**EUROPEAN**
Harvesting	1,4	1,4
Snow prod	5,6	9,0
Ice prod	0,0	0,0
Summer storage	6,8	6,8
Transportation	0,0	0,0
Distribution	3,0	3,0
Operation	9,0	17,7
TOTAL	**25,7**	**37,9**

This alternative is closest to how they currently operate the system in Granåsen. Ice production is replaced with summer storage, and the absence of ice production equalizes the distribution of impact between the remaining processes included. Total GWP is 25,7 ton CO_2-eq with Nordic energy mix and 37,9 ton with European mix. This is slightly lower than in alternative A1 – 1 and 3 tons lower for Nordic and European energy mixes, specifically. The only difference between these two alternatives is that harvesting in this case replaces a share of snow production from A1, leaving all other processes the same. From this, we know that environmental impacts from snow harvesting are marginally lower than if the same volume is produced by fan guns.

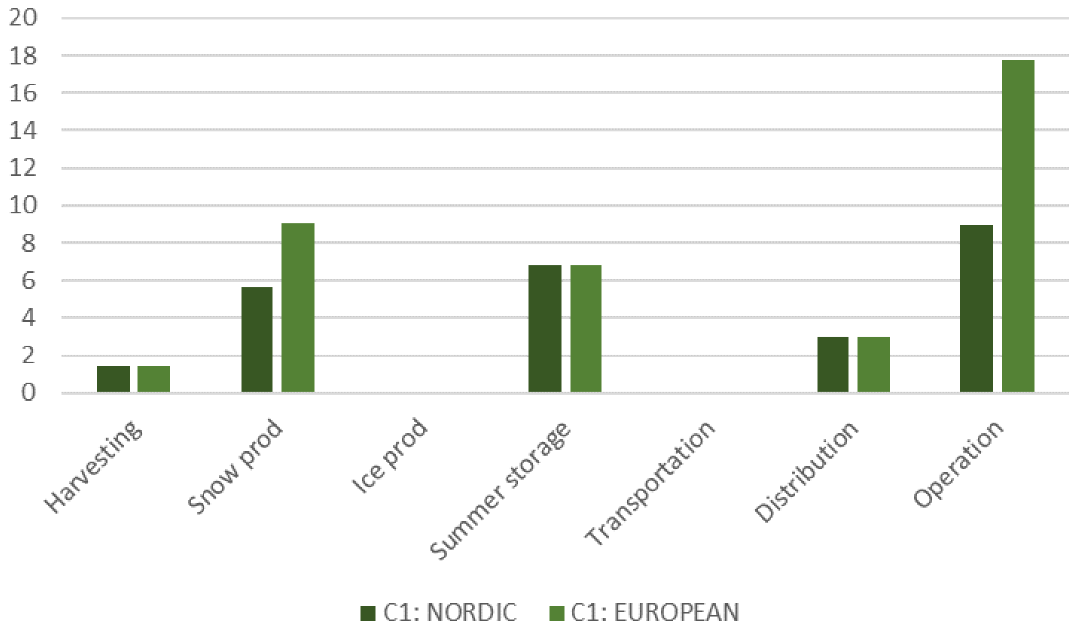

Figure 23 - GWP from alternative C1 in ton CO_2-eq/yr, using Nordic and European electricity mixes

4.3.2 C2

Table 10 - Overall performance of C2 with respect to GWP, using Nordic and European el-mix

C2 [ton CO2-eq]	**NORDIC**	**EUROPEAN**
Harvesting	2,8	2,8
Snow prod	3,4	5,2
Ice prod	0,0	0,0
Summer storage	6,8	6,8
Transportation	0,0	0,0
Distribution	3,0	3,0
Operation	9,0	17,7
TOTAL	**24,9**	**35,5**

C2 include the same processes as C1, but assume a higher share of harvesting, reducing the required amount of produced snow. Total GWP is now 24,9 and 35,5 tons CO_2-eq for Nordic – and European electricity mix, making this the best alternative considered in terms of global warming potential. Knowing this, we can conclude that increased harvesting as a replacement for snow production correlates with increased environmental benefits. Note that these benefits are negligible and make little difference on the overall performance. This do, however, correspond to what we found in alternative B, where B2, including long distance harvesting, had a lower GWP than B3, that produced the corresponding amount of snow.

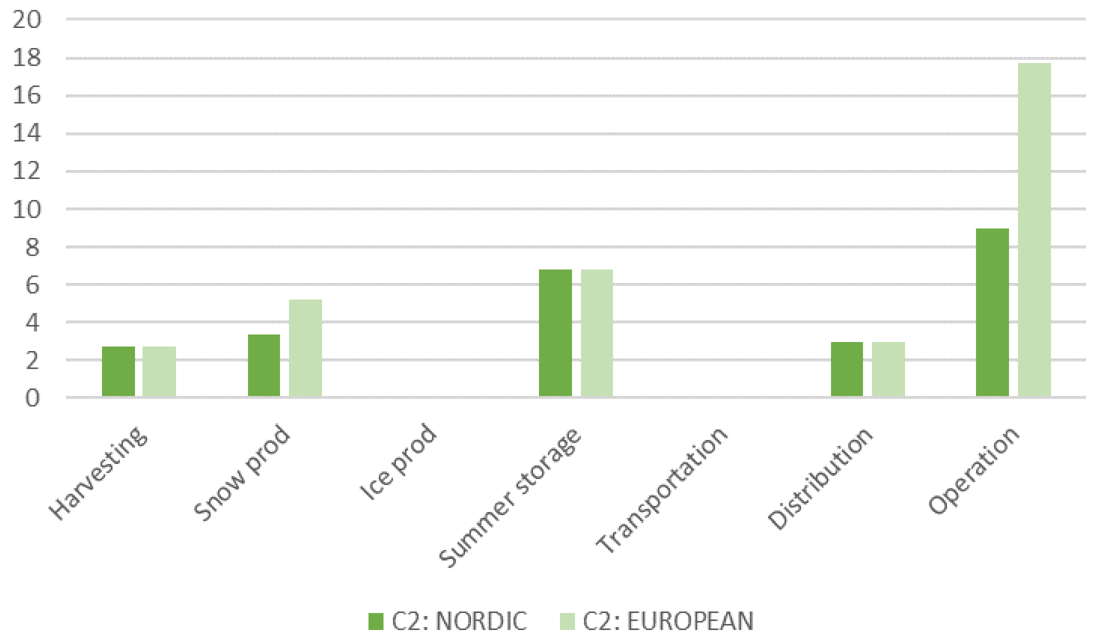

Figure 24 - GWP from alternative C2 in ton CO_2-eq/yr, using Nordic and European electricity mixes

4.4 Energy use

Because electricity stands out as the by far largest contributor to environmental impact, it is interesting to take a closer look on how electricity use is distributed between the alternatives studied. Table 11 shows electricity use in kWh for each alternative, and how it is distributed between the respective processes.

Table 11 - Total electricity use in all alternatives studied [kWh/yr]

Alt.	SNOW PRODUCTION	ICE PRODUCTION	OPERATION	TOTAL
A1	14609		23650	**38259**
B1		1054074	23650	**1077724**
B2		720274	23650	**743924**
B3	3944	720274	23650	**747868**
C1	9197		23650	**32847**
C2	4896		23650	**28546**

Figure 25 provides a visual illustration of the results, clearly showing the large electricity use linked to alternative B1, B2 and B3.

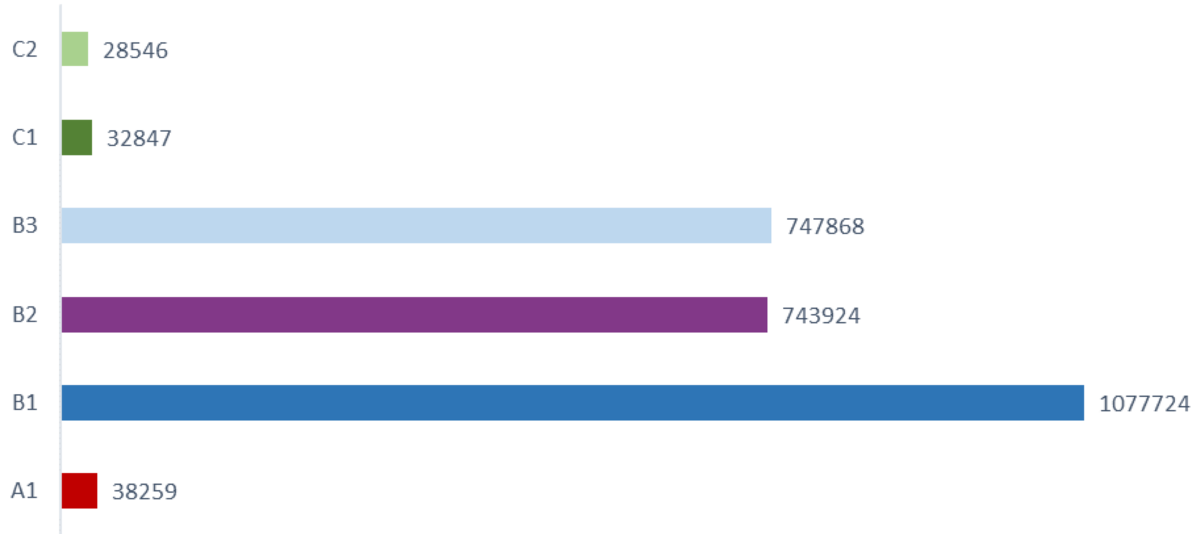

Figure 25 – Total electricity use, all alternatives [kWh/yr]

Because we want to focus on the best alternatives for snow production, a closer look at the three alternatives with the lowest electricity consumption follows. For A1, C1 and C2, snow production and operation are the only two processes involving direct electricity use. Operation is constant in all three alternatives, but electricity use in snow production varies to some extent, depending on how much of the snow production has been exchanged with harvesting. The performance of these alternatives with respect to electricity use is shown in Figure 26.

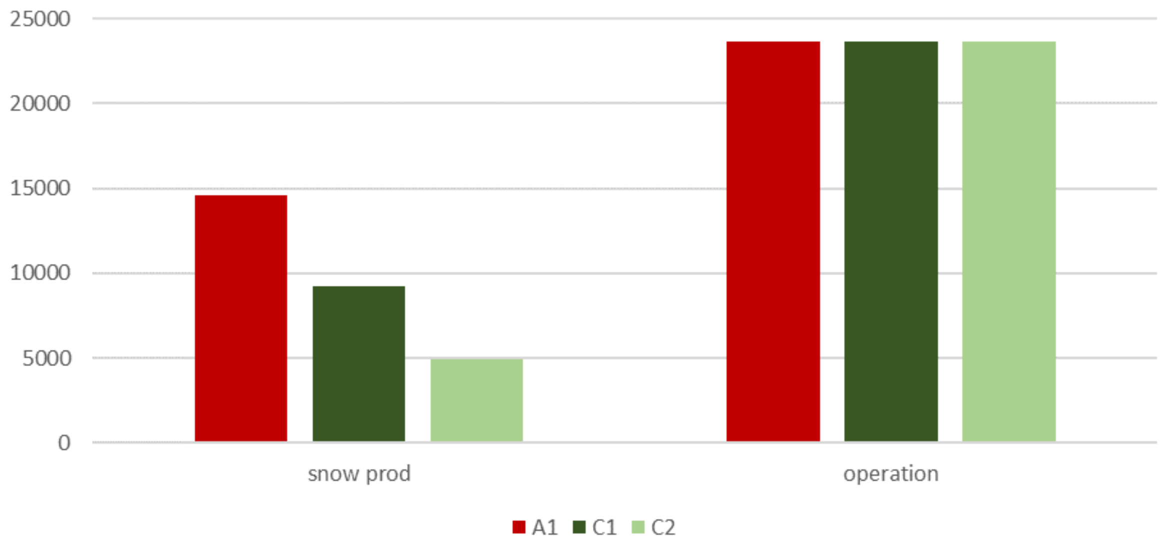

Figure 26 - El-use in each process from alternative A1, C1 and C2, using Nordic electricity mix [kWh/yr]

4.5 Nitrous oxides and particulate matter

NO_x emissions are presented in Figure 27, showing that the B alternatives are the highest contributors to local air pollution in the form of NO_x.

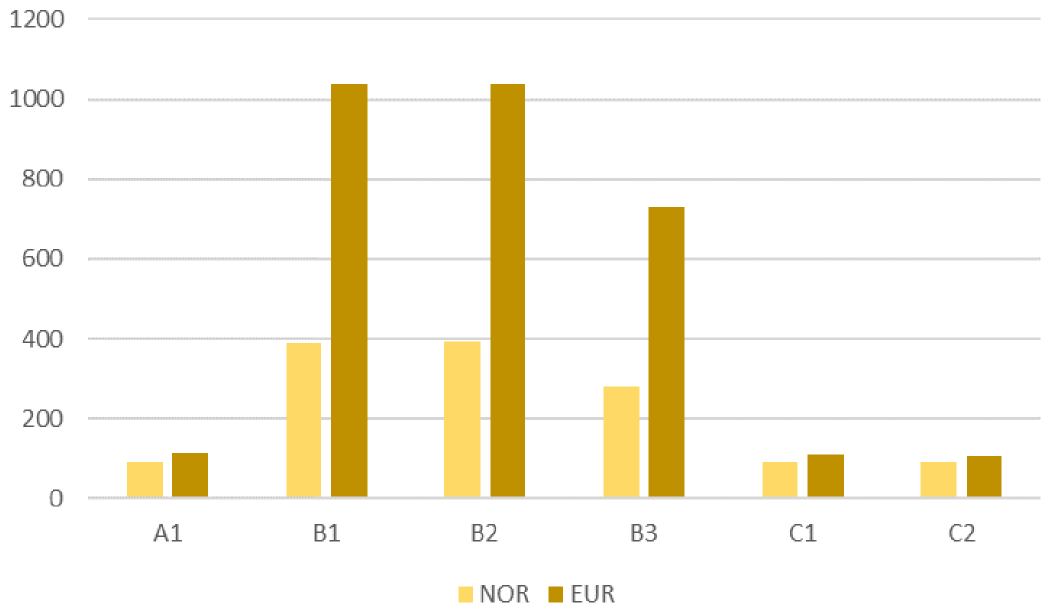

Figure 27 - NOx-emissions from Nordic and European electricity mix [kg NO_x/yr]

To get a better insight in where emissions occur, a percentage distribution between the different processes from each alternative is presented in Figure 28.

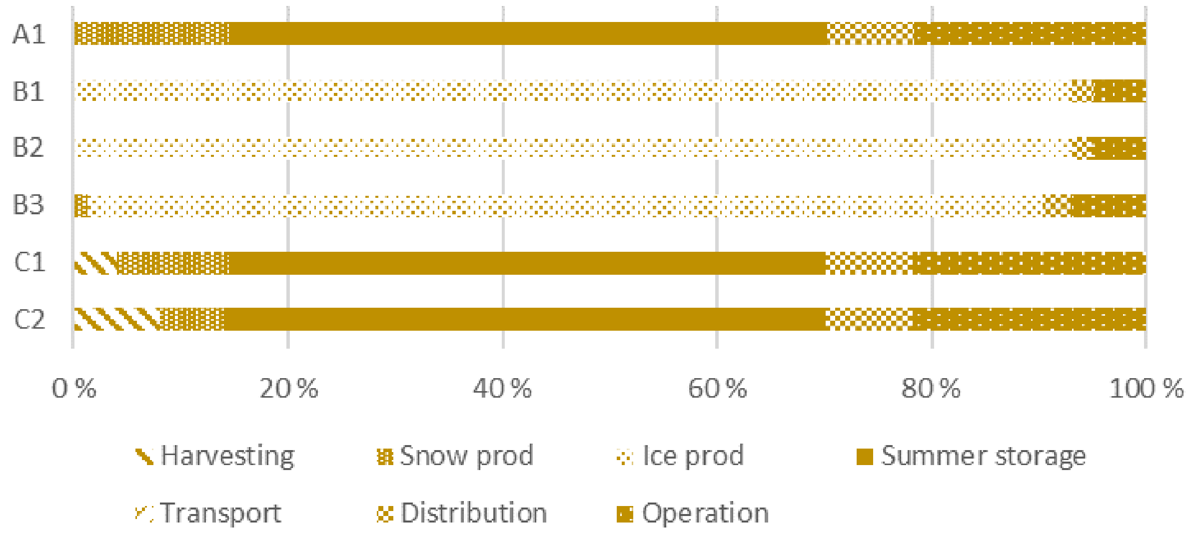

Figure 28 – Percentage contribution to total NOx-emissions from the different processes, using a Nordic electricity mix

Studying the structural path of NO_x emissions, we find that about 20% of the emissions linked to summer storage is from road transport, which is a stressor that affects the local environment in Granåsen. NO_x emissions to ice productions, on the other hand, is almost solely linked to energy production. These emissions do not directly affect the local environment, as they are linked to the production phase.

For particulate matter, we have similar results. Alternative B stands out as the significantly biggest contributor to emissions because of ice production. This is presented in Figure 29.

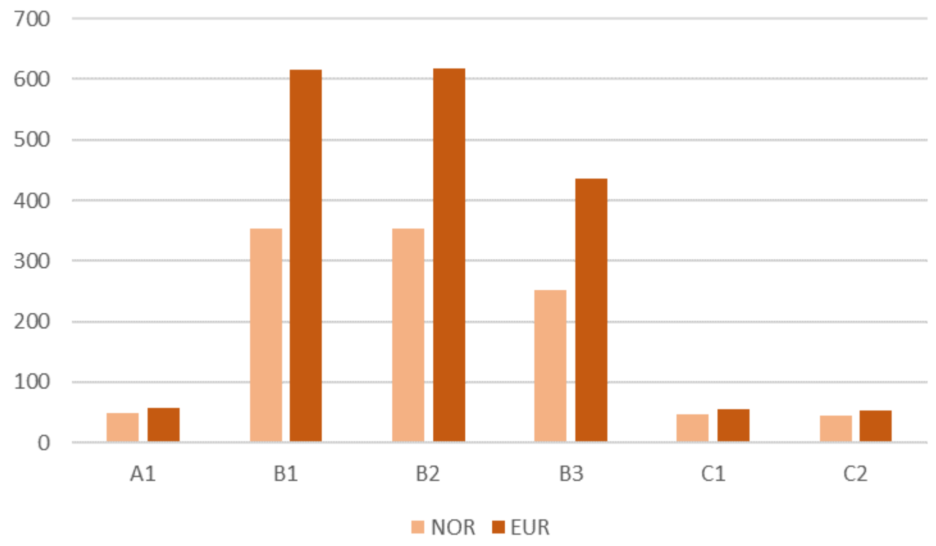

Figure 29 - PM-emissions from Nordic and European electricity mix [kg PM/yr]

Figure 30 provides a closer look at where the system PM-emissions occur.

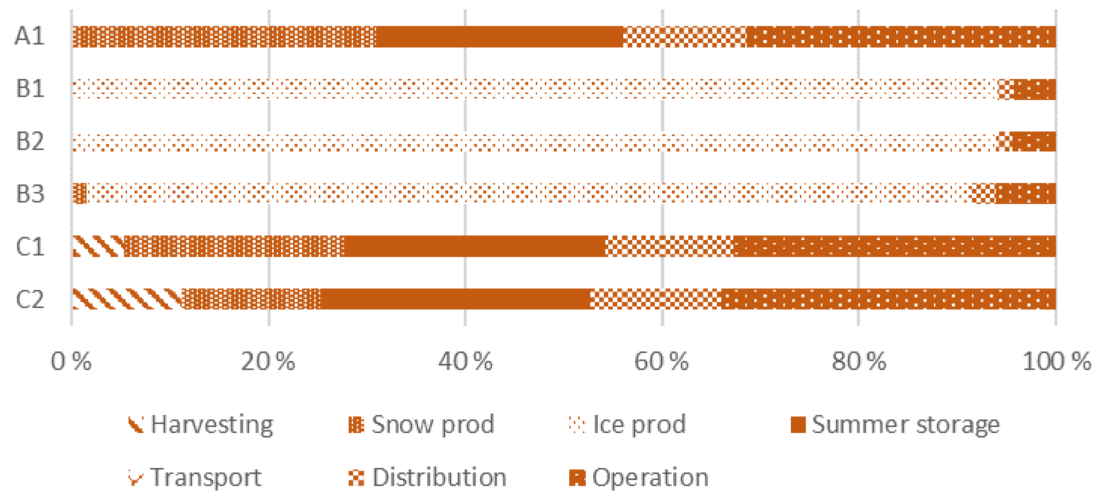

Figure 30 - Percentage contribution to total PM-emissions from the different processes, using a Nordic electricity mix

Structural path analysis of PM gives similar results than what we found with NO_x, but a smaller share of the emissions related to summer storage can be assigned to transport causing impacts on local environment. Reduced impact on local environment occur because a higher share of the pollution happens in the production phase of aluminum and electricity, which is assigned to other geographical areas. However, about 10% of the PM stems from sawdust production, which affects locally.

5. DISCUSSION

5.1 Main findings

Put together, we have this distribution of GWP from the six different alternatives studied, shown in Figure 31. This clearly illustrates the huge contribution to global warming potential stemming from ice production.

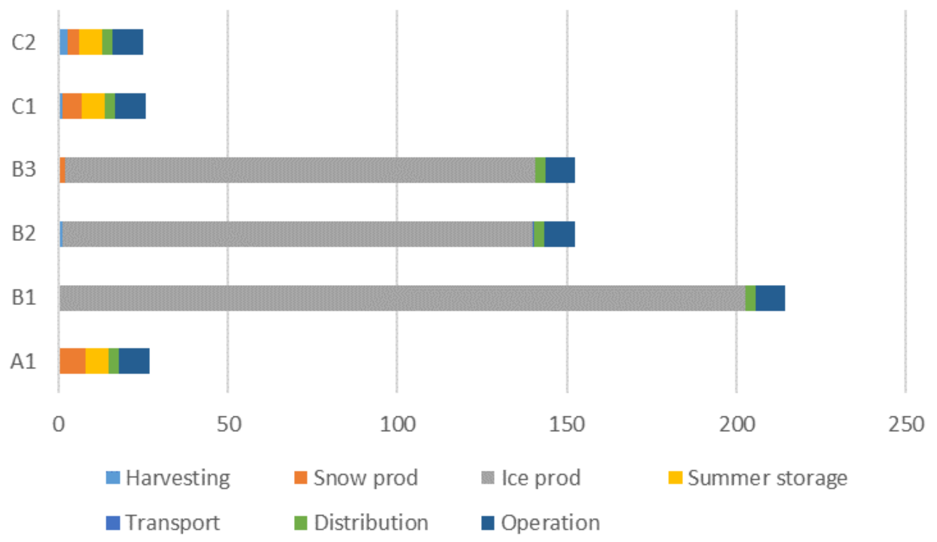

Figure 31 - Total GWP from all processes, using a Nordic electricity mix [ton CO_2/yr]

Based on the results, alternative A and C stands out as the best options for snow production when considering both global – and local environment. Considering a Nordic electricity mix, these alternatives perform on average 6,7 times better than alternative B with regard to global warming potential. C2, including a combination of snow production and harvesting for summer storage, has the best overall performance of all alternatives considered, with C1 and A1 following with marginally higher GWP.

Knowing this, we can take a closer look at the three best options with regard to impact on climate change. Alternative A1, C1 and C2 are presented in Figure 32, showing how impacts are distributed between the different processes in each alternative.

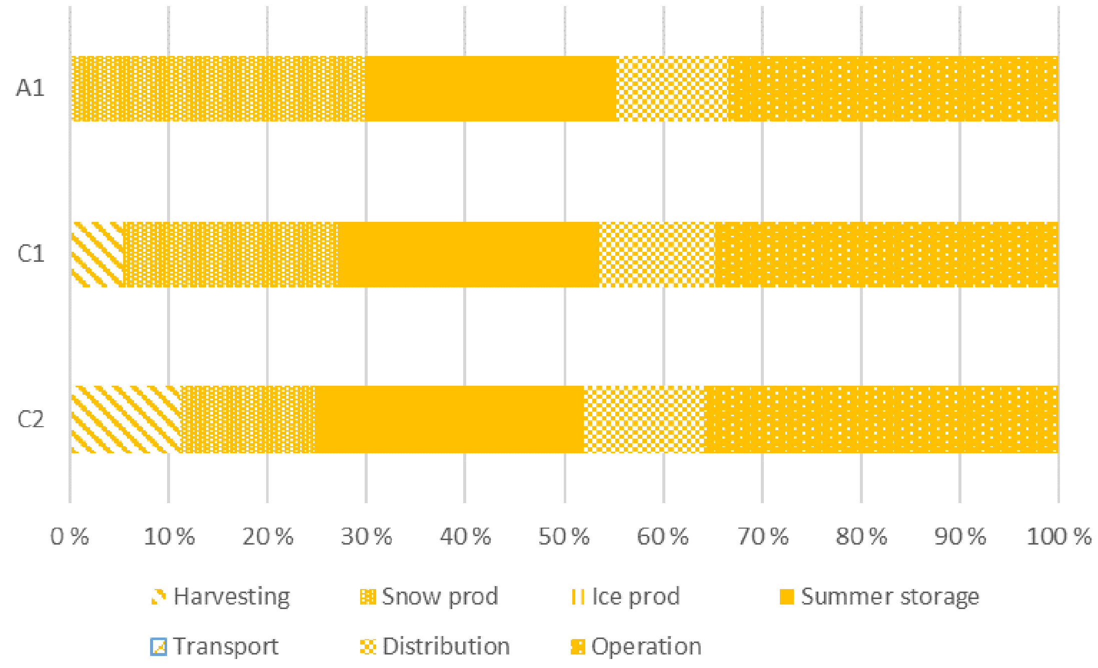

Figure 32 – Percentage distribution of greenhouse gas emissions between processes for alternative A1, C1 and C2, using a Nordic electricity mix

Operation of tracks during winter, involving replenishment from lances and grooming on a daily basis stands for around 35% of total contribution to climate change and is responsible for the largest impact in all three alternatives. Transport – and production of sawdust for summer storage, causes a 25% contribution. Harvesting and snow production stands for between 25% and 30% of the total GWP together, with decreasing impact the more is being harvested. The distribution process is 10% to 15% of total GWP.

The environmental impact related to these options for snow production is generally low. With an average GWP of 26 ton CO_2-eq, the emissions related to a full snow season equals the annual energy consumption of less than three average Norwegian citizens [41]. An almost negligible difference between the three alternatives, in addition to generally low emissions linked to each of them, opens for a freer discussion on which alternative to choose as the best method for snow production in the case studied.

In Granåsen today, a combination of snow production, harvesting and summer storage is conducted. Based on personal communication with the operations team in Granåsen, it is promoted desire for a less labor-intensive process. Given the results from the LCA analysis, a process that exclude the labor-intensive harvesting process and produce all the snow directly in the summer storage is an alternative that could be considered in line with today's methods, with respect to GWP and local air pollutants. This will reduce labor use, and the impacts on climate change from such restructuring will be negligible. Excluding the harvesting process means higher electricity costs linked to increased snow production, but will, on the other hand, decrease costs linked to machinery use and labor costs.

An illustration of the significant correlation between electricity use and GWP is shown in Figure 33. The correlation is stronger than anticipated, making electricity use the by far biggest contributor to environmental impacts in this case. Prior to a future Nordic World Ski Championship, Granåsen is going to invest in new improved snow production systems. Automated machinery that is less labor-intensive and more effective will be prioritized. When decisions are to be made upon which investments to be done, the certainty that electricity is the biggest contributor to environmental impact will be highly relevant.

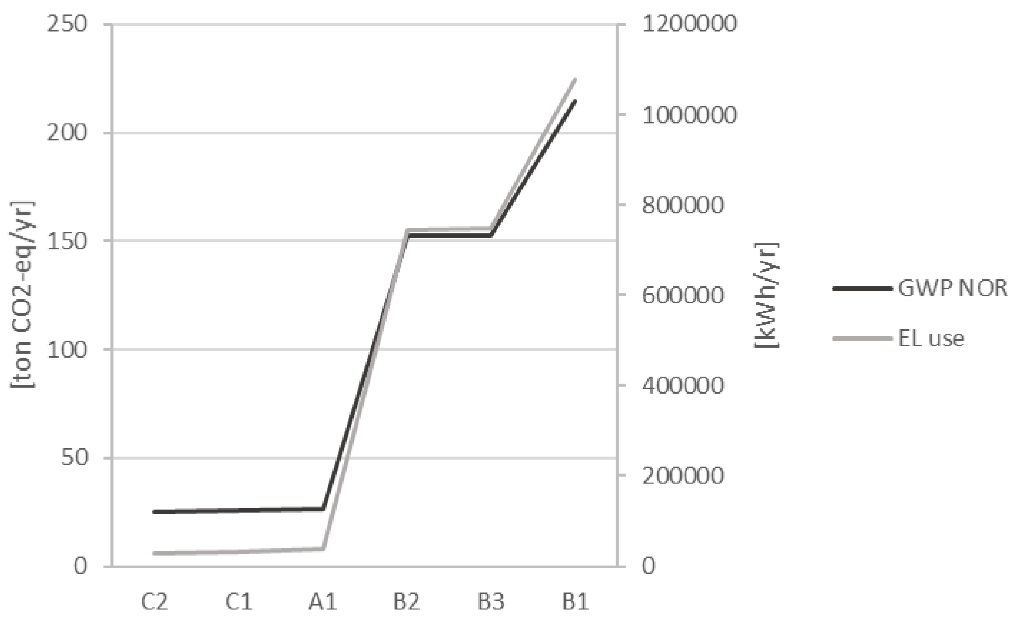

Figure 33 - Correlation between GWP and el-use, sorted with respect to performance

Fuel consumption, which initially was assumed to have the main impact on the results beside energy use, seem to be an almost negligible contributor to the total GWP in the case studied. We know that emissions from a Nordic electricity-mix are linked to the production process, not the use phase. Fuel consumption differ from electricity in this sense because it highly affects the local environment when the fuel is burned. The large share of impact stemming from electricity rather than fuel consumption do therefore inflict reduced impacts on local environment. This corresponds to the results on NO_x and PM emissions.

Ice production is responsible for the biggest contribution to global warming potential. The energy intensive process of ice production as an alternative to a combination of harvesting and/or snow production with summer storage leads to large environmental impacts. This matches with other studies on this field, which ascertain that this technology is too energy intensive to be a perfect substitute for the conventional methods [42].

The reference scenario, considering 100% ice production (B1) is the most energy intensive alternative considered, where a majority of GWP is related to electricity production alone. When changing a fraction of ice production with long distance snow harvesting or snow production, GWP is reduced to some extent. Here, a transport distance of 40 km both ways was considered. Based on this, it could be of interest to see how far it will be possible to harvest snow and still outperform the alternative entirely based on ice production.

Despite knowing that ice production causes larger impacts on the environment, the possibility of being able to produce snow independent of air temperature is highly valuable. Considering the fact that Granåsen probably will be hosting a Nordic World Ski Championship in the near future, ice production can serve as a necessary backup if periods of extreme temperatures increases melting and thus limits the possibilities for snow production. Another important strength of ice production worth mentioning is the low operation requirements, making it possible to produce the same amount of snow in a significantly lower number of labor hours. The valuation of labor efficiency relative to environmental impact depends on the interests of the decision makers.

5.2 Perspective

How big are the impacts from one snow season in Granåsen? Although the biggest share of users of the ski arena in Granåsen use it for recreational reasons, a significant share is athletes at all ages that use the tracks for training towards competitions and championships. For them, Granåsen provides necessary training facilities prior to – and during winter season. If these facilities are not provided in Trondheim, some of these athletes will therefore need to travel for longer distances to find snow. Lillehammer and Oslo are destinations relevant to consider as substitutes in this case. Longer travels could also be considered more often in the absence of predictable snow conditions locally. Hypotetically, one can assume that travels to e.g. the Austrian Alps to combine good snow conditions and altitude training increases. To put the impacts from providing one snow season in Granåsen into perspective, the CO_2-equivalents emitted during one full season of operation equals about 70 round trips to München, which is one of the typical destinations when flying to the Alps [43]. In comparison, this equals about 450 round trips from Trondheim to Oslo in a Ford Fiesta with diesel motor, assuming two passengers per car [44]. Doing the same comparison with respect to local transport, we find that total annual emissions from operating the system equals 22 500 round trips to Granåsen from Trondheim city center. Divided by the season length, set to181 days, this equals 124 cars per day on average [44].

5.3 Further work

A modelling of the real world will always be associated with uncertainties. Recommendations for further work to reduce these differences follows:

- **Inventory development**

A development of the inventory provided in the EcoInvent database would be valuable in further investigation. As discussed in chapter 3.7, the database has significant limitations in data availability, making a model highly dependent on assumptions. All assumptions are associated with uncertainties, but these can be largely reduced if an improved inventory database is accessible.

- **Logistics**

It would be beneficial to have better data on how the logistics in Granåsen is done. Today, it only exists information about working hours, which is very uncertain because we don't know the exact time when machinery is operating. In comparison, data providing information about fuel consumption would be a better measurement.

- **Socioeconomic analyze of the Granåsen performance**

Following from the comparison done in chapter 5.2, a socioeconomic analyze of Granåsen as a part of the cityscape would be interesting to look at in further work. With total environmental emissions equal to a daily travel of 124 cars to Granåsen, an analyze of possible methods for reduction in car transport will possibly have a larger potential for improvements due to GWP than any improvements in the snow production system in Granåsen itself. Such an extension of the system boundaries will give a wider overview of where it is appropriate to focus on improvements with respect to environmental impacts.

6. CONCLUSION

As presented in the literature chapter, temperatures are predicted to increase towards 2100, following from global warming. For snow production, this will require methods that makes it possible to provide snow in temperatures down to zero degrees Celsius. Most important, the ability to adapt to climatic changes without creating new problems for the future will be of big importance. Environmental analysis of the system performance is therefore valuable and should be conducted when deciding on new investments.

In the case of Granåsen, environmental impacts from operating one snow season is low. This case study has analyzed alternatives considering different combinations of snow harvesting, snow – and ice production. From an environmental perspective, production with a long time horizon involving summer storage of snow from one season to the next is preferred due to significantly lower emissions than that of ice production. Further, the environmental differences between an alternative based entirely on snow production and an alternative that includes harvesting is negligible. The operation team in Granåsen wants to minimize the comprehensive logistics linked to operation of the system. From this, a strategy based entirely on snow production and summer storage is recommended. From an environmental perspective, on the other hand, a strategy involving harvesting of the tracks for summer storage in combination with snow production is the best option. However, the difference between the two are negligible and the decision on which solution to choose is a question of valuation that should be done by decision makers.

Electricity use is the definitely largest contributor to GWP. Knowledge about the strong correlation between el-use and GWP is important when decisions on further investments are done, because energy efficient solutions will be preferred from an environmental perspective.

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APPENDIX

A – Calculations, size of storage and grooming

GRANÅSEN		
tracks	3300 m	Google maps
stadium	1700 m	Google maps
width	6 m	*Finnland, V. & Arnesen, H. (March 2017)*
depth	0,5 m	*Finnland, V. & Arnesen, H. (March 2017)*
snow requirement, excl. Stadium	9900 m3	
snow requirement, inkl. Stadium	15000 m3	
melting rate, summer storage	20 %	*Finnland, V. & Arnesen, H. (March 2017)*
total snow requirement for storage	**18750 m3**	

SNOW STORAGE		
	37500 m3	
r^2	2985,67 m	
r	54,64 m	
volume, hemisphere	341507,96 m3	
r with sawdust	55,04 m	
volume, hemisphere with sawdust	344000,00 m3	
total requirement, sawdust	**2492,04 m3**	

SEASON		
01.nov - 30.apr	181 days	Assumption
total length, tracks	5 km	
functional unit	**181 days**	
equal to	**1 snow season**	

GROOMING		
fuel consumption, Prinoth groomer	17,5 l/hour	*Ødegård, R. S. (2014)*
average speed	10 km/hour	*Finnland, V. & Arnesen, H. (March 2017)*
working width, Prinoth groomer	4,5 m	*"Prinoth - technical data"*
total tråkkelengde derfor	10 km	
totalt forbruk, full løypelengde	14,7 kg	

B – Calculations, harvesting

HARVESTING (10002)			
Prinoth groomer	76	hours	*Vagle, B. H. (2016)*
lifetime	10000	hours	EcoInvent 3.2
assumed working rate	0,8		Assumption
fuel consumption	17,5	l/hour	*Ødegård, R. S. (2014)*
total fuel consumption	**894**	**kg**	
production share	**0,0076**	**unit**	
lorry, wille & aibi	88	hours	*Vagle, B. H. (2016)*
lifetime	10000	hours	EcoInvent 3.2
assumed working rate	0,5		Assumption
storage capacity, lorry	16,5	m3	*Vagle, B. H. (2016)*
snow, total	15000	m3	
number of truckloads	909	pc	
average distance, storage to tracks (t/r)	0,7	km	Google maps
total distance	636	km	
fuel consumption	0,45	l/km	*Ødegård, R. S. (2014)*
speed	15	km/h	Assumption
total fuel consumption	**249**	**kg**	
production share	**0,0088**	**unit**	
tractor & trailer	70	hours	*Vagle, B. H. (2016)*
lifetime, tractor	7000	hours	EcoInvent 3.2
weight, tractor	3000	kg	EcoInvent 3.2
lifetime, trailer	1200	hours	EcoInvent 3.2
weight, trailer	1500	kg	EcoInvent 3.2
fuel consumption	0,45	l/km	Assumption
speed	15	km/h	Assumption
total fuel consumption, tractor & trailer	**318**	**kg**	
production share, tractor	**30**	**kg**	
production share, trailer	**88**	**kg**	
wheel loader	111	hours	*Vagle, B. H. (2016)*
lifetime	10000	hours	EcoInvent 3.2 (for lorry)
assumed working rate	0,8		Assumption
speed	10	km/h	Assumption
size share relative to lorry	0,25		EcoInvent 3.2 (for lorry)
total fuel consumption	**336**	**kg**	
production share	**0,0022**	**unit**	
excavator, 8T	35	hours	*Vagle, B. H. (2016)*
excavator, 30T	60	hours	*Vagle, B. H. (2016)*
lifetime	10000	hours	EcoInvent 3.2
assumed working rate	0,8		Assumption
fuel consumption	15	l/hour	*Ødegård, R. S. (2014)*
total fuel consumption	**958**	**kg**	
prod.share, 8T	**0,0035**	**unit**	
prod.share, 30T	**0,006**	**unit**	
SUMMARIZE			
prod.share lorry, wille & aebi	0,0088	unit	
prod.share wheel loader	0,0022	unit	
	0,0110	unit	
operation, wheel loader	336	kg	
operation, groomer	894	kg	
operation, tractor and trailer	318	kg	
operation, excavator	958	kg	
operation, lorry, wille&aibi	249	kg	
	2754	kg	
prod.share, excavator 8T	0,0035	unit	
prod.share, excavator 30T	0,006	unit	
	0,0095	unit	

C – Calculations, snow – and ice production

SNOW PRODUCTION (10003)			
aluminium weight, fan gun	537	kg	*"Info, fan guns" Retrieved from Finnland, V. (March 2017)*
el.use, fan gun	22	kW	*"Info, fan guns" Retrieved from Finnland, V. (March 2017)*
production efficiency, fan gun	60	m3/hour	*"Info, fan guns" Retrieved from Finnland, V. (March 2017)*
energy use, m3	0,367	kWh/m3	
energy use, season	6875	kWh/season	
number of fan guns	8	pc	*Finnland, V. & Arnesen, H. (March 2017)*
lifetime, fan gun	10	years	
lifetime, fan gun	87600	hours	
total aluminium, fan guns	4296	kg	*"Info, fan guns" Retrieved from Finnland, V. (March 2017)*
aluminium per year, fan gun	430	kg	
energy use, pumps	18769	kWh	
B3: snowprod.	5000	m3	
total req, inkl snow melt	18750	m3	
5000 m3 - share of total req	26,7	%	
C1: snowprod.	13750	m3	
13750 m3 - share of total req	73,3	%	
C2: snowprod.	8750,0	m3	
8750 m3 - share of total req	46,7	%	

SUMMARIZE, ALU PR. SEASON		
electricity use, fan guns	6875	kWh
electricity use, water pumps	7734	kWh
	14609	kWh

ICE PRODUCTION (10004)			
production efficiency, SF220	220	m3/day	*Vagle, B. H. (2016)*
	9	m3/hour	
el.use, SF220	227	kW	*Vagle, B. H. (2016)*
energy use, m3	24,76	kWh/m3	
snow requirement, year	15000	m3	
melting rate	5	%	Assumption
total snow requirement, year	15789	m3	
production days	72	days	
	1722	hours	
el-req per m3	24,76	kWh/m3	*Vagle, B. H. (2016)*
lifetime, heat exchanger	10000	hours	EcoInvent 3.2
size, heat exchanger (relative to inventory)	1,5		Assumption based on kWh
(inventory size)	160,0	kW	EcoInvent 3.2
(size, studied heat exchanger)	227,0	kW	*Pircher, P. (March 2017)*
prod.share, heat exchanger	0,258	unit	
production share per m3	0,00002	unit	
weight, SF220	30000	kg steel	*Pircher, P. (March 2017)*
lifetime, steel	20	years	EcoInvent 3.2
	175200	hours	
total production, lifetime	1606000	m3	
prod.share per m3, SF220	0,0187	kg/m3	
	0,17		
prod.share steel per m3	0,0000057	unit	
B1:			
steel, pumps	0,0015	kg	
el.required	42,0000	kWh/m3	

SUMMARIZE, B1		
steel, SF220	0,0187	kg
steel, pumps	0,0015	kg
	0,0202	**kg**
electricity req, SF220	24,76	kWh/m3
electricity req, pumps	42,00	kWh/m3
	66,76	**kWh/m3**

SUMMARIZE, B2		
steel, SF220	0,0187	kg
steel, pumps	0,0022	kg
	0,0209	**kg**
electricity req, SF220	24,76	kWh/m3
electricity req, pumps	42,00	

D – Calculations, summer storage and transport

SUMMER STORAGE (10005)			
Kjelstad sawmill - Granåsen	71	km	Google maps
capacity, lorry transport	110	m3	*Simonsen, A. (March 2017)*
number of loads required	23	pc	
average speed	60	km/h	Assumption
total time required	1608	minutes	
	27	hours	
lifetime, lorry	10000	hours	EcoInvent 3.2
prod.share to sawdust transport	0,0027	units	
density, diesel	0,84	kg/l	
fuel consumption, lorry (110m3)	0,45	l/km	*Simonsen, A. (March 2017)*
fuel consumption, Skevig	1216	kg	

TRANSPORT (10006)			
distance, Granåsen-Vassfjellet	20	km	Google Maps
capacity, lorry transport	110	m3	*Simonsen, A. (March 2017)*
fuel consumption	0,45	l/km	*Simonsen, A. (March 2017)*
speed	60	km/hour	Assumption
density, diesel	0,84	kg/liter	
fuel consumption /m3 snow	0,14	kg	
lifetime, lorry	10000,00	hours	EcoInvent 3.2
hours /lorry load	0,67	hours	
time /m3 snow	0,006	hours/m3	
prod.share, lorry	0,00000061	unit	

E – Calculations, Distribution

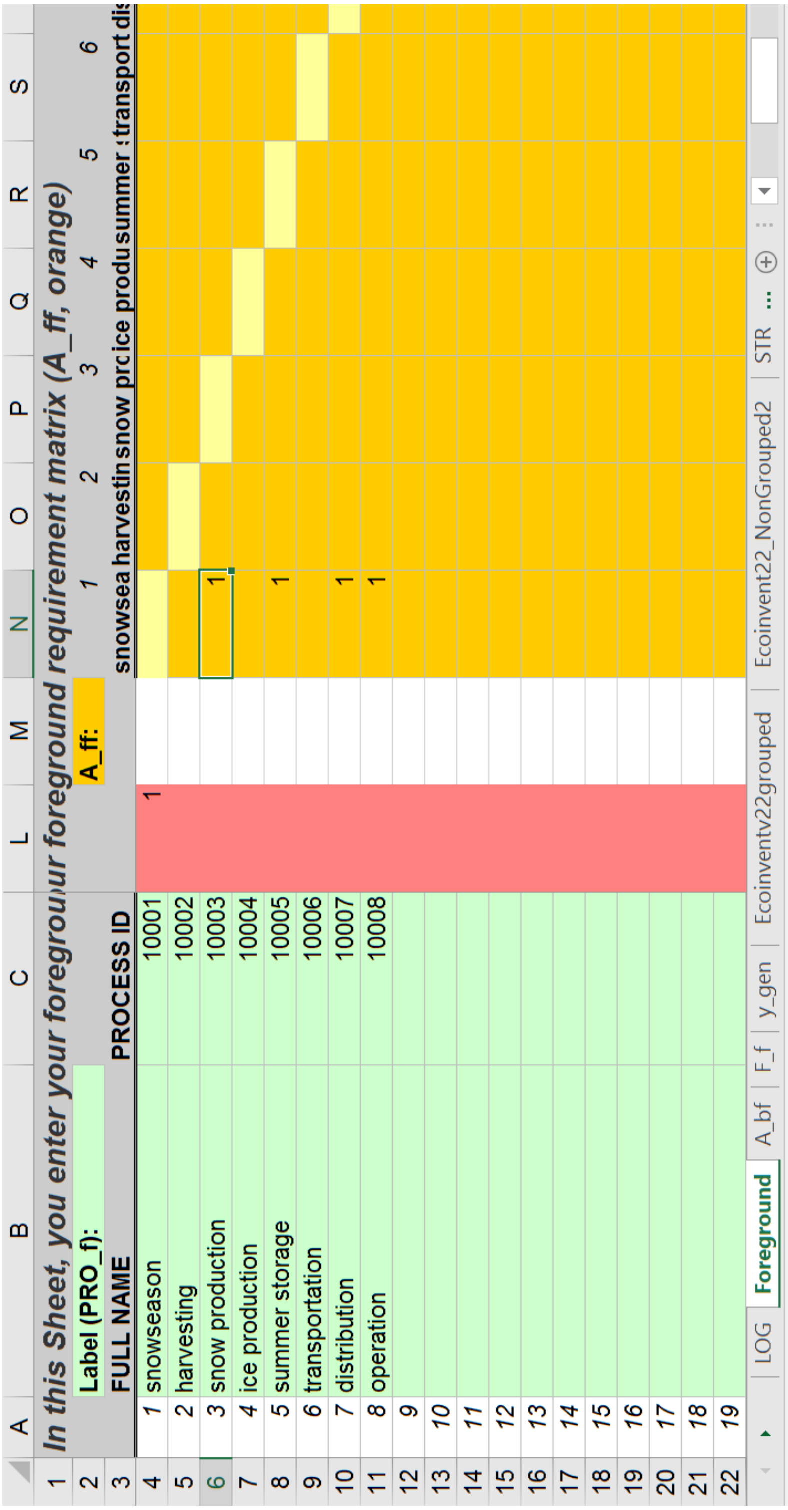
DISTRIBUTION (10007)			
lorry	91	hours	*Vagle, B. H. (2016)*
driving share	0,5		Assumption
speed	15	km/hour	Assumption
fuel consumption, lorry distribution	258	kg	
lifetime, lorry	10000	hours	EcoInvent 3.2
prod.share, distribution	0,0091		
fuel consumption, distribution	0,45	l/km	
excavator	86	hours	
lifetime, excavator	10000	hours	EcoInvent 3.2
prod.share, distribution	0,0086		
fuel consumption	15	l/hour	*Ødegård, R. S. (2014)*
work share	0,8		Assumption
total fuel consumption, excavator	867	kg	
wheel loader	43	hours	*Vagle, B. H. (2016)*
driving share	0,8		Assumption
speed	10	km/hour	Assumption
fuel consumption	0,45	l/km	Assumption
total fuel consumption, wheel loader	130	kg	
prod.share, wheel loader	0,25		EcoInvent 3.2 (of lorry)
lifetime	10000	timer	EcoInvent 3.2 (of lorry)
prod.share knyttet til distribution	0,0009	unit	
groomer	54	hours	*Vagle, B. H. (2016)*
lifetime	10000	timer	Assumption
prod.share, distribution	0,005		
driving share	0,8		Assumption
fuel consumption, groomer	17,5	l/hour	*Ødegård, R. S. (2014)*
total fuel consumption, groomer	635	kg	
tractor with trailer	142	hours	*Vagle, B. H. (2016)*
tractor, weight	3000	kg	EcoInvent 3.2
lifetime	7000	hours	EcoInvent 3.2
trailer, weight	1500	kg	EcoInvent 3.2
lifetime	1200	hours	EcoInvent 3.2
prod.share, distribution tractor	61	kg	
prod.share, distribution trailer	178	kg	
fuel consumption	0,45	l/km	Assumption
speed	15	km/hour	Assumption
work share	0,5		Assumption
total fuel consumption, tractor w.trailer	403	kg	
SUMMARIZE			
prod.share, lorry	0,0091	unit	
prod.share, wheel loader	0,0009	unit	
	0,01	**unit**	
operation, wheel loader	130	kg	
operation, groomer	635	kg	
operation, tractor and trailer	403	kg	
operation, excavator	867	kg	
operation, lorry	258	kg	
	2293	**kg**	

F – Calculations, operation

OPERATION (10008)			
groomer	1	hour/day	
lifetime	10000	hours	Assumption
fuel consumption, groomer	17,5	l/hour	*Ødegård, R. S. (2014)*
speed	10	km/hour	*Finnland, V. & Arnesen, H. (March 2017)*
width, groomer	4,5	m	*"Prinoth - technical data"*
total distance	10	km	
total fuel consumption, tracks	14,7	kg	
total fuel consumption, season	2660,7	kg	
working hours, season	181	time	
prod.share, season	0,0181	unit	
snowmobile	1	hour/day	*Finnland, V. (March 2017)*
working hours, season	181	hours	
fuel consumption	10	l/hour	
total fuel consumption	1520	kg	
lifetime	10000	hours	Assumption
share, size of groomer	0,2		Assumption
prod.share, season, snowmobile	0,0036		
alu.weight, lance	42	kg	*"Info lance" Retrieved from Finnland, V. (March 2017)*
weight, compressor, Granåsen	1500	kg	*Klette, R. (May 2017)*
weight, compressor, EcoInvent	4600	kg	EcoInvent 3.2
share Granåsen vs EcoInvent	0,3		
lifetime, compressor	10	years	Assumption
prod.share, season	0,03		
el-use, compressor	128,2	kW	*Atlas Copco - Instructionsbok (2013)*
number of lances	25	pc	*Finnland, V. & Arnesen, H. (March 2017)*
lifetime	10	years	Assumption
alu.tot, lances	1050	kg	
alu/year, lance	105	kg	
compressor	110	kW	*Klette, R. (May 2017)*
prod.share, lance per season	3000	m3	Assumption
prod.efficiency	15	m3/hour	*"Info lance" Retrieved from Finnland, V. (March 2017)*
hours used	200	hours	
el-use, season	22000	kWh/season	

SUMMARIZE		
building machine, groomer	0,0181	unit
building machine, snowmobile (0,2* groomer)	0,0036	unit
	0,02172	unit
diesel, groomer	2660,7	kg
diesel, snowmobile	1520	kg
	4181,1	kg
electricity use, compressor	22000	kWh
electricity use, pumps	1650	kWh
	23650	kWh

G – Arda inventory, foreground (represented by alt.A1)



	A	B	C	L	M	N	O	P	Q	R	S
1	In this Sheet, you enter your foregrouur foreground requirement matrix (A_ff, orange)										
2		Label (PRO_f):			A_ff:	1	2	3	4	5	6
3		FULL NAME	PROCESS ID			snowsea	harvestin	snow prc	ice produ	summer s	transport dis
4	1	snowseason	10001	1							
5	2	harvesting	10002								
6	3	snow production	10003			1					
7	4	ice production	10004								
8	5	summer storage	10005			1					
9	6	transportation	10006								
10	7	distribution	10007			1					
11	8	operation	10008			1					
12	9										
13	10										
14	11										
15	12										
16	13										
17	14										
18	15										
19	16										
20	17										
21	18										
22	19										

H – Arda inventory, background

	A	B	C	D	E	F	G	
1	*In this sheet, you enter the coordinates of the requirements placed on the background by the foreground. This will be assembled*							
2								
3	**Background Name**	**Foreground Process Name**	**(Arda ID)**	**(Process ID)**		**Unit**		
4	*Comment*	*Comment*	**BACKGROUND ID**	**FOREGROUND ID**	**AMOUNT**	*Comment*	*Comment*	*Co*
5	lorry 16t/ RER/ unit	lorry, wille & aebi, wheel loader	3947	10002	0,011	unit	(sesong)	
6	diesel, at regional storage/ RER/ kg	operation, wheel loader, groomer, tr	2343	10002	2754	kg	(sesong)	
7	building machine/ RER/ unit	groomer	3659	10002	0,0076	unit	(sesong)	
8	tractor, production/ CH/ kg	tractor, prod	3624	10002	30	kg	(sesong)	
9	trailer, production/ CH/ kg	trailer, prod	3625	10002	88	kg	(sesong)	
10	hydraulic digger/ RER/ unit	excavator, 8T and 30T	3658	10002	0,0095	unit	(sesong)	
11	aluminium, primary, at plant/ RER/ kg	aluminium, fan gun	1755	10003	430	kg	sesong	
12	electricity, low voltage, production NORDEL, a	el-use season, fan gun and pumps	961	10003	14609	kWh	sesong	
13	heat exchanger of cogen unit 160kWe/ RER/ u	snowfactory, prod, heat exchanger	3781	10004	0,0001	unit	m3	
14	steel, low-alloyed, at plant/ RER/ kg	snowfactory, prod, steel	1914	10004	0,0187	kg	m3	
15	electricity, low voltage, production NORDEL, a	el-use per m3	961	10004	24,76	kWh	m3	
16	sawdust, Scandinavian softwood (plant-debarl	sawdust	3568	10005	2492	m3	sesong	
17	lorry 40t/ RER/ unit	lorry	3949	10005	0,0027	unit	sesong	
18	diesel, at regional storage/ RER/ kg	operation, lorry	2343	10005	1216	kg	sesong	
19	lorry 40t/ RER/ unit	lorry, transport	3949	10006	0,00000061	unit	m3	
20	diesel, at regional storage/ RER/ kg	operation, lorry per m3	2343	10006	0,14	kg	m3	
21	lorry 16t/ RER/ unit	lorry, wheel loader	3947	10007	0,01	unit	sesong	
22	diesel, at regional storage/ RER/ kg	operation, wheel loader, groomer, tr	2343	10007	2293	kg	sesong	
23	building machine/ RER/ unit	groomer	3659	10007	0,005	unit	sesong	
24	tractor, production/ CH/ kg	tractor, prod	3624	10007	61	kg	sesong	
25	trailer, production/ CH/ kg	trailer, prod	3625	10007	178	kg	sesong	
26	hydraulic digger/ RER/ unit	excavator, 30t	3658	10007	0,0086	unit	sesong	
27	building machine/ RER/ unit	groomer & snowmobile	3659	10008	0,02172	unit	sesong	
28	diesel, at regional storage/ RER/ kg	groomer & snowmobile, operation	2343	10008	4181,1	kg	sesong	
29	aluminium, primary, at plant/ RER/ kg	aluminium, lance	1755	10008	105	kg	sesong	
30	air compressor, screw-type compressor, 300	air compressor	3711	10008	0,03	unit	sesong	
31	chromium steel 18/8, at plant/ RER/ kg	steel use, pumps	1779	10008	24	kg	sesong	
32	electricity, low voltage, production NORDEL, a	el-compressor and pumps	961	10008	23650	kWh	sesong	
33								

LOG | Foreground | A_bf | F_f | y_gen | Ecoinventv22grouped | Ecoinvent22_NonGrouped2 | STR ...