SIEPPUR
Sustainable snow management

Co-funded by
the European Union

Roadmap to Sustainable Snow Management for European mid-mountain Nordic venues

Medium Latitude - Medium Altitude

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IBU · Peak63 OUTDOOR LAB · SLF · SMA SUSTAINABLE MOUNTAIN ALLIANCE · POLSKI ZWIĄZEK BIATHLONU POLISH BIATHLON ASSOCIATION · SLOSKI Biathlon · SWE

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1. OVERALL ROADMAP TO SUSTAINABLE SNOW MANAGEMENT

The overall roadmap, as developed in D3.1, laid out a comprehensive, generalised strategy for transitioning current snow management practices into a more sustainable, more efficient, and increasingly climate-resilient framework. Developed to address the ecological, societal, and operational challenges facing snow management, the overall roadmap identified the necessary transformations across snow production, storage, transportation, grooming and handling on a broad basis. It also examined overarching governance practices and the socio-economic context within which these activities occur.

2. ELABORATED GEOGRAPHY-SPECIFIC ROADMAPS TO SUSTAINABLE SNOW MANAGEMENT

The overall roadmap to sustainable snow management serves as a common strategy, upon which more specific snow management activities and strategies, as well as different governance practices were investigated considering the geographical regions with their different constraints as follows:

- Alps venues (high altitude, low latitude)
- Scandinavian venues (low altitude - high latitude)
- Central & Eastern European mid-mountain venues (mid altitude - mid latitude)

Like the overall roadmap, the geography-specific roadmaps aim to ensure a transition towards resource-efficient operations, reduced environmental impacts, and increased societal acceptance of modern snow management practices, ensuring the long-term sustainability of snow sports venues and events under the purview of the International Biathlon Union (IBU). Key components of this transition are operational activities, as well as the incorporation of governance practices which enable effective decision-making, infrastructure development, and technology adoption and development.

Key factors that must be addressed include:

- Understanding the **microclimate** of each venue to evaluate the site-specific snow production potential and snow reliability.
- Assessing **water availability** for snow production and addressing hydrological constraints, as well as influencing venue-specific technical factors.
- Resolving potential **ecological conflicts** arising from snow management infrastructure and practices.
- Overcoming **socio-economic** barriers, including financing and societal acceptance of resource-intensive venues.

Beyond the generalised concepts formulated in the overall roadmap, the geography-specific roadmaps integrate more specific research carried out in the SIEPPUR project to gain new knowledge (T3.2 to T3.5) on snow production, storage, transport, grooming and handling. Moreover, good governance practices typical for the three geographical regions are presented in D3.5 and integrated with the roadmap description.

3. ROADMAP TO SUSTAINABLE SNOW MANAGEMENT FOR EUROPEAN MID- MOUNTAIN VENUES

Snow management at European mid mountains venues faces three major challenges:

1) Warming climate without persistent natural snow covers and limited snow production potential.
2) Limited societal and economic relevance of Nordic winter sports and therefore limited availability of funding and lack of viable operating models.
3) Environmental conflicts preventing snow management infrastructure expansion.

PRODUCTION

2025 STATE

- 2 ... 4 kWh/m³
- 70% renewable
- Water flow: 10 ... 170 m³/h
- Water limitations
- High level of know-how

OPERATIONAL PROCESSES, TOOLS & TECHNOLOGY	· Infrastructure optimisation adapted to venues, climate, hydrology, flora & fauna · Resource use monitoring with management software · Delivery risk & production planning tool (management software)
CLIMATE, SNOW & HYDROLOGY	· Microclimatological descriptions of venue · Production potential model · Hydrological constraints of a venue · Water availability model (prospections) · Snow reliability model (prospections)
GOVERNANCE PRACTICES	· Fast approval procedures · Funded compensation for landowner · Federal funding to expand/renew infrastructure · Clear rules for water use concessions

2030 GOALS

- 1 ... 2 kWh/m³
- 100% renewable
- Water flow > 50 m³/h
- Sustainable water reservoirs
- Efficient optimization of existing infrastructure

STORAGE

2025 STATE

- 4 ... 6 kWh/m³
- 11 ... 45% volume loss
- 9 ... 12 EUR /m³
- Self-made cover solutions
- Considerable level of know-how

OPERATIONAL PROCESSES, TOOLS & TECHNOLOGY	· Planning tool for cost & feasibility estimation · Structural measures: access roads, soil reinforcement, storage throughs etc. · HVO fuels · Production infrastructure · New, climate & site-specific, long living, easy-to use covers
CLIMATE, SNOW & HYDROLOGY	· Microclimatological descriptions of venue · Production potential prospections · Storage loss model · Melt model for distributed storage snow (prospections) · R&D towards new cover methods
GOVERNANCE PRACTICES	· Federal regulations defining land use for snow storage · Fast approval procedures · Funded compensation for landowner

2030 GOALS

- 2 ... 3 kWh/m³
- 10 ... 30% volume loss
- 4 ... 6 EUR /m³
- Professional cover solutions
- High level of know-how

GROOMING

2025 STATE

- 1 … 3 kWh/m²
- 10 … 20% renewable
- Biofuels costly or unavailable
- E-groomers limited range
- High level of know-how

OPERATIONAL PROCESSES, TOOLS & TECHNOLOGY	· HVO fuels · Automated snow height measurement · Fleet management tools for resource monitoring · Groundwork to minimize snow and off-season use · Automated grooming param. to max. track quality · E-groomer
CLIMATE, SNOW & HYDROLOGY	· Weather data / forecasting for automated grooming management · Improve understanding of snow strengthening due to grooming and weather interaction
GOVERNANCE PRACTICES	· Fiscal stimulus using HVO (equal prices as fossil fuels) · R&D funding of industry- science collaborations

2030 GOALS

- 0.5 … 1.5 kWh/m²
- 80% renewable
- Biofuels widely used
- E-groomers well used for shorter tracks
- Advanced grooming management tools

HANDLING

2025 STATE

- Improvised practices & procedures
- Lacking tools
- Rain & melting events
- Considerable level of know-how

OPERATIONAL PROCESSES, TOOLS & TECHNOLOGY	· HVO fuels to replace fossil fuels · Small, (e)-vehicles for snow specific preparation tasks Groomer · Nature-friendly snow hardener · Snow hardening calculation tool · Snow conserving actions
CLIMATE, SNOW & HYDROLOGY	· Snow hardening model · Snow hardeners effects on soil and plants · Investigating new methods for conserving snow tracks
GOVERNANCE PRACTICES	· Application rules & guidelines for chemical hardening by national/international ski federations · Fundings to investigate effects on soil, flora and fauna using snow hardener

2030 GOALS

- Well protocolled practices & procedures
- Proper similarly tools at various venues
- Rain & melting events manageable
- High level of know-how

TRANSPORT

2025 STATE

- New, increasing task in snow management
- Fossil fuel based
- No snow conveying systems exist
- Moderate level of know-how

OPERATIONAL PROCESSES, TOOLS & TECHNOLOGY	· HVO fuels to replace fossil fuels · Groundwork/roads reducing soil damage & better access · Collect data on resources used Transport · Pneumatic conveying systems · E-vehicles powered by renewable sources
CLIMATE, SNOW & HYDROLOGY	· Soil wetness, temperature & strength monitoring/ forecasting for planning snow distribution
GOVERNANCE PRACTICES	· Fiscal stimulus using HVO (equal prices as fossil fuels)

2030 GOALS

- Well managed, minimized transport distances
- Renewable fuel based
- Pneumatic snow conveying systems
- High level of know-how

GENERAL SNOW MANAGEMENT ISSUES

2025 STATE

- Rising costs
- 24% of venues produce renewable electricity
- Poor financing of new infrastructure
- Political & societal dissents

OPERATIONAL PROCESSES, TOOLS & TECHNOLOGY	· Staff snow-how training / transfer · Information campaigns & political debate · Fees for Nordic skiing · Events & Sponsoring · Creating synergies of Nordic skiing & other touristic offers
CLIMATE, SNOW & HYDROLOGY	· Local analysis of future snow reliability and water availability · Societal role, tradition, and economic weight of Nordic skiing in the region
GOVERNANCE PRACTICES	· Funding / operation by the National Sport Association · Federal funding of venues with over-regional relevance · Finding political positions on the future of Nordic venues · National Nordic skiing consolidation plan

2030 GOALS

- Stabilizing costs
- 50% of venues produce renewable electricity
- Quantified benefits gained resource use
- Political & societal consensus

3.1 Snow Production

For the European mid mountain venues **snow production is the major mitigation technology** to sustain Nordic skiing throughout the next decades. Moreover, snow production is the **basis for snow storage**, which also has become be an indispensable component of Nordic venues' snow strategy.

European mid-mountain venues comprise a mix of smaller venues with relatively poorly developed snow production infrastructure (e.g. Notschrei, Jakucsyze, Arber), and several larger venues (e.g. Oberhof, Ruhpolding, Nove Mesto na Morave) with high-level infrastructure.

In many regions in the mid-mountains, there are **no space conflicts** with snow production infrastructure. However, **three major challenges** are notable:

1) **Political and societal will** to support Nordic snow sports exists in many regions, but not in all. Lack of recreational and touristic users.
2) **Ecological conflicts** to expand snow production infrastructure such as water reservoirs, which are key to provide high production rates to take advantage of the low number of cold days.
3) **Limited investment** available for snow production infrastructure.

3.1.1 Operational processes, tools & technology:

At several venues, **infrastructure expansion** is required considering the number of snow guns, pump capacity and water reservoirs able to reliably provide enough water. Snow production units are needed independently for on-track production and storage production as storage production must be available throughout the winter to be able to completely fill storages in most winters at present and going forward.

3.1.2 Climate, snow & hydrology:

The warming climate, especially in the warmer western European mid-mountains requires intensive production of snow to reliably provide a minimum amount of snow as core offer. At most venues natural snow can only serve as surface snow for better quality and during some weeks or in over-average winters, to provide additional skiing courses.

Water availability may differ from venue to venue although most regions have enough annual precipitation. As mid mountains venues mostly lay atop those mountains, no large water bodies are accessible. Therefore, the building of water reservoirs (mainly filled with rainwater) is a prerequisite.

Along with expanded snow production infrastructure, venues need **tools to reliably provide snow** throughout a rather short ski season. To do so, **micro-climatological characteristics of venues** need to be used to calculate **snow production volume probabilities (Fig. 2 & 3) and melting rates** over the season (November-March).* Such detailed micro-climatological studies are needed 1) to evaluate and justify investment, and 2) to plan event and snow management activities throughout the season.

To make decisions on snow production infrastructure expansion, the **site-specific hydrological constraints** should be known and developed into small-scale **hydrological models** to assess current and future water availability in detail.

* To be described in more detail in the final (legacy) SIEPPUR report

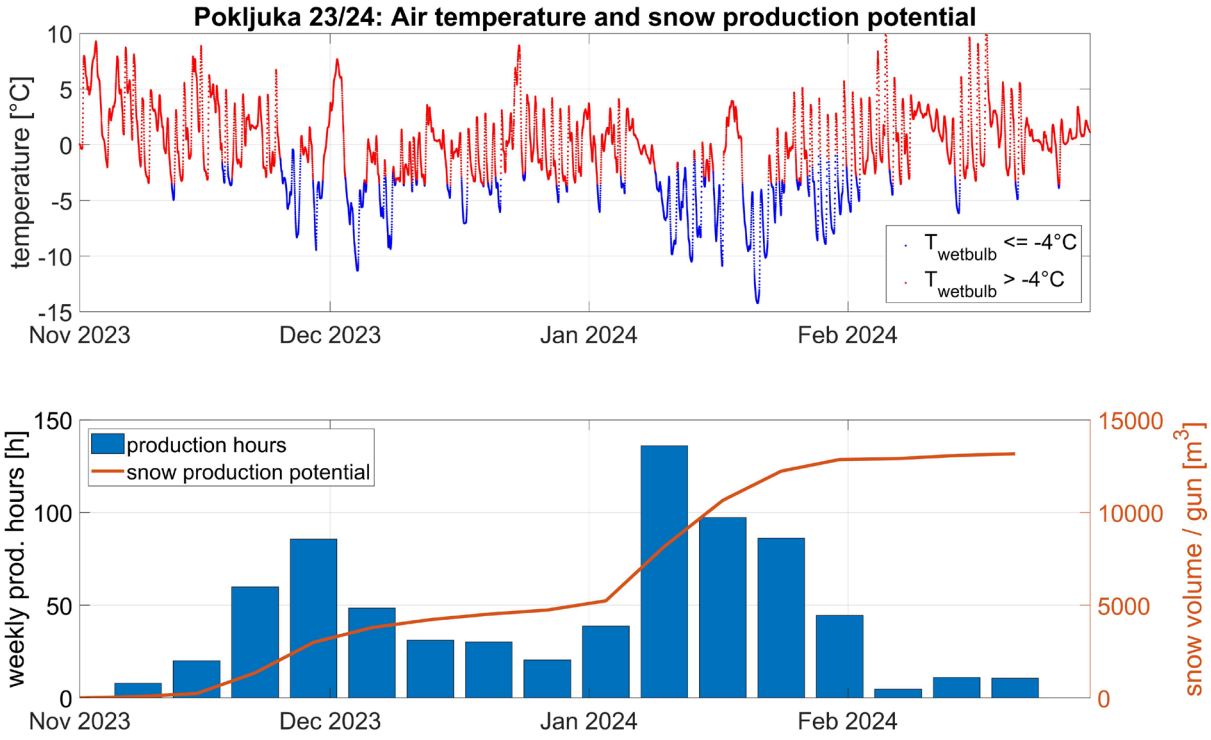

Figure 2 Example of calculated production hours and snow volume which could potentially have been produced (bottom) based on weather data (top) in Pokljuka, SLO during the season 2023/2024.

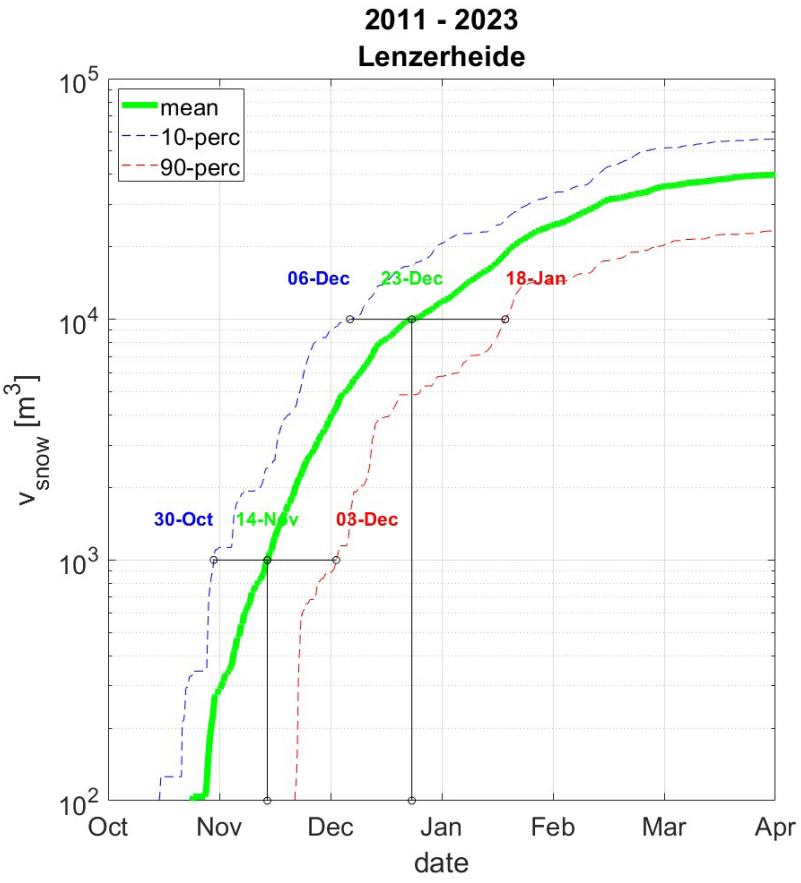

Figure 2 Figure 3 Example of calculated snow volume probabilities expected to be produced until a given date during winter at Lenzerheide based on 12-year climate data. The dashed red curve represents the accumulated produced snow volume in a warmest-case scenario (1 out of 10 winters). The green line represents the average accumulated snow volume. The dashed blue curve represents the accumulated snow volume in a coldest-case scenario (1 out of 10 winters).

3.2 Snow Storage

Snow storage will be one of the crucial adaptation measures for most Nordic ski venues in the European mid-mountains since it is an effective method providing snow in challenging climate conditions. With snow storage it is possible to utilise the cold days during the entire season for snow production. Snow storage can also buffer the annual variations in winter climate since stored snow can compensate for the lack of natural snow and cold temperatures for snow production.

3.2.1 Operational processes, tools & technology:

The Nordic ski venues in the European mid-mountains need to have extensive **production infrastructure** to generate a high productivity (snow volume per time) maximising snow produced into storage on the few cold days that allow snow production. Investment in upgraded infrastructure around storage is also necessary, such as **soil reinforcement and storage troughs**, to improve storage capacity and to minimise losses. Storage troughs also reduce the amount of space needed for snow storage.

The transportation of snow from snow storage is the most resource intensive and costly part of snow storage. To create a more efficient transportation process for stored snow, the Nordic ski venues need to have sufficient **access roads and soil reinforcements**. In general, there is space at European mid-mountain venues to update transportation roads. If possible, they can be combined with roller skiing tracks that both support heavy snow transportation vehicles and provide opportunities for roller skiing and other summer activities at the venue, enabling higher usage.

3.2.2 Climate, snow & hydrology:

As for snow production infrastructure, when considering snow storage infrastructure development or expansion, a good estimate is needed of how much snow per snow production unit can be produced in warm (worse) and cold (better) case scenarios, at present and in the next three decades. To calculate such **snow production potential projections**, regional climate change projections are required (e.g. Kotlarski et al., 2024) to incorporate appropriate estimates for temperature increase over the historical climate data.

Moreover, venues with a too warm climate for snow sport, such as is typical in the western European mid-mountains (Francois et al. 2023), **snow melt** of technical snow should be modelled to accurately describe the reliability of technical snow (e.g. Steiger et. al., 2013; Hanzer et al., 2020).

3.3 Snow Grooming

3.3.1 Operational processes, tools & technology:

To minimise the need for snow it is important that **proper groundwork that also enables off-season use** is well done. A paved road for roller skiing has both, a smooth surface requiring less snow as well providing options for year around activity. The installation of a **snow height measurement system** on snow groomers will also be a beneficial technological upgrade to optimise the distribution of the limited amounts of snow.

Nordic ski venues in European mid-mountain are recommended invest in electric groomers powered with renewable electricity to show that the operation can be fossil free and therefore improving the social acceptance of resource intensive snow management. Electric groomers will be especially suitable in the European mid-mountains where the trails will consist of rather short (up to 5 km) courses with snow production. Furthermore, electric groomers will also be cheaper to operate, reducing the cost of the ski venue.

3.4 Snow Handling

3.4.1 Operational processes, tools & technology:

Due to the increasing use of snow hardeners in the rather mild climate with little natural snow in the European mid-mountains, there is a need for nature friendly snow hardeners without negative impact on nature. As mentioned in the roadmaps for the venues in the Alps and in Scandinavia (D3.2 & D3.3), **calculation tools** are recommended for practitioners to optimally apply snow hardeners depending on weather and snow parameters.

3.4.2 Climate, snow & hydrology:

Moreover, mid mountain venues should **investigate new methods for conserving snow tracks** (reduce snow melting). One of the possible snow conserving actions might be using wind fences to reduce heat flux from warm surrounding air towards snow tracks, especially on green fields. Within this project, as a preliminary study (Fig. 4), the effect of such wind fences was investigated, and will be described in more detail within the Final Report of the SIEPPUR project.

Figure 4 Experiments on the influences of wind fences on the turbulent heat flux from the air towards the snow. Left: Overview of the experimental setup at the cross-country track made of storage snow at Livigno, ITA (31 Oct. 2025) with mobile fences and a mobile weather station to measure air temperature and humidity, solar radiation and snow temperature. Right. Heat flux measurement station located in the middle of the fences with 15 sensors revealing differences of vertical air temperature profiles with and without fences.

3.5 Snow Transport

3.5.1 Operational processes, tools & technology:

Nordic ski venues in European mid-mountain should aim to **replace fossil fuel with HVO** on all vehicles used for transporting snow, reducing the climate impact of the operations and countering the negative publicity and public opinion while improving the social acceptance of resource intensive snow management.

3.5.2 Governance practices

Soil wetness and warm temperatures strongly impact the strength of the soil. A sufficient strength of the soil is crucial for many venues to enable access to the ski courses for distributing stored snow in the early season. Moreover, soil temperatures should be below 0°C so as not to introduce additional melting from geothermal heat. Therefore, **monitoring and forecasting tools for soil wetness, temperature and strength**, which are available in some regions for agricultural purposes, should be made available for snow managers to determine the optimal day(s) for snow distribution.

3.6 General snow management issues

3.6.1 Operational processes, tools & technology:

Proactive information campaigns on snow operations, as well as on the needed, planned or desired investments in snow management infrastructure should be increasingly managed by professionals using modern communication channels and techniques. The same applies to Nordic ski club activities, offers and events. Although snow management activities are often scrutinised, the pros and cons of offensive and transparent communication are preferable compared to a “hiding” strategy with no external communication. Moreover, political debates on the future of Nordic snow sports should be initiated as in many mid-mountain Nordic ski venues decisions concerning larger investments for the next 30-year cycle have to be taken now. In addition, innovative, interdisciplinary **events and sponsoring** formats need to be developed for the near future.

3.6.2 Climate, snow & hydrology:

As described in 3.1 and 3.2, a local analysis of **future snow reliability and water availability** is crucial for enabling efficient decision making regarding future snow management strategy and related investments. Such data is also crucial on an operative level when events and snow management activities are planned throughout the season. Private consulting companies applying climate science to tourism and sport in a changing climate may fill this gap of service provision.

3.6.3 Governance practices

Given the current “on-the-edge” situation at many European mid-mountain venues characterised by already too warm climate, insufficient snow management infrastructure and lack of societal support for Nordic skiing, a stronger lead from politics (may it federal or state/regional level) might be required. This could be in form of new funding channels together with national or regional **consolidation plans** for Nordic ski activities.

4. CONCLUSION

This roadmap presents a structured approach for transforming snow management at European mid-mountain venues into a sustainable and future-fit practice that widely aligns with environmental, economic, and societal goals to address the challenges posed by resource constraints and an already today, a critically warm climate. The path forward needs to focus on three key areas: 1) innovation in snow management technology and tools, 2) the use of climate, snow and hydrological models, and 3) enhance governance practices to help Nordic skiing venues ensure long-term existence based on limited but reliable snow activities as a core offer. Moreover, new strategies and weather independent infrastructures could be opportunities to grow participation in Nordic skiing in this geographical area that is home to more than hundred million people.

The roadmap specifically names research topics that will partly be addressed in the frame of the SIEPPUR project or should be investigated in the future. However, a major part of the transformation must be carried out by decision-making focused on innovation and step-by-step improvements by the managers at European mid-mountain venues. Providing them with this mid-term strategic roadmap based on a wide base of knowledge and good practices aims to help strengthen the resilience of Nordic skiing throughout a warmer, natural snow-deprived future.

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