SIEPPUR
Sustainable snow management

Co-funded by
the European Union

Roadmap to Sustainable Snow Management

Deliverable 3.1 | 30TH November 2024

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

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1. ROADMAP TO SUSTAINABLE SNOW MANAGEMENT

This roadmap lays out a comprehensive 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, this plan identifies the necessary transformations across production, storage, transportation, grooming and handling snow. It also examines overarching governance practices and the socio-economic context within which these activities occur.

The roadmap integrates the latest and expected findings from the SIEPPUR project, and highlights areas requiring further research and development. By 2030, this transformation aims to ensure resource-efficient operations, reduced environmental impacts, and increased societal acceptance of snow management practices, ensuring the long-term sustainability of snow-dependent venues and events. Although the focus is set on Nordic skiing venues and events, which are particularly exposed to climate warming due to their lower elevations, this strategy is in many parts transferable to other snow sports venues and events.

2. INTRODUCTION

To achieve sustainable snow management, it is essential to transform the operational processes used by venues. This roadmap focuses on venues under the purview of the International Biathlon Union (IBU) and begins with identifying gaps in current practices and understanding the variables that influence the transformation process, including climatological, ecological, hydrological, and socio-economic factors. A key component of this transition is the incorporation of governance practices that 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 the snow reliability.
- Assessing **water availability** for snowmaking 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.

New knowledge generated by the SIEPPUR project will address critical issues such as snow production potential, snow storage practices, grooming efficiency, and environmental impacts of snow handling and transport. However, achieving the goals outlined in this roadmap will require ongoing research, policy adjustments, and stakeholder engagement.

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 · Hydraulic 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. SNOW PRODUCTION

3.1 Current Gaps (2025 State)

Snow production currently faces significant challenges, particularly due to climate change. Increasingly dry summers limit water availability for snowmaking, and small water sources such as rivers, creeks, and ponds often cannot support large-scale operations.

Additional barriers include:

- A lack of detailed climate data, hindering accurate modeling of snow production potential.
- Pump and reservoir capacity limitations restrict snowmaking during peak demand.
- Noise and ecological regulations, particularly in protected areas, that limit the type and number of snow production units.

3.2 Transformation Goals and Pathways

By 2030, the goal is to optimise snow production processes to minimise energy use and maximise sustainability:

- Reduce energy consumption to **1-2 kWh/m³** (from 2-4 kWh/m³).
- Transition to **100% renewable energy** for snowmaking operations.
- New and efficient optimisation of existing infrastructure **providing robust water availability** in a future of dryer summers. For several regions building sustainable water reservoirs providing multiple uses beyond snowmaking will be key to success.

3.2.1 Operational Improvements

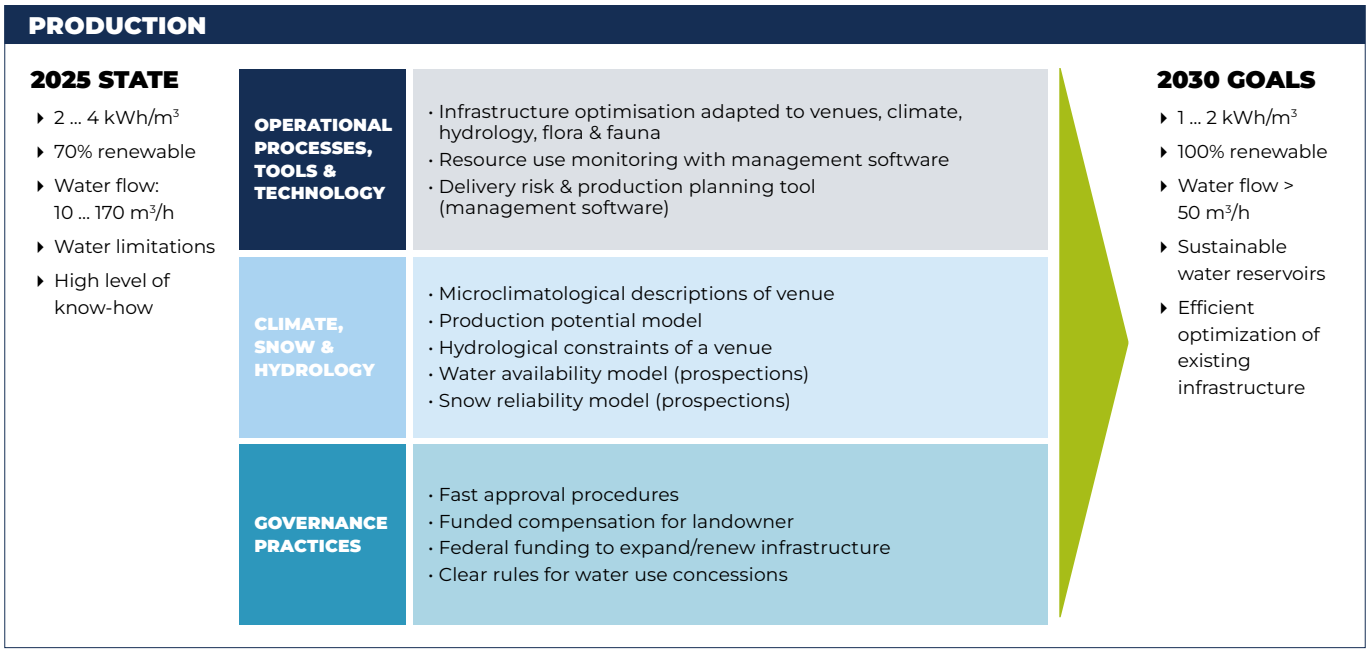
- Use resource-monitoring software to track water and energy use in real time.
- Introduce snow delivery risk and production planning tools to ensure efficient snowmaking under varying climatic conditions as well as to be able to resiliently invest in new snow-making infrastructure. The snow delivery risk of not being able to provide snow on a certain date requires consideration of meteo-hydrological, technical and economical parameters. Providing the desired tools, further research and development efforts are required.

3.2.2 Climate, Snow & Hydrology Data and Models

- Develop detailed microclimate descriptions for venues.
- Implement hydrological and snow reliability models to assess water availability and snowmaking feasibility.
- Couple snow production planning with real-time hydrological monitoring
- Model commitments to resolve ecological constraints for snowmaking to prevent over-extraction from limited sources (small rivers, ponds, creeks).

3.2.3 Governance Enhancements

- Streamline water use approval procedures to avoid delays in realising new infrastructure.
- Implement funding programs to upgrade infrastructure including guidance on how to apply for national and regional funding.
- Clarify regulations on water extraction and promote compensation for landowners affected by snowmaking activities.



4. SNOW STORAGE

4.1 Current Gaps (2025 State)

Snow storage requires significant land use and competes with other priorities such as agriculture, nature preservation, or tourism use in summer. The high cost of snow storage, combined with societal skepticism, makes large-scale storage challenging.

Key issues include:

- Average storage volume loss of **up to 45% annually** due to melting and settling.
- Energy-intensive storage practices require **4-6 kWh/m³** (including 2 kWh/m3 for snow production).
- High costs, ranging from **9-12 EUR/m³**.
- Self-made, inefficient cover solutions.

4.2 Transformation Goals and Pathways

By 2030, snow storage practices should achieve:

- Reduced energy consumption to **2-3 kWh/m³**.
- Lower costs of **4-6 EUR/m³**.
- Reduced average volume loss to **20%**.

4.2.1 Operational Improvements

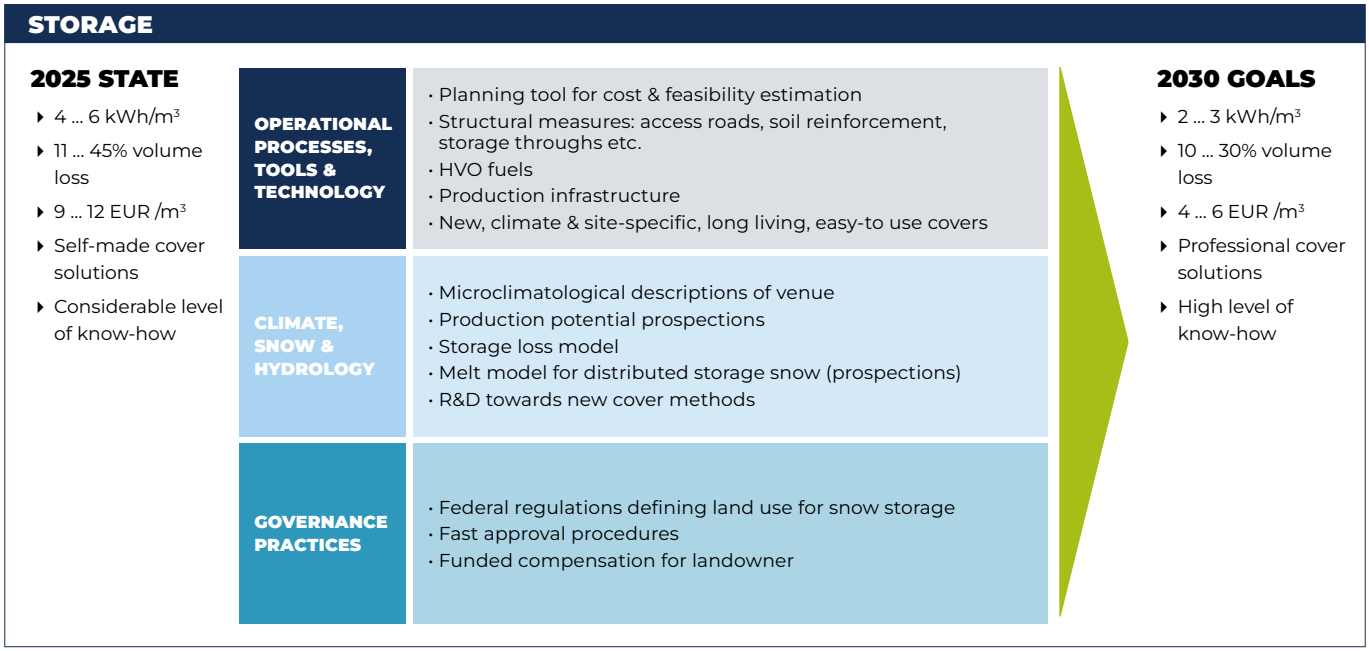
- Design new storage covers that are durable, climate-specific, and easy to use.
- Upgrade infrastructure, such as soil reinforcement and storage troughs, to improve storage capacity and minimise losses.
- Transition to HVO (hydrotreated vegetable oil) fuels to replace fossil fuels in any storage-related machine use.
- Introduce electric vehicles (EVs) as they become more available and efficient, and as grooming procedures are adapted to the limited range of operation currently available (approximately 4 hours duration for e-groomers).

4.2.2 Climate, Snow & Hydrology Data and Models

- Use storage loss models and models describing the melting of distributed stored snow to predict snow durability under different climatic conditions.

4.2.3 Governance Enhancements

- Advocate for regulations that define land use policies for snow storage.
- Provide compensation for landowners who allocate land for storage purposes.
- Streamline snow storage approval.



5. SNOW TRANSPORT

5.1 Current Gaps (2025 State)

Snow transport remains resource-intensive, with limited data on energy use and emissions. External contractors often exacerbate the lack of data and knowledge amongst IBU venues.

Challenges include:

- Snow transport is a new, increasingly important task for which optimal machinery is usually not owned by venues.
- Most machinery used for transport uses fossil-based fuel.
- Even for rather short distances, no systems for conveying snow exist.

5.2 Transformation Goals and Pathways

5.2.1 Operational Improvements

- Replace fossil fuels with HVO and adopt electric vehicles powered by renewable energy.
- Reduce transportation costs, by upgrading transportation roads and logistic measures as well as better planning of the venue and possibly multiple storages.

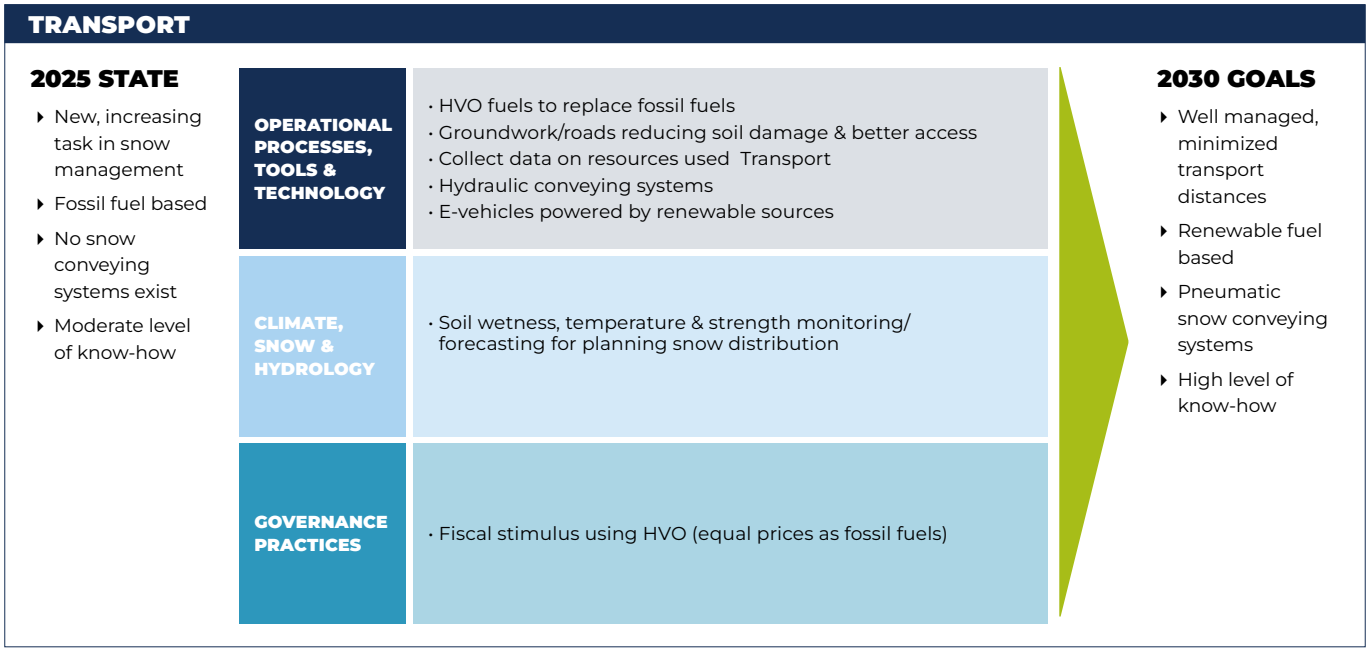
- Conduct ground modifications and alternative roads reducing soil damage and providing better access.
- Develop hydraulic conveying systems to reduce manual and vehicle-based snow transport efforts.

5.2.2 Climate, Snow & Hydrology Data and Models

- Implement soil wetness, temperature and strength monitoring/forecasting to plan snow distribution.

5.2.3 Governance Enhancements

- Provide fiscal stimulus promoting the use of biofuels creating equal or more favourable prices than the use of fossil fuels.



6. SNOW GROOMING

6.1 Current Gaps (2025 State)

Although current grooming practices exhibit a high level of expertise, gaps remain in terms of resource efficiency and adaptation to changing technologies.

Challenges include:

- Energy intensive snow management component **1-3 kWh/m2** which is only **20 - 30% renewable**.
- Costly and unavailable biofuels e.g. HVO.
- Lack of data on fuel consumption and emissions from grooming equipment.
- Operational inefficiencies with electric groomers, which have limited battery capacities.

6.2 Transformation Goals and Pathways

By 2030, snow grooming practices should achieve:

- Reduced energy consumption to **0.5-1 kWh/m2**.

- Energy provided **80% from renewable sources**.
- Transition to sustainable fuels synthesised from renewable sources like HVO
- Use electric groomers powered by renewable energy.

6.2.1 Operational Improvements

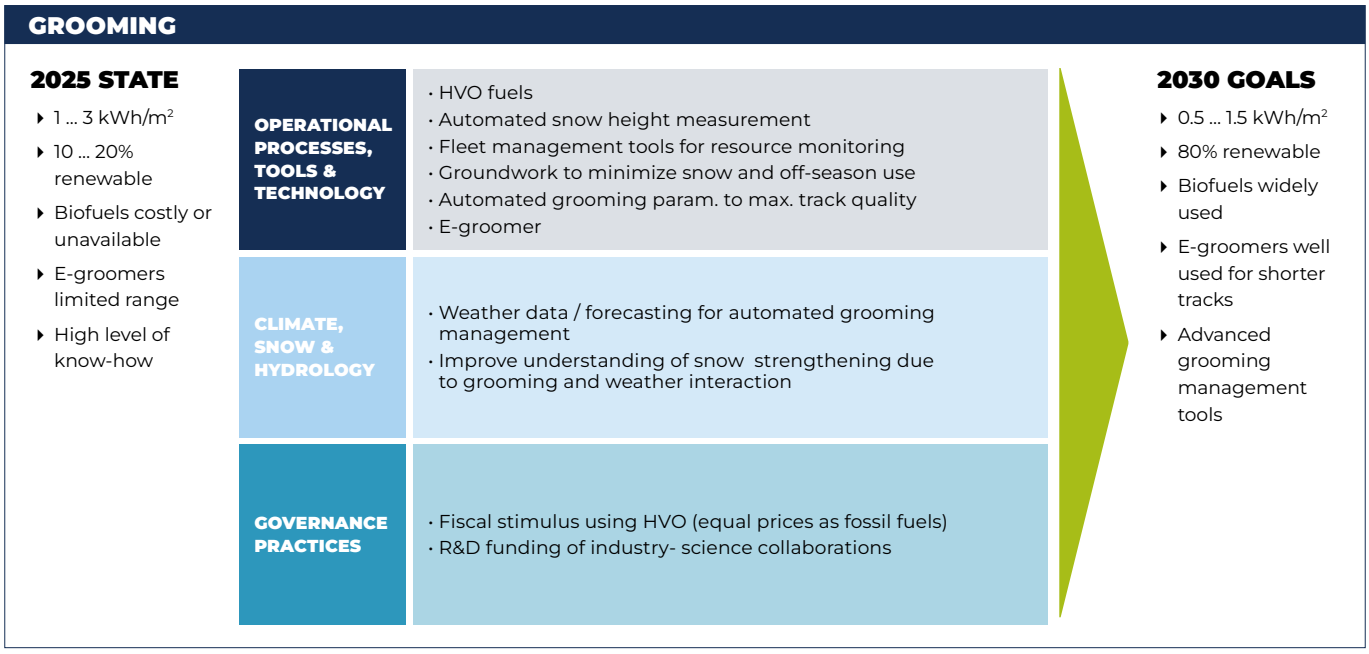
- Use fleet management tools to monitor resource use and improve operational efficiency.
- Implement automated snow height measurement systems to optimise grooming operations.
- Monitor usage and wear of trails to avoid unnecessary grooming or use of unsuitable grooming machines.
- Minimise snow loss during grooming by refining groundwork processes. Synergies can be achieved by considering and improving off-season use of the trails (without snow).

6.2.2 Climate, Snow & Hydrology Data and Models

- Leverage weather forecasting tools to optimise grooming schedules and minimise fuel consumption.
- Study the interactions between grooming activities, snow properties, and weather conditions.

6.2.3 Governance Enhancements

- Provide fiscal stimulus using biofuels (equal prices than fossil fuels).
- Provide R&D funding for industry-science collaboration developing models describing the groomer-snow-weather interactions.



7. SNOW HANDLING

7.1 Current Gaps (2025 State)

Snow handling practices require improved practices and defined procedures, as well as a better understanding of snow-hardening processes and their environmental impacts. This is particularly required in a warmer future with an increasing number of rain-on-snow events and strong melting periods during winter.

Challenges include:

- Improvised practices and procedures reacting to extreme melting events.
- Lack of professional tools e.g. pumps to remove water etc.
- Insufficient knowledge of how snow hardeners interact with snow, soil, and plants.
- Lack of predictive tools to optimise snow hardening under varying weather conditions.

7.2 Transformation Goals and Pathways

7.2.1 Operational Improvements

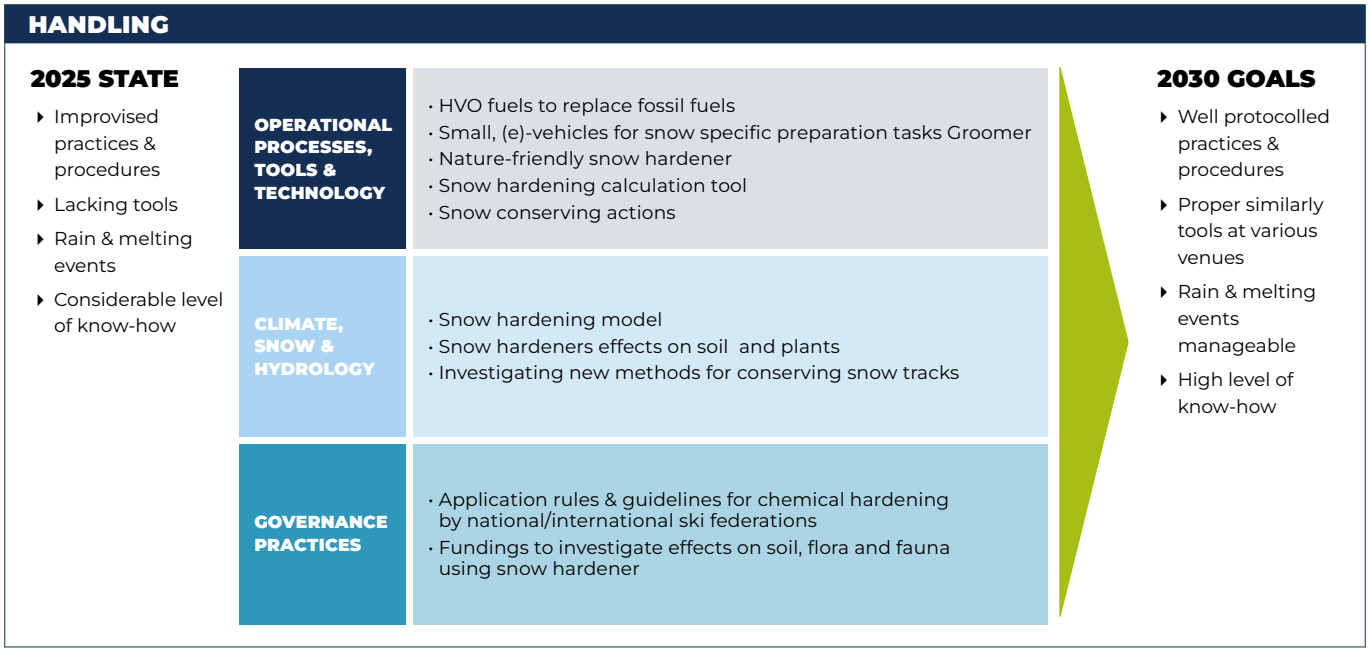
- Develop nature-friendly snow hardeners and tools to calculate the optimal hardening process.
- Introduce small electric vehicles for snow-specific tasks to reduce loads and damage to the snow as well as emissions.
- Implement already existing good practices and tools.
- Investigate and develop new methods for conserving snow tracks.

7.2.2 Climate, Snow & Hydrology Data and Models

- Develop a model describing the physical or empirical relation between snow strength increase/dynamics from the hardener and water distribution, and snow physical properties.

7.2.3 Governance Enhancements

- Establish national guidelines for snow hardening practices to standardise methods and ensure environmental safety.
- Provide funding to investigate effects on soil, flora, and fauna using snow hardener.



8. GENERAL SNOW MANAGEMENT ISSUES

8.1 Current Gaps (2025 State)

Sustainable snow management is hindered by political disagreements, insufficient funding for infrastructure, a general increase in costs, and societal concerns about the environmental impact of increasing infrastructure needed for Nordic skiing, already today; concerns that will only be enhanced in a warmer future.

8.2 Transformation Goals and Pathways

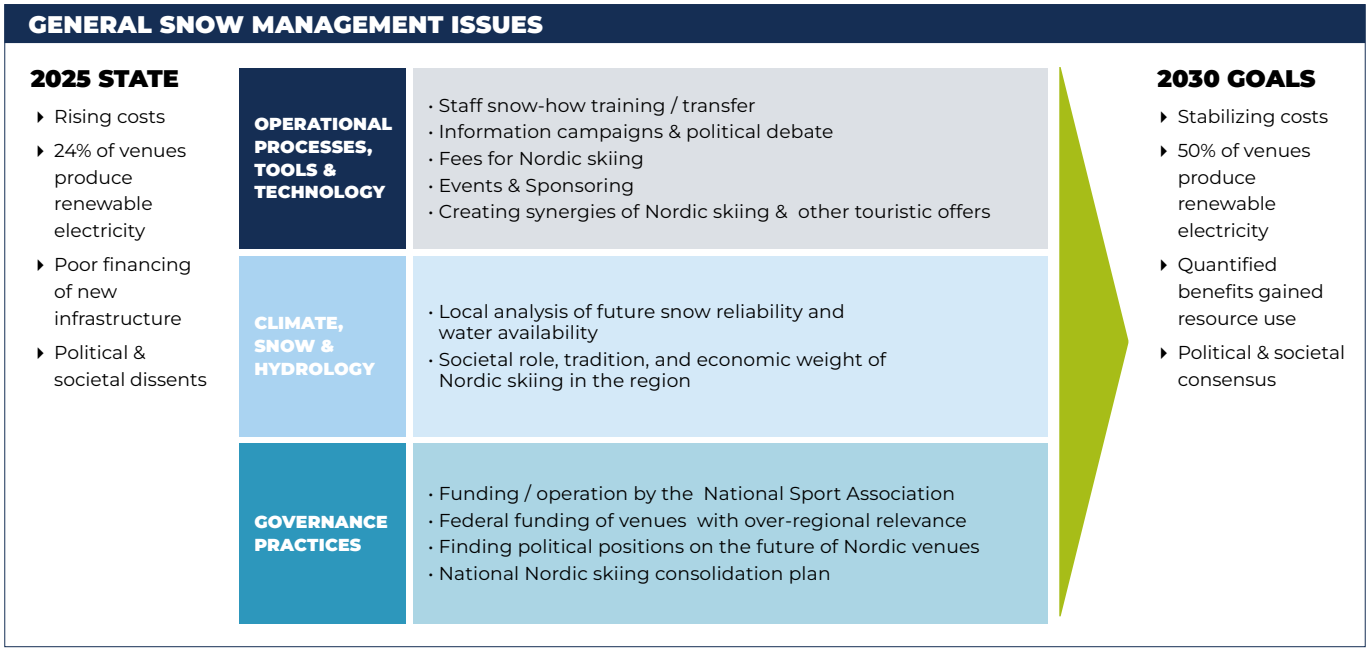
- Achieve political and societal consensus on sustainable snow management practices by 2030.
- Stabilise costs through government funding and private-sector partnerships.
- Quantify the societal benefits of Nordic skiing related to the resources used.

8.2.1 Operational Improvements

- Information campaigns and political debate
- Fees for Nordic skiing course use, events, and sponsoring.
- Create synergies between Nordic skiing and other touristic offers.

8.2.2 Governance Enhancements

- Promote public debates and awareness campaigns to foster societal support.
- Develop national consolidation plans for Nordic skiing venues, prioritising long-term sustainability.
- Promote research investigating the societal role, tradition, and economic weight of Nordic skiing in the region.
- Promote privately funded business concepts in Nordic Skiing.



9. CONCLUSION

This roadmap presents a structured approach to transforming snow management into a sustainable practice that aligns with environmental, economic, and societal goals. The path forward requires innovation in technology, governance, and public engagement to address the challenges posed by climate change and resource constraints.

The roadmap specifically names research topics that will partly be addressed in the frame of the SIEPPUR project or should be investigated within the following years. However, a major part of the transformation must be carried out by decision-making focused on innovation and step-by-step improvements of the venue managers. 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, snow-unfriendly future.

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