Project: European Week of Winter Sport
Project Number: 101133676

D2.2 Impact of Winter Sports in the Environment -

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Co-funded by the European Union

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Education and Culture Executive Agency (EACEA). Neither the European Union nor EACEA can be held responsible for them.

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1. Introduction

Environmental sustainability has emerged as one of the most critical and complex challenges facing the contemporary world. This issue, central to many of the United Nations' Sustainable Development Goals (SDGs), manifests in various forms, including climate change, carbon emissions, waste management, and the degradation of natural ecosystems. In addition, the use of scarce resources, such as water and energy, and the impact of modern living and tourism on biodiversity are pressing concerns that demand immediate and sustained attention. The interplay between these factors highlights the urgency of addressing environmental sustainability across all sectors of society, including winter sports, physical activity, education, and outdoor life.

The impact of winter sports and outdoor activities on the environment is significant and complex. Most of the research available focuses on alpine skiing and snowboarding, with limited information on other types of winter sports. The construction and maintenance of sports facilities, the organization of events, and participation (including mobility and transport) all have significant impact on the climate. The use of natural resources, energy consumption, and waste generation associated with these activities contribute to the degradation of the environment, including the destruction of natural habitats, pollution, and the depletion of wildlife. Moreover, the relationship between sports and the environment is bidirectional—while sports activities impact the environment, environmental changes, such as climate change, also affect the viability and sustainability of these activities. This dynamic is particularly evident in winter sports, where the dependence on snow and cold climates makes them highly vulnerable to climate change.

The growing popularity of winter tourism and sports has intensified the pressure on fragile ecosystems, particularly in mountainous regions. Despite increasing awareness of these issues, many winter sports organizations remain unprepared to address the challenges posed by a changing climate. The complex relationship between winter sports and environmental sustainability underscores the need for comprehensive strategies that address the environmental, economic, and social impacts of these activities. This report will explore these issues in depth, focusing on the impact of winter sports on climate change, the environmental and economic effects of winter sports, and the social impact of these challenges.

2. Impact of winter tourism and sports on climate change

Tourism is one of the most climate-sensitive sectors, with its impacts closely tied to global warming and climate dynamics. The relationship between tourism and climate change is complex and multifaceted, operating on multiple levels. As global demand for travel increases, the tourism industry—including winter sports tourism—is rapidly expanding. However, this growth comes at a significant environmental cost (1,2).

Tourism is highly income-elastic and carbon-intensive, meaning that as people's incomes rise, their demand for travel increases, leading to greater carbon emissions. Despite efforts to decarbonize tourism operations, the global demand for tourism is growing at a faster pace, resulting in an accelerated increase in carbon emissions. Between 2009 and 2013, the global carbon footprint of tourism surged from 3.9 to 4.5 gigatons of CO2 equivalent (GtCO2e), accounting for approximately 8% of global greenhouse gas emissions.

The majority of this carbon footprint is driven by activities in high-income countries, with transport, shopping, and food being the most significant contributors (3,4).

Winter tourism, a niche yet significant segment of the global tourism industry, exemplifies the sector's environmental challenges. The carbon footprint of winter sports can be divided into three areas. **Travel**, **accommodation** and **skiing** itself. The journey to and from the ski resort alone is responsible for 50% to 74% of total emissions. Accommodation on site, on the other hand, only accounts for 20% and skiing operations and energy consumption for just under 5%, depending on the resorts (5). Studies from Austria and France indicate that emissions per skier day range from 3.5 to 7 kg CO2, with substantial variations depending on the destination and activities involved (5).

This growing carbon footprint of winter tourism not only exacerbates global climate change but also threatens the resources upon which the industry depends, such as snow reliability and winter ecosystems. As the tourism industry continues to expand, the need to address its impact on climate change becomes increasingly urgent.

2.1 Traveling and CO2 emissions in winter sport tourism

Austria ranks as the second most popular ski destination globally, with around 54.2 million skier visits per year (5,6). As such, it serves as a key focus for evaluating CO2 emissions and transportation in winter sports tourism.

A study by Austria's Federal Environment Agency highlights that transportation choice has the most significant impact on the environment. Air travel, particularly long flights, produces the highest greenhouse gas emissions. For example, a flight from Austria to the Maldives emits approximately 426 kg of CO2 per person per day, while a flight to Spain emits around 138 kg. In contrast, travel for winter vacations within Austria emits between 3 and 21 kg of CO2, depending on the mode of transport, with trains being the least carbon-intensive (7). Austria estimates that in winter tourism, 50% of emissions come from travel, 32% from accommodation and dining, and 18% from skiing. Similarly, a French ski area study found that 74% of emissions stem from travel, 18.7% from accommodation and dining, and 1.9% from ski area operations (5,8).

In Austria, 76% of winter tourists travel by private car, making it the dominant mode of transport. Air travel, used by only 13% of travelers, has increased nearly 50% since 2012, posing a growing concern due to its high carbon footprint. Rail travel (7%) and coaches (3%) are underutilized despite their lower environmental impact. This presents an opportunity for significant emission reductions by enhancing public transport options and investing in rail infrastructure (5). Associations like Protect our Winters have recently developed a mobility platform to facilitate low-carbon journeys to more than 110 ski resorts in France (9).

These findings extend to major winter sports events, where travel remains a major emission source. For example, the 2010 Vancouver Winter Olympics, though marketed as carbon-neutral, did not account for emissions from spectator and athlete travel, which comprised nearly half of the event's total emissions. However, events like the 2017 FIS Women's World Cup and the Winter X Games have shown progress by prioritizing environmental responsibilities (1).

2.2 Accommodation and ski resorts

Accommodation is an important part of the tourism value chain, and accounts for a substantial share of the sector's greenhouse gas emissions. Winter tourism is a major driver of Austria's hospitality industry, accounting for nearly half (48%) of the country's annual overnight stays. During the 2018/19 winter season alone, Austria recorded 73 million overnight stays. A significant portion of these stays—about 66%—occur in ski resorts, defined as municipalities with at least three ski lifts (5).

The accommodation sector is, in comparison to transportation, already a low-carbon sector, and has a good potential to fully decarbonize until 2040. However, carbon management is still required in this business. Most accommodation establishments still waste energy due to its perceived low cost. Yet, switching to renewable sources like solar, wind, or biogas is only marginally more expensive than using fossil fuels. Energy-efficient designs in new buildings, such as passive heating and cooling, can also lower energy use and operational costs. Incentives, energy consulting, and legislation can further motivate resorts to adopt sustainable practices. Additionally, promoting climate-friendly practices in marketing and training staff in energy management are key to achieving and maintaining low-carbon operations (10).

Research on ski resorts has tried to identify determinants of sustainability of these accommodations. Results show that ski resorts with longer pistes (over 65 km) and higher altitudes (over 2400 m) tend to be more sustainable. They have better stakeholder participation, political support, and policies, and actively improve sustainability awareness. They also adopt new technologies and renewable energy, collaborate effectively, and innovate to meet the growing demand for sustainable ski-related services. Small and low altitude ski resorts represent the problematic ones, since they face many issues that need the attention of ski resort managers in order to improve their competitiveness (11).

2.3 Operations and energy consumption in ski resort

The operation of ski resorts has seen a significant **increase in energy consumption** due to the widespread adoption of **artificial snowmaking**. This trend is evident in Switzerland, where the coverage of ski slopes with artificial snow rose from 10% in 2000 to 36% in 2010, and even more dramatically in Austria and parts of the Italian Alps, where artificial snow now covers nearly all ski runs (12). Snowmaking is energy-intensive, with demands ranging from 15,000 to 20,000 kWh per hectare annually, depending on the depth of snow required (13)(14). In Austria, the total energy consumption for snowmaking alone could range from 355 to 950 GWh per year, equivalent to the average energy consumption of 215,000 to 570,000 households (5). As the climate warms, the need for artificial snow—and thus the associated energy and water use—is raising concerns about sustainability.

While technological advancements have made snowmaking and mountain lift operations more energy-efficient, the overall environmental impact needs to be assessed. Earlier studies suggested that snowmaking could have a cooling effect on the climate due to the increased reflection of sunlight, known as the albedo effect. However, subsequent research revealed that this cooling effect had been overestimated (5). Furthermore, snowmaking not only demands substantial energy but also a **significant amount of water**, which can lead to water shortages in drier regions. Losses due to sublimation, evaporation, and wind can result in up to 50% of the water used being unrecoverable, exacerbating conflicts during periods of water scarcity (15,16).

The extent of CO2 emissions from artificial snowmaking is closely tied to the type of energy used, offering a pathway to reduce the carbon footprint of these operations. If the energy required for snowmaking

comes from renewable sources, CO2 emissions could be significantly decreased, dropping from around 200 grams of CO2 per kilowatt hour with conventional energy to just 10 grams per kilowatt hour with green electricity. Thus, by **transitioning to renewable energy sources**, ski resorts have a significant opportunity to make snowmaking more sustainable, reducing their overall environmental impact while continuing to meet the growing demand for artificial snow in a warming climate (17,18).

3. Environmental impact of winter sports

The environmental impact of winter sports resorts is a topic of growing concern, yet the scientific understanding of this subject remains fragmented. Despite a significant increase in research exploring how these resorts affect the natural environment—or conversely, how the changing environment due to global warming influences ski resort operations—the literature is often narrowly focused on specific issues. For instance, some studies examine the effects of ski resort development on particular species of amphibians or grasses, often within a specific geographical context. What is lacking, however, is a more comprehensive exploration of the broader relationship between winter sports resorts and the environment as a whole (19).

Over the past two decades, research has primarily concentrated on three key areas: **environmental impact** of the construction and operation of winter sports resorts ("environmental impact"), **management of the sustainable development** of resorts ("management"), and the effect of **climate change-induced environmental shifts** on the operation of winter sports and resorts ("climate change"). However, these topics have not been treated with equal importance or attention over time (19). It is worth noting that while environmental impact and management remain crucial areas of study, climate change has risen to prominence in recent years, driven by the urgent need to address its consequences in winter sports (19).

In this section, however, we will focus specifically on understanding the **impacts of winter sports in the environment**. Most studies in this field aim to identify how the operation of a winter sports resort—or specific aspects of it—affects certain elements of the environment. The impact of constructing resorts and developing **new ski runs** is frequently analyzed, with **snowmaking** and **grooming** considered the most environmentally harmful practices (19–24). The most commonly studied environmental elements include soils and grasslands, or more broadly, vegetation (22,25,26). Comparatively fewer studies have examined the influence of ski resorts on wildlife, though some research has explored their impact on water quality (27). One study by Kuš̌cer and Dwyer offers a different perspective by comparing the environmental impacts of various resorts, suggesting that larger resorts might generate a smaller environmental footprint per visitor compared to smaller resorts (11).

3.1 Natural sites affectation and soil erosion

The construction and maintenance of ski resorts, particularly the development of ski lifts and runs, causes long-term changes in the environment, affecting many essential ecosystem properties and services. The ecological consequences of, and the recovery from ski run construction, hugely depend on the methods used to construct the ski runs as well as on the land restoration work employed (25,28).

The process of ski run construction, especially through techniques like **machine grading**, exacerbates **natural destruction and soil erosion**. Machine grading, a widely used method, involves the complete removal of the vegetation cover and the topsoil, which contains crucial elements like seedbanks and soil biota. This

method disrupts the physical, chemical, and biological properties of the soil, leading to compaction, loss of organic matter, and reduced nutrient levels. These changes in the soil structure increase the risk of erosion, particularly on slopes above the timberline, as compacted soil has diminished infiltration rates and water storage capacity. As a result, overland flows are intensified, further contributing to erosion (22,29). After grading, what remains is typically a mineral substrate with low organic matter and poor water-holding capacity. The absence of a stable plant cover makes it difficult to retain sediments and nutrients, thereby destabilizing the ecosystem. Therefore, **revegetation processes** become essential for stabilizing slopes and reducing erosion. The selection of the appropriate combination of plants can speed up ecological restoration and prolong the process of stabilizing and recovering slopes. However, the use of nonnative species, which are often chosen for their cost-effectiveness and rapid growth, poses additional threats, which can disrupt local ecosystems and alter nutrient levels (24,30).

A study on the recovery of ski runs constructed in the 1990s, which used machine-graded and hydroseeded, revealed that while plant cover on the ski runs remained stable over time, the diversity and richness of plant species increased, eventually resembling nearby undisturbed areas. However, despite decades of recovery, the soil on these ski runs still exhibited higher pH, lower organic carbon content, and reduced stability compared to undisturbed sites, highlighting the long-term challenges of restoring disturbed environments (30). It is worth noting that the ecological damage from ski resort construction can be, in some cases, severe and difficult to revert. For instance, the construction of ski slopes at the PyeongChang 2018 Winter Olympics resulted in the destruction of forests over 500 years old, with restoration efforts proving inefficient and incomplete. This underscores the significant financial and ecological costs associated with both the restoration of natural habitats and the development of eco-tourism in these regions (31).

Careful management and continuous monitoring of ski resort areas, especially those near protected regions, are essential for mitigating these impacts. **Effective restoration** requires not only financial investment but also a commitment to sustainable practices that prioritize the long-term health of the ecosystem.

3.2 Alterations on biodiversity and decline of wildlife

The expansion of winter sports and tourism into remote areas has escalated over the past decades, posing a significant threat to vulnerable wildlife. **Human disturbances**, such as the repeated flushing of resting wildlife can trigger **stress responses in animals**, leading to compensatory behavioral adaptations that increase their energetic costs (32). Such disturbances frequently force animals to occupy suboptimal habitats, adversely affecting their reproductive success, survival rates, and overall fitness (33). Over time, these negative impacts contribute to a **decline in local population densities** and, in severe cases, a diminishment of wildlife (34) . Additionally, the increased presence of humans in these areas can attract generalist predators, whose populations are artificially boosted by food waste near mountain lodges and restaurants (34,35).

The **construction of ski lifts and runs** also exacerbates the loss of endemic species, including some that are endangered, by further fragmenting their already limited habitats. A good example is the black grouse (*Tetrao tetrix*), a key indicator species of timberline ecosystems, which has experienced significant population declines in the Alps (34). The International Union for the Conservation of Nature (IUCN) has suggested that the spread of winter sports may be contributing to this decline, although definitive scientific evidence is still needed (36). Another study found that climate change and human adaptation will likely push both ski resorts and bird

habitats to higher elevations, leading to a 58–67% reduction in suitable areas for birds. As a result, the **overlap between skiing areas and bird habitats** is expected to increase, especially in regions that host the most species or the most threatened species, intensifying conflicts between skiing and biodiversity conservation (37).

The **use of artificial snow** and the preparation of ski slopes have been shown to alter biodiversity significantly. These practices **delay plant phenology**, alter species composition, and reduce species richness and diversity (22,24). Studies have reported a decrease in the diversity of carabid beetles, spiders, and grasshoppers on ski slopes compared to natural sites, highlighting the negative impact of these artificial environments on arthropod communities (26). Furthermore, the potential for conflict between avian species and future ski piste distribution may increase with climate change and alterations in the snowpack (25).

Ultimately, these combined detrimental effects from winter sports and tourism lead to a reduction in local wildlife population density and species richness, emphasizing the need for more environmentally conscious practices and conservation efforts in these vulnerable regions.

3.3 Impact on glacier retreat

The impact of winter sports on glacier retreat in the Alps is a complex issue that intertwines with both environmental and economic factors. The Alps currently host around 3,500 glaciers, which cover an area of approximately 1,700 square kilometers, mostly located above 3,000 meters. Over recent decades, there has been a significant and **accelerating decline in global glacier mass**. For instance, Austrian glaciers lost 26% of their area and 30% of their volume between 1969 and 2006, with an additional 22% volume loss recorded in the following decade (38,39). This rapid glacier retreat is impacting water resources, disaster risk management, hydropower, agriculture, and tourism (40).

Glaciers in the European Alps play a vital role in the national economy, contributing to hydropower generation and serving as key attractions for both summer and winter tourism (41). Some of the most visited sites in the Alps, such as Aiguille du Midi and Mer de Glace, draw over a million visitors annually, underlining the economic importance of glacier tourism. During the 1970s and 1980s, a period of positive glacier mass balance, ski resorts were even built directly on glaciers. By 2009, Austria had eight glacier ski resorts operating on 15 glaciers, highlighting the close relationship between winter sports and glaciers (41,42).

Despite this, an Austrian publication from 2011 suggested that the presence of ski resorts on glaciers had minimal impact on the rate of glacier volume loss. This study showed that between 1969 and 1997, glaciers with ski resorts lost 11.5% of their area, compared to a 15.4% loss for other glaciers. This trend continued between 1997 and 2006, with resort glaciers shrinking by 6.6%, slightly less than the 8.3% reduction experienced by non-resort glaciers. These results should be interpreted cautiously, as the lesser impact may be partially attributed to the fact that many resorts have a north-facing exposure. Additionally, the study only covers glacier recession up until 2006, and climate conditions have since changed, potentially altering these dynamics (42).

In 2023, the deployment of heavy machinery on the Theodul Glacier for the Ski FIS World Cup cross-border race, raised significant concerns among environmental groups such as Protect Our Winters (POW). The Theodul Glacier is vital for maintaining the region's ecological balance, and the ongoing excavation threatens to disrupt this delicate equilibrium. Such disruption not only hampers the glacier's ability to store water but may also accelerate its retreat. Visuals of diggers filling crevasses on the glacier highlight the growing tension

between the demands of winter sports and the imperative to preserve these fragile environments (43,44).

In response to the rapid glacier retreat, adaptation strategies are being developed in the Alps, though these efforts raise questions about the sustainability and ethics of such interventions. In some ski resorts, methods like **piste grooming**, **water injection**, and **snow-farming** are used to mitigate glacier melt (45). For a detailed analysis of the environmental impact of snow production, refer to section 3.4 on water use and energy consumption from snowmaking. For instance, in Switzerland, geotextiles—synthetic blankets designed to reflect sunlight and insulate snow—are employed to slow down glacier melting, reducing ice loss by up to 50%. While effective locally, these measures are expensive, unsustainable on a large scale, and may have negative ecological impacts. While these localized strategies may temporarily protect glaciers, experts stress that reducing greenhouse gas emissions is the only effective long-term solution to slowing glacier retreat and preserving these critical landscapes. Without global action on climate change, the continued loss of glacier mass is inevitable, threatening the very existence of winter sports in the Alps (46,47).

3.4 Snowmaking impact on water usage and energy consumption

Since its inception in 1952, snowmaking technology has become a cornerstone of the ski industry, particularly over the last 25 years, where significant investments have integrated it deeply into most regional markets. As climate change continues to reduce natural snowpack in mountain regions (40), ski industry leaders are increasingly turning to **snowmaking as a climate adaptation strategy**. However, this has raised concerns about its environmental impact, particularly regarding water usage and energy consumption.

The **sustainability of snowmaking** is a contentious issue. Some researchers argue that it is inherently unsustainable as it can be highly resource-intensive, leading to concerns about greenhouse gas (GHG) emissions, water-use conflicts, and other environmental impacts. In regions with scarce water resources or high energy costs, snowmaking can exacerbate existing environmental and social tensions (48). Other studies suggest that its impact depends on regional contexts and the specific snowmaking systems used. For instance, Moser & Baulcomb indicate that snowmaking can be an effective adaptation strategy in certain locations, particularly where tourism systems and energy sources are managed sustainably (49).

A Canadian study provides a national analysis of snowmaking's environmental sustainability, estimating that 136 Canadian ski areas use 478,000 megawatts (MWh) of electricity and 43.4 million cubic meters of water to produce over 42 million cubic meters of artificial snow. With climate change projections indicating a potential 55% to 97% increase in snowmaking requirements by 2050, energy and water use are expected to rise proportionally. However, decarbonization of provincial electricity grids may mitigate the associated CO2 emissions (18).

Snowmaking's environmental impacts extend beyond water and energy use. The practice has been linked to **biodiversity loss and soil health degradation**, as artificial snow delays snowmelt and shortens the growing season for alpine plants (25,50). Additionally, snowmaking reservoirs can disrupt local water conditions, similar to the effects observed in agriculture and forestry (27).

Therefore, the assessment of snowmaking as an adaptive or maladaptive strategy must be based on

local contexts. While it offers a potential solution to the challenges posed by climate change, its sustainability depends on the efficiency of the systems used, the availability of water and energy resources, and the socio-ecological context of each region. Therefore, improving the efficiency of snowmaking and ensuring it aligns with broader sustainability goals should be a priority for the ski industry and its stakeholders.

3.5 The impact of light pollution on the environment

Light pollution is an increasingly recognized environmental issue and encompasses various adverse effects caused by excessive artificial lighting. This phenomenon disrupts natural processes and impacts the physiological and ecological balance of many species. The consequences of light pollution extend beyond urban centers, reaching even remote areas such as mountain ecosystems due to the presence of ski resorts.

The introduction of artificial lighting into nocturnal environments **interferes with the biorhythms of many organisms**. Species adapted to natural light-dark cycles face significant disruptions. For instance, birds that rely on dusk and dawn cues for their breeding behaviors may experience altered nesting times and migratory patterns (51). Similarly, nocturnal animals that depend on darkness for foraging and hunting can become disoriented or change their activity patterns due to artificial light (51).

Plants are also adversely affected by light pollution. Many species use natural light cues to **regulate growth and reproductive cycles**. For instance, artificial light can delay or alter processes such as flowering and leaf senescence, leading to maladaptive growth patterns (52). Studies have shown that even moderate artificial lighting can disrupt plant phenology, affecting their resource allocation and survival (53). Trees and flowering plants exposed to artificial light may experience delayed dormancy and altered physiological responses, such as leaf color changes and increased vulnerability to frost (51).

4. Economic impact of winter sports

Winter sports and tourism are crucial economic drivers in many alpine regions, significantly contributing to the GDP of countries such as Austria, where winter sports alone generate nearly €7.4 billion in direct value annually, accounting for about 3.16% of the nation's GDP. When considering indirect contributions from sectors like transportation, the figure rises to €11 billion, or 4.1% of the total GDP—similar to the scale of Austria's retail sector. Germany, as Europe's largest source market for winter sports, contributes significantly to this economy, with Germans spending over €16.4 billion annually on winter sports activities such as skiing and cross-country skiing (54).

However, the **economic landscape of winter tourism is complex** and varies significantly depending on the country and the events hosted there. The industry faces increasing challenges due to rising temperatures and snow-poor winter seasons, which disproportionately affect lower-altitude resorts. These areas are more vulnerable to climate change, leading to a potential decline in tourist numbers and a subsequent rise in prices for winter tourism to offset operational costs (8,55).

The costs associated with winter sports are not limited to the activities themselves but extend to the significant expenses of **maintaining and operating facilities**, particularly in the production of artificial snow. Moreover, the environmental and economic impacts are exacerbated when existing infrastructure is underutilized, prompting the construction of new facilities and procurement of equipment in unsustainable ways.

The maintenance of these new infrastructures often falls on the local population, further straining the economy, especially when the promised economic growth fails to materialize (18).

To address these challenges, **sustainable development practices** in winter tourism are essential. For instance, in Croatia, winter sports contribute to local economies by creating jobs in rural and mountainous areas. Sustainable tourism marketing that emphasizes the country's natural beauty and cultural attractions can enhance economic benefits while minimizing social and environmental impacts. Additionally, **fostering public-private partnerships** can help fund eco-friendly initiatives, while diversifying winter sports activities beyond traditional skiing and snowboarding can attract a broader range of tourists and reduce dependence on seasonal snow conditions (18,56).

Additionally, policy frameworks at local, national, and international levels are crucial in shaping the sustainability of winter sports events, ensuring that they contribute positively to the economy while mitigating environmental damage and supporting long-term economic growth.

4.1 Artificial snow production and facility operations

Rising temperatures, more frequent snow-scarce winters, and escalating energy prices threaten the future profitability of artificial snow production. The economic impact of these factors on winter sports facilities is complex and has been extensively discussed in several studies (55,57,58). Still, the economic limits of snowmaking are still poorly understood and vary much depending on the area. Limiting factors of snowmaking are not only increasing temperatures and decreasing efficiency of snow production, but also potential increases in energy prices owing to higher taxes and/or shortage of fossil fuel, which would affect the profitability of snowmaking (59). The ski resorts' susceptibility to the lack of natural snow is rather high due to their low elevation. Approximately 40% of ski areas in Austria, and about 30% in the five Alpine countries—Austria, France, Germany, Italy, and Switzerland—are situated at average altitudes of 1,320 meters or lower (60).

An Austrian study examined the economic feasibility of snowmaking in future climate conditions by conducting a cost-revenue analysis for a case study ski area. The findings provide a useful benchmark for other low-elevation ski areas, but additional factors such as the ski area's size, slope orientation, operational economics, and snowmaking infrastructure are required to be taken into account (55). The study highlights that increasing temperatures will reduce snowmaking hours due to decreased efficiency. Furthermore, rising electricity prices, which account for about a third of snowmaking costs, are expected to significantly impact financial viability. In the long term, declining snow depths are anticipated to decrease ski visitor numbers, particularly during peak periods like Christmas and Easter. To mitigate this, ski areas may need to diversify into alternative winter activities like wellness tourism or winter hiking, and attract off-peak visitors with targeted offers. To maintain profitability, ski ticket prices will likely need to increase beyond recent trends. This raises the question of whether visitors will be willing to accept higher ticket prices in the future (55).

The operation and management of winter sports facilities also have significant economic implications, particularly when hosting major international events. Such events often drive social and economic development initiatives, as evidenced by PyeongChang's investments for the 2018 Winter Olympics. The city constructed high-cost venues like the $1 billion sliding center and the $5 billion ski jump stadium with the expectation of long-term local benefits. However, these facilities failed to meet these prospects (31). The sliding center, used for bobsleigh, luge, and skeleton events, faced high maintenance costs and minimal public use, leading to its

closure shortly after the Games. Similarly, the ski jump stadium has been underused and costly to maintain. PyeongChang continues to cope with the financial burdens associated with these venues, highlighting the economic risks of large-scale investments in specialized sports infrastructure. The experience underscores the importance of careful planning and sustainable management in leveraging major sporting events for lasting community and economic benefits (31).

4.2 Local economic impact of winter sports in Italy

Winter sports events often draw a significant number of domestic and international tourists to Italy, especially to regions like the Alps and Dolomites. These events boost local economies by increasing demand for accommodations, dining, and other services.

Large events contribute to job creation, both directly within the sports industry and indirectly in sectors like hospitality, retail, and transportation. Hosting major winter sports events, like the Alpine Ski World Cup and the biennial Winter Universiade, can lead to improvements in infrastructure, including better transportation systems and upgraded sports facilities, which serve the community long after the events have ended.

For recent examples of the economic impact of winter sports events in Italy, the upcoming 2026 Winter Olympics in Milan and Cortina d'Ampezzo offer some insights. This event is anticipated to have significant economic implications, leveraging existing sports infrastructure to limit economic and environmental impacts. Historical data from the 2006 Winter Olympics in Turin also suggests that such events can bring substantial economic benefits through increased tourism and job creation, enhancing local businesses and the overall infrastructure of the host cities. However, in light of PyeongChang's challenges with underused facilities and financial burdens, it is crucial for Milan to implement more effective and sustainable management strategies to ensure they reap long-term economic benefits (31,61).

4.3 Local economic impact of winter sports in Germany

Winter sports play a crucial economic role in Germany, particularly in the Alpine regions. German tourists are significant contributors to the winter sports market, spending over 16.4 billion euros annually on activities such as skiing and cross-country skiing. This highlights Germany's position as the most important source market for winter sports in Europe.

The reliance on artificial snowmaking systems has become essential for the sustainability of ski resorts in Germany. These systems help mitigate the financial impact of "bad" winters with insufficient natural snowfall. For instance, research conducted by the University of Munich at the Sudelfeld ski resort near Bayrischzell showed that the financial discrepancy between a "good" winter (2005/06) and a "bad" winter amounted to nearly twelve million euros. After expanding their snowmaking capabilities, the difference between the "good" winter of 2017/18 and the "bad" winter of 2015/16 was reduced to 4.5 million euros. However, the limitations of this technology were evident during the past winter, when an early cold spell was followed by a Christmas thaw, necessitating additional snow production and incurring extra costs both economically and ecologically (62).

Various regions in Germany are investing in infrastructure to support winter sports and mitigate the environmental impact. In Saxony, an additional six million euros is being allocated to enhance the snow retention system and install new conductor rails. In the city of Altenberg, funding of 600,000 euros is designated for

expanding the Zinnwald biathlon facility, including new disabled-friendly amenities and a rainwater retention basin to aid snow production. A grant of 2.83 million euros will support the expansion of the snowmaking system to ensure independence from the town's system and improve water supply, in WSC Erzgebirge Oberwiesenthal. Finally, in Landkreis Sächsische Schweiz-Osterzgebirge, 1.21 million euros will be invested in necessary renovations and refrigeration technology to maintain the long-term operation of the luge and bobsleigh track (54).

5. Social impact of winter sports

Winter sports have a profound impact on society, extending well beyond the excitement of competition. These events play a key role in **community engagement**, as they offer opportunities for volunteering and bring together individuals from diverse backgrounds to engage in sportive activities. An essential aspect of this community engagement is raising awareness about the environmental impacts of winter sports and encouraging sustainable practices among both participants and spectators. By involving local communities in decision-making processes, these sports also address community concerns and ensure that the benefits of tourism and recreation are shared.

Accessibility and inclusivity are also prioritized in winter sports, with efforts made to ensure that people of all ages, abilities, and socioeconomic backgrounds can participate. This might involve offering affordable equipment rentals, beginner ski lessons, and improving infrastructure to accommodate individuals with disabilities. By making winter sports more inclusive, more people can experience the physical, mental, and social benefits these activities provide. **Cultural preservation** is another important dimension of the social impact of winter sports. In places like Croatia, winter sports are deeply intertwined with the country's rich cultural heritage, including traditional customs, cuisine, and arts. Sustainable tourism initiatives aim to protect and promote this cultural identity while minimizing the negative effects on local traditions and lifestyles. International winter sports events also play a role in cultural exchange, enhancing the global image of destinations known for their warm and vibrant atmospheres. The **health and wellbeing** of participants are also significantly impacted by winter sports. Engaging in these activities promotes physical fitness and health awareness, encouraging more people to incorporate exercise into their daily lives. Research from the German Sport University in Cologne has shown that winter sports contribute to preventing exercise-related illnesses, supporting child development, and strengthening the immune system. These activities are beneficial not just physically but also mentally, as they improve psychological well-being and foster social integration across all age groups (63).

Education is a crucial element in the social impact of winter sports. Educational initiatives targeted at those involved in winter sports encourage responsible interaction with natural environments, helping to reduce the negative environmental impacts of these activities (64,65). Through workshops, campaigns, and outreach programs, individuals are empowered to make informed choices and adopt environmentally friendly behaviors while enjoying winter sports. This educational approach ensures that participants can enjoy these activities in a sustainable way, benefiting both society and the environment. The *Esport Blanc Escolar* (EBE) program is a Catalan initiative aimed at introducing 3rd and 4th graders in the Pyrenees to winter sports. Since its inception in 2013, it has been supported by the General Secretariat of Sport and Physical Activity, in partnership with the Department of Education and local organizations. While teachers appreciate the program as a valuable

introduction to winter sports, they note challenges such as reduced snowfall and concerns that the program may prioritize creating future consumers over fostering a genuine connection with nature. Few students continue participating in winter sports after the program (66).

5.1 Implications for long term winter sport participation and climate awareness

Public engagement in winter sports and **awareness of climate challenges** are interlinked issues with significant implications for the future. Exercising in natural settings, such as skiing or snowboarding, has been shown to provide substantial mental health benefits and encourage regular physical activity (67). However, as climate change increasingly affects these natural environments, the benefits and **motivation for winter sports are at risk**. The retreat of glaciers, reduced snowfall, and altered snow conditions in alpine regions are creating a challenging scenario for winter sports enthusiasts.

Predictions indicate a significant reduction in skiing season lengths (1,59), with many former Winter Olympic host cities becoming unsuitable for winter sports by mid-century. Studies have highlighted that public awareness of climate change's impact on winter sports is growing. Researchers have shown that participants' intention to engage in winter sports decreases when exposed to images of climate-affected ski resorts, emphasizing how climate change is altering perceptions and behaviors (67). The shift in attitudes reflects a broader trend where declining snow conditions and shorter seasons are leading to reduced participation, particularly among vulnerable groups such as women, low-income individuals, and urban dwellers. This shift is further exacerbated by the varying impacts of climate change across different regions, creating disparities in the suitability of ski areas and influencing travel patterns and sport choices. Despite growing awareness, many winter sports organizations are still unprepared to address these challenges (1,68). Therefore, proactive adaptations are crucial to preserving the long-term viability of winter sports.

5.2 Collaboration between stakeholders

Collaboration among stakeholders—governments, sport federations, local communities, and environmental organizations—is vital for tackling the challenges climate change poses to winter sports. Inclusive and cooperative efforts, particularly in organizing mega-events, can create platforms for sharing knowledge on climate and sustainability issues, fostering ongoing **dialogue among diverse groups**. However, some researchers argue that the financial-driven nature of the sports industry is often marked by undemocratic and opaque decision-making, which complicates these collaborative efforts (69).

To meet climate action goals in the context of sport mega-events, it's essential to involve a broad range of actors**,** including NGOs, policymakers, urban planners, and researchers. Their **combined expertise** is key to developing effective climate strategies and fostering resilience. Some examples of sport mega-events illustrates the current gap in climate and sustainability knowledge within the industry, underscoring the need for a more inclusive and coordinated approach to ensure sports can adapt to and mitigate climate change impacts (70).

6. Research and communication needs

Climate change is not necessarily the end for snow-based winter tourism, although its impacts vary by region and influence the available adaptation strategies. Assessing climate risks is crucial for tourism businesses, and while existing models offer useful insights, there is a need for more research into recent snow management practices to evaluate their efficiency, effectiveness, and ecological impacts (5).

There are also significant knowledge gaps regarding winter sports. It is unclear whether tipping points exist that could permanently alter tourists' preferences, such as their choice of destinations or winter activities. Future assessments should consider multiple factors beyond climate change, as demographic shifts (population decline or trend to aging), may have a more substantial impact on ski tourism in places like Tyrol, Austria, compared to climate change alone (71). Additionally, research should focus on snow-independent tourism products to determine their appeal to non-skiers and identify what types of destinations—whether established winter sports resorts or less developed areas—might attract new winter tourists. Furthermore, more research is required to accurately quantify greenhouse gas emissions from winter tourism, as existing studies in Alpine countries are often outdated or incomplete. To effectively mitigate climate impacts, a comprehensive understanding of current emission levels and the effectiveness of mitigation measures is essential (5).

7. Conclusions

In conclusion, the intersection of winter sports, tourism, and environmental sustainability presents a complex challenge that requires immediate and sustained attention. The significant carbon footprint of winter tourism, particularly from travel, highlights the urgent need for sustainable transportation solutions. The environmental impact of winter sports is multifaceted, involving not only greenhouse gas emissions but also the degradation of natural habitats, biodiversity loss, and the strain on water and energy resources due to practices like artificial snowmaking. These challenges are further intensified by the economic pressures on ski resorts to maintain profitability in a changing climate, which often results in a greater dependence on practices that harm the environment.

Addressing these issues requires a holistic approach that integrates environmental, economic, and social considerations. The transition to renewable energy for snowmaking, investment in low-carbon transport infrastructure, and the development of sustainable tourism practices are critical steps toward mitigating the environmental impact of winter sports. Furthermore, collaboration among stakeholders—governments, sports organizations, local communities, and environmental groups—is essential for creating adaptive strategies that ensure the long-term viability of winter sports. As climate change continues to alter the landscape of winter tourism, proactive measures and comprehensive research are necessary to sustain these activities while minimizing their environmental footprint.

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